

Reduction of ship steering gear load at high sea states by decreasing rudder angular velocity

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Abstract

The article discusses causes of steering gear overload at high sea states when a ship is kept on course in auto-pilot mode. The presented research results refer to simulations of a ship-autopilot system on a preset course in the presence of varying intensity disturbances (various sea states), with updated alterations of rudder angular velocity (the velocity changes are executed discretely) determined by the function block for conventional sea state determination.

Introduction

To achieve the required quality of course keeping (directional stability) of a ship sailing in various weather conditions, the power of control signals should be comparable with the power of disturbance signals. The intensity of disturbing signals acting on the ship proceeding in changing hydro-meteorological conditions is highly variable – from very low (sea states up to 3) to very high (sea states 8 to 9). In most cases the installed power of an electro-hydraulic steering gear (executing a control signal) is fixed and when the ship is being kept on a preset course this power is utilized in its wide range, from minimum (good weather conditions) to the rated power and one pump unit in operation. In specific conditions, in navigationally difficult areas, for instance, national maritime administrations require that the ship's steering gear should work with two pump units in operation. In such cases, the steering gear power is increased by adding another pump unit working in parallel.

Steering gear power (for one pump unit) is chosen for a particular ship so as to satisfy the condition: rudder angular velocity at full ahead and ship's draft to the summer load line is not less than 2.33 degree per second. It should be noted that there is a requirement that time of changing the rudder from 35 degrees on one side to 30 degrees on

the other side should not exceed 28 seconds [1]. The condition to obtain such rudder angular velocity is derived from another requirement: safe passing of ships proceeding on opposite courses, or from the practical condition, proposed by ship captains, to obtain a non-dimensional angular velocity (rate of turn) of the ship equal to 0.2 after it covers a distance equal to the ship's length [2]. The steering gear power selected to guarantee an appropriate rudder angular velocity (as a rule, the assumed velocity ranges from 3°/s to 5°/s) corresponds to the power of disturbances affecting the ship at sea state 3 to 4. Therefore, a lack of equilibrium is observed between control power and disturbances power at low and high sea states. As a consequence of this inequilibrium, the quality of course stability varies despite correct control algorithms. At low sea states, an average yaw angle amplitude is minimal, while at high sea states low power of the steering gear does not allow to effectively compensate the effects of disturbances (waves, wind, current). Along with an increase of sea state the amplitude of yaw angle also increases (up to five degrees), and so do rudder angles. Besides, reversals of the steering gear become more frequent. Although the mechanical, hydraulic and electrical requirements for the steering gear, according to classification society regulations, are very strict assuring high reliability,

failures of steering gear do occur, mainly due to exceeded design parameters – temperatures, number of reversals within one hour, or pressures – resulting from engine orders necessitating too intensive control signal sent by the heading controller. The algorithm of heading controller (mainly PID) should execute control assuring that the assumed quality criterion (figure of merit) is satisfied. One such criterion is economical – keeping the ship on the preset course, understood as a requirement to develop a maximum velocity in given conditions. Meeting this criterion will result in lower fuel consumption when covering one mile, for example (at constant propulsion power) thanks to shorter operation time of the main engine. A synthesis of the optimal algorithm of the controller for meeting the above criterion comes down to looking for a control that will minimize the functional:

$$\Delta v \cong \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T (m^2 \Delta \psi^2 + \beta^2) dt \quad (1)$$

where:

- $\Delta \psi$ – heading angle deviation;
- β – rudder angle expressing mean speed loss from stopping forces due to the hull moving along the drift angle and with deflected rudder.

The functional includes a coefficient m^2 , which is not the Lagrange multiplier determined from control constraints. For a given ship, it is a constant:

$$m^2 = \frac{B_1}{B_2} \quad (2)$$

where:

- B_1 – hydrodynamic coefficient dependent on the shape of underwater part of the hull;
- B_2 – hydrodynamic coefficient dependent on the size and shape of the rudder.

The constant coefficient m^2 can be defined for each ship, and ranges from 4 to 16 [3].

