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Increased accuracy of ship's steering gear with constant delivery pump using the rudder angular velocity signal

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Abstract

This article presents properties of a follow-up system executing ship's rudder deflection using a constant delivery hydraulic pump. Furthermore, a solution is discussed which increases static and dynamic accuracy of such a system using the rudder angular velocity signal. This signal has been used for changing the level of a three-position controller insensitivity. The paper also shows the method of determination of the function describing variations of dead-zone width of the three-point controller. Two kinds of such function are shown, namely linear and quadratic. A computer model was prepared in MATLAB-Simulink environment, showing the operation of the system with correction of error signal, which carries out given by function variations of points of switching. Also included are the simulation results of the described solution, indicating a significant enhancement of accuracy of rudder angle control process for the steady state as well as during transients.

Introduction

As ships have started using electronic autopilots, which have a relatively low-power rudder angle output signal (a few watts), it has become necessary to amplify the signal. The power of the preset rudder angle signal (the signal from the manual steering setting device fixed to the steering wheel) is amplified by the ship's steering gear. As the required power signal ranges from a four to five-digit value in kilowatts, these amplifiers (steering gears) mainly use electrohydraulic solutions, which have a number of advantages (Wyszkowski, 1982; Waguszczienko, 2002):

- simple design, providing smooth rudder movement with proper accuracy;
- high moment of force can be obtained on the rudder stock;
- relatively small mass and dimensions;
- long failure-free operation time under hard conditions of vibration and high humidity;
- simple overload protection.

Engineering solutions for the hydraulic part of the system are based on constant delivery and constant discharge direction hydraulic pumps as well as variable delivery and discharge direction pumps. For handling steering gear with a power below 20 kW, a system solution with a constant delivery and discharge direction pump is used. For higher power output, a pump with variable delivery and discharge direction is used. These two solutions provide sufficient accuracy for the steering gear. This is hard to obtain in high power units because of the substantial inertia of advance and rotary movement of mechanical parts. In low power steering gear, the inertia can be controlled by connecting the constant delivery pump to the appropriate side of the hydraulic cylinder or disconnecting the pump from the cylinder, using a simple three-position control.

According to relevant regulations of classification societies, the steering gear shall be designed so that, with the ship running ahead at maximum service speed, the rudder can be put over from 35° on one side to 30° on the other side in not more than 28 seconds. This yields an average of rudder turn of 2.33° per second (PRS, 2007). Modern steering gears ensure even higher rates of turn: 3° to 4° per second.

Actual rudder movement covers the whole range of angular velocities, from zero to the maximum value. Maximum angular velocities (e.g. 4°/s) are obtained only when the set angle is 5° to 6° larger than the current rudder angle. For set rudder angle changes in the range from zero to five degrees, the steering gear does not manage to develop its full angular velocity while deflecting the rudder due to the system delays and inertia. This is what occurs when a ship is being steered on a set course in good weather conditions.

If the steering gear does not develop a full angular velocity at the rudder, the kinetic energy of mechanical elements will be below maximum and, after the pump is disconnected from the hydraulic cylinders, the gear will cover a shorter angular distance than if maximum angular velocity is developed.

The accuracy of reaching set values, therefore, depends on rudder angular velocity at the moment the pump is disconnected from the working cylinders (assuming there is a constant stopping moment on the rudder stock, which is typical of balanced rudders at a wide range of angles). To obtain a similar accuracy of steering gear when it develops various angular velocities, a procedure is used in which the insensitivity of a three-position controller is changed – as the angular velocity increases, the insensitivity is raised. Such solutions are based on observations of the time the pump is connected to the cylinder through an inertial or integral element (Stefanowski, 2006). This author proposes a change in controller insensitivity as a real function of rudder velocity.

Classification society requirements do not define static and dynamic accuracies of machines. It is assumed in operational practice, however, that the static accuracy of a machine should not be lower than the accuracy, required by classification societies, of the rudder position indicator. That is (PRS, 2007):

- set angle 0° – executed angle 0° ±1°;
- set angle $0° < \beta \leq 5°$ – executed angle β degrees ±1.5°;
- set angle $\beta > 5°$ – executed angle β degrees ±2.5°.

The accuracy with which the rudder can be put at a set angle affects the durability of steering gear, because angle overshoots above the value of the three-position controller insensitivity cause unnecessary movement of the gear in the opposite direction. This consequently raises the frequency of pump switching, the number of oil pressure surges, the number of electrohydraulic distributor overshoots etc. (Stefanowski, 2011; 2013; Stefanowski & Zwierzewicz, 2012).

The accuracy of rudder angle performance also affects a ship's speed and associated cost-effectiveness. Overshoots during rudder deflections increase the longitudinal component of rudder force that decelerates the ship movement ahead, which at constant fuel charges in the engine cylinders, increases fuel consumption required to cover a specific distance, equivalent to higher transport costs (Lisowski, 1981).

The concept of the solution

Figure 1 shows a simplified diagram of steering gear control with a constant delivery pump.