However, the determined optimal controller algorithm for the above criterion, taking into account control constraints, causes steering gear overloading in high seas. One dangerous symptom of improper work of the steering gear in high waves is a large number of steering gear reversals performed in one hour. Steering gear is designed for 350–400 reversals per hour, while at sea states 8–9 the figure may reach even 2000. So frequent changes of rudder motion direction lead to fast wear of systems controlling the capacity of variable displacement hydraulic pumps (directional valves, telemotors), wear of electro-hydraulic directional valve springs, heating of pump drive motors, and may cause leaks

in the hydraulic system due to pressure surges. The machine sends an alarm signal when allowable values of such parameters as temperatures or mean current of main electric motors are exceeded. This forces the crew to switch off the autopilot and start manual steering by a helmsman. Such situations could be avoided if the steering gear was more powerful. However, a more powerful steering gear, with a given moment at the rudder stock, translates into higher rudder movement speed, wider frequency band executed by the steering gear. Such states correspond to wider rudder angles being set at higher frequency (lower attenuation of controller signal). This, in turn, increases stopping forces from the rudder and ship speed reduction. The ultimate effects are higher fuel consumption and higher transport costs.

For the above reasons, the selection of a steering gear power is an optimization problem. On the one hand, safe manoeuvring criterion has to be met, on the other hand cost-effective operation of the ship in various sailing conditions has to be assured. As it is estimated that as much as 70% of ship's operating time falls to low and medium sea states, there is no reason to install power units of much higher capacity [3]. For the remaining 30% time of operation in difficult conditions created by high sea states action has to be taken to protect steering gear from overloading by giving up optimized control executing an assumed figure of merit.

Among many methods of reducing the intensity of steering gear operation with autopilot at high sea states common actions include [3, 4, 5, 6]:

- increasing the dead zone width of the P-type heading angle controller, or the power amplifier of the controller;
- reducing the gain of derivating part of heading angle controller;
- filtering out higher frequencies in the heading angle signal;
- reducing rudder angular velocity;
- increasing the idle time of steering gear;
- changing the criterion (functional) for algorithm optimization (adaptive controllers).

The above actions are performed automatically in modern autopilots, depending on the results of analysis of signals from the course keeping stability system. It should be noted, however, that each of the above actions limiting the steering gear power causes the mean yaw amplitude to increase. Further in this article proposals will be made in reference to the control of steering gear angular velocity depending on the intensity of its work, defined by the function block analyzing the control signal.

Assessment of steering gear work intensity operating at high sea states

As it was stated previously, during the steering gear-autopilot co-operation at high sea states the power unit gets heated (electric motors of pump drives, pumps, hydraulic oil, hydraulic cylinders). Besides, the steering gear performs a large number of reversals per time unit, harmful for its durability. The alarm system monitors the condition of the machine by observing temperatures or mean currents of electric motors and, in case a parameter is exceeded, engine personnel are alerted on a dangerous situation that may lead to a failure. The personnel are obliged to immediately reduce the load by disconnecting the autopilot and continuing the voyage with the ship being steered by a helmsman. Return to automatic mode (autopilot) should take place only after the power unit cools down (alarm signal disappears) and upon selecting new autopilot settings in the heading controller. The alarm system does not monitor the intensity of steering gear loads by counting the number of reversals within a time unit. Although such count is possible by counting the number of changes in the sign of rudder angle derivative, it is difficult due to a lack of proper devices onboard with such functionality. Besides, counting the number of reversals by recording the actions of electrohydraulic directional valves controlling the flow of hydraulic fluid from fixed displacement pumps to hydraulic cylinders is also troublesome due to numerous additional switchings, resulting from the action of feedback around the three-point controller of the steering gear (follow-up control with dynamic correction).

The author proposes an assessment of steering gear work intensity based on the results of an algorithm analyzing the signal of rudder angle variance and rudder angular velocity variance taken in appropriate proportions. The algorithm is executed by a function block, whose diagram is shown in figure 1.

The block input gets a rudder angle signal $\beta(t)$ from a rudder stock sensor. The constant compo-

nent is eliminated from the signal by its differentiation, then integration. The obtained signal $\beta_1(t)$ is amplified k_1 times, then squared. The signal $[\beta_2(t)]^2$ is subtracted from the square of properly amplified signal of rudder angular velocity (amplified k_2 times). The obtained difference is averaged by a first order inertial element with a relatively large time constant. The resultant signal $X(t)$ is considered as a measure of the steering gear work intensity. A characteristic feature of the above system operation is the fact that the signal $X(t)$ assumes 0 value for $k_1/k_2 = \omega_0$ (k_1, k_2 – gains of rudder angle term and rudder angle derivating term), whilst ω_0 is a signal frequency $\beta(t)$ for navigation in calm water, and the signal increases as sea state rises. The results of the presented function block operation are described in detail in [7].

It is proposed to use the block output signal $X(t)$ for changes of rudder angular velocity in order to reduce the intensity of steering gear work intensity.

Application of the function block for rudder angular velocity control

Reduction of steering gear load when it is controlled by an autopilot at high sea states can be achieved by decreasing the angular velocity of rudder ($P = M\omega$). The choice of a new rudder angular velocity should satisfy the regulations (minimum $2.33^\circ/s$), and cause such reduction of load that in given conditions the autopilot could be used and that the new control would not lead to a substantial decrease of the relevant figure of merit (e.g. significant drop in ship's speed).

Technical solutions allowing to control the rudder angular velocity may vary. A simple method consists in decreasing the displacement of hydraulic pumps by reducing their rotary speeds. Electric motors of these pumps should be multiple-speed motors or fed by voltage inverters with controlled U/f ratio, with discrete control obtained by changing the number of pole pairs or discretely forcing a new U/f ratio.

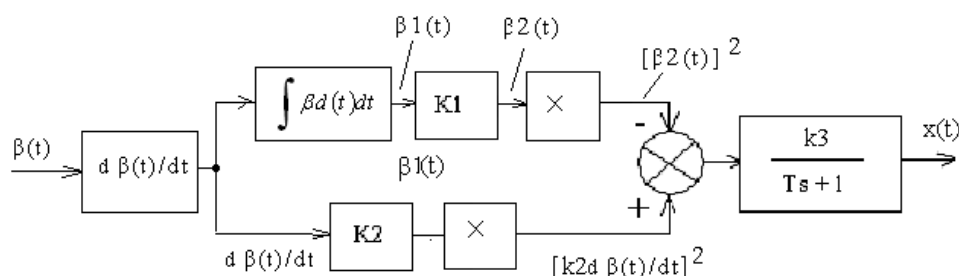


Fig. 1. Diagram of the function block, $\beta(t)$ – rudder angle signal

It is proposed that two rotary speeds are chosen, dependent on the level of function block signal $x(t)$ and preset levels of switching two-point controller governing motor speeds. The idea of this solution is illustrated in figure 2.

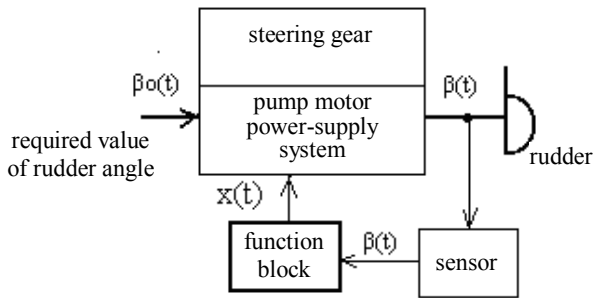


Fig. 2. Method of using the function block for changes of rudder movement speed

To explain the operating effectiveness of the rudder angular velocity control system at high sea states by means of a function block, we have modelled a heading angle stability system with a PID controller (without parameter adaptation) (Fig. 3).

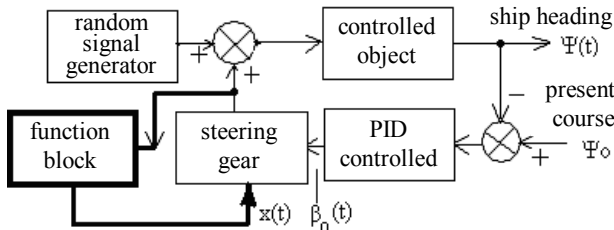


Fig. 3. Model of heading angle stability system with rudder angular velocity control

The assumed model is a simplified, linear model of ship dynamics with the transmittance expressed by the formula [8]:

$$G(s) = \frac{0.05}{s(20s + 1)}$$

A steering gear with fixed displacement pump and fixed delivery direction is modelled as a non-linear follow-up system with a three-point controller without dynamic correction, with a constant coefficient of integrating real part gain and with a restriction of an output signal at a level of ± 30

degrees. A change of rudder angular velocity in this model is obtained by changing the gain coefficient of the integral real term (with inertia).

A schematic diagram of a steering gear model is shown in figure 4.

The integral gain coefficient for a steering gear working at normal (designed) movement speed is assumed at $k = 4^\circ/s$ while for a gear being shifted at a reduced velocity – at a level $2.5^\circ/s$. A time constant of the integral real term is assumed to be $T = 0.8$ s.

Responses to a step change of a setpoint $\beta_0(t)$ of the modelled steering gear working at various speeds are shown in figure 5.

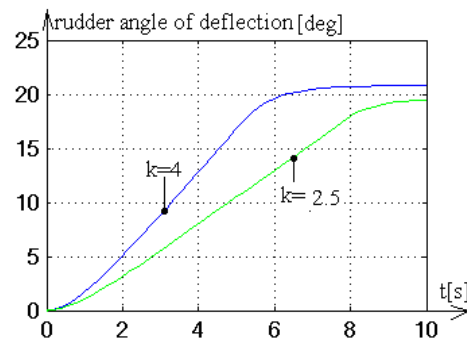


Fig. 5. Responses to step changes executed by the steering gear model at full ($k = 4$) and reduced ($k = 2.5$) velocity

Controller settings were chosen so as to give 10% overshoot when a ship changes its heading (at no disturbances condition).

A random setpoint was sent at the model input, reflecting the action of forces and moments on the hull due to waves. The output signal was a random signal with the following power spectrum density:

$$S(\omega) = \frac{2Dr\alpha(\alpha^2 + \beta^2 + \omega^2)}{\omega^4 + 2(\alpha^2 - \beta^2)\omega^2 + (\alpha^2 + \beta^2)^2}$$

where: β – resonance frequency of the spectrum, $\alpha = 0.21\beta$, Dr – process dispersion.

The function block was tuned to a frequency $\omega = 0.1$ ($X = 0$). The values of parameters β and Dr were taken from available publications, for waves corresponding to sea state 8 ($Dr = 3.398 \text{ m}^2$, $\beta = 0.55 \text{ rad/s}$, $\alpha = 0.115 \text{ rad/s}$) [3].

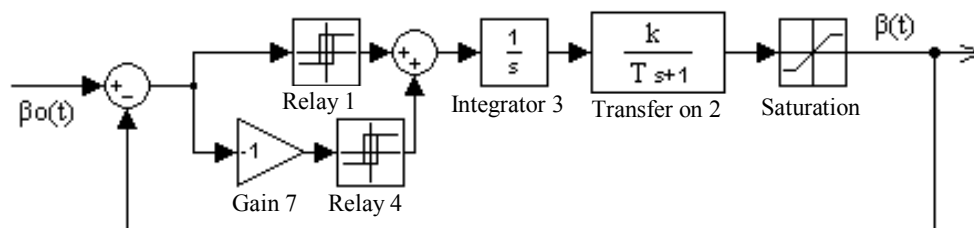


Fig. 4. A steering gear model

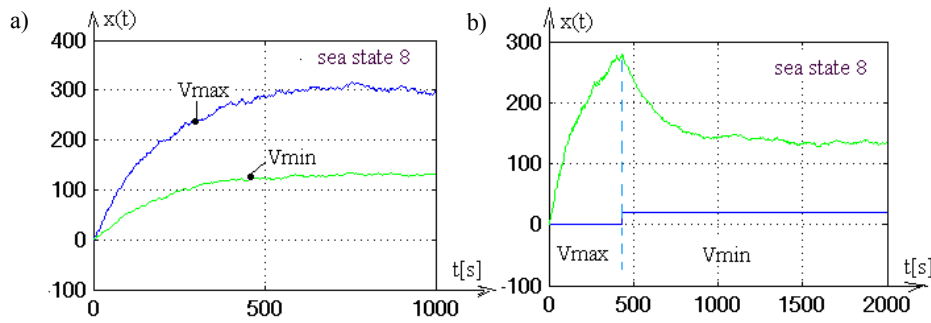


Fig. 6. Changes of the output signal $x(t)$ of the function block; a) for full and reduced velocity of steering gear movement, b) when switching the gear from full to reduced movement speed

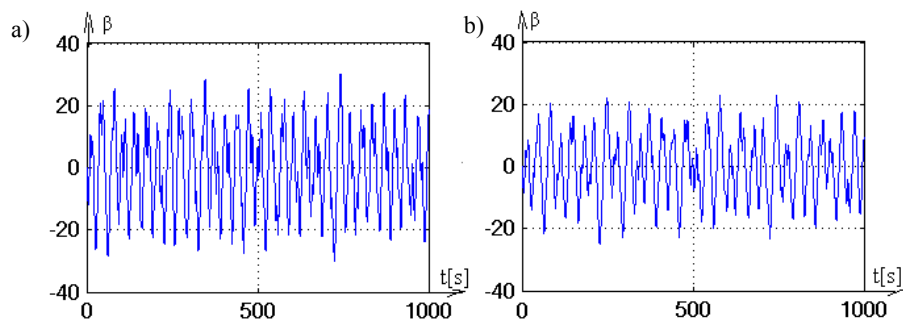


Fig. 7. Rudder angle signal; a) full rudder angular velocity, b) lower rudder angular velocity

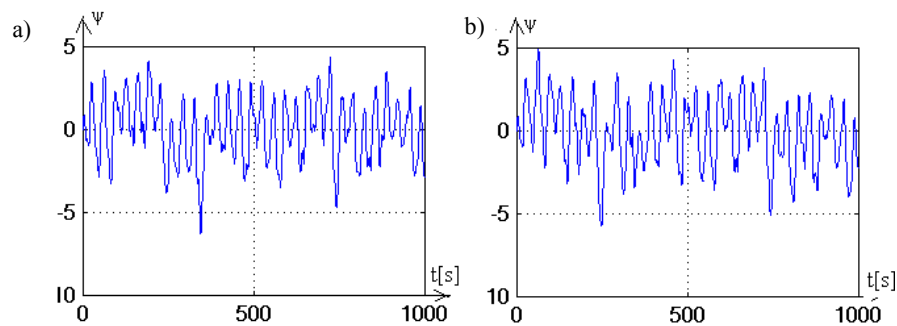


Fig. 8. Ship's yawing angle signal; a) full rudder angular velocity, b) lower rudder angular velocity

The simulation was performed using the MATLAB Simulink.

Figures 6, 7 and 8 demonstrate the results of simulated action of the function block (signal $X(t)$), rudder angle signal (signal $\beta(t)$) and ship's yaw angle signal (signal $\psi(t)$) for sea state 8, at full and reduced angular velocity of the rudder.

The change of output signal was used to reflect automatic alterations of rudder angular velocity from full to reduced and the other way by adding a switching block to the system.

A substantial hysteresis was applied in this block to assure stable operation of the system in case the function block signal drops after a reduced velocity signal input. Levels of switching a two-point controller were set at 280 and 100, so that the system could switch the gear to a lower velocity before reaching the saturation of signal $X(t)$ (about

300) and to prevent the gear from returning to full velocity after a drop of signal $X(t)$ value after velocity reduction. The action of the system with the switching function is shown in figures 6b and 9.

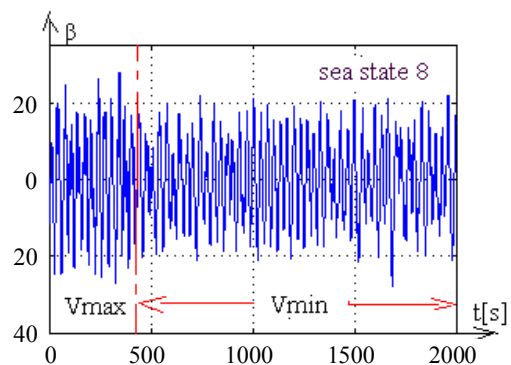


Fig. 9. Change of the rudder angle signal after steering gear angular velocity alteration

Conclusions

It follows from the presented simulation results that a reduction of rudder angular velocity critically decreases the output signal of the function block, and the mean amplitude of rudder angle and slightly increases the yaw angle. A decrease in mean rudder angle amplitude is significant, which reduces the intensity of gear operation. Besides, the number of rudder movement directions in a period of time slightly drops. The use of the function block and its output signal $X(t)$ enables the automation of the process of switching the rudder angular velocity when sailing at high sea states from full to reduced velocity (and *vice versa*), which should enhance the safety of ship operation by decreasing the probability of steering gear failure.

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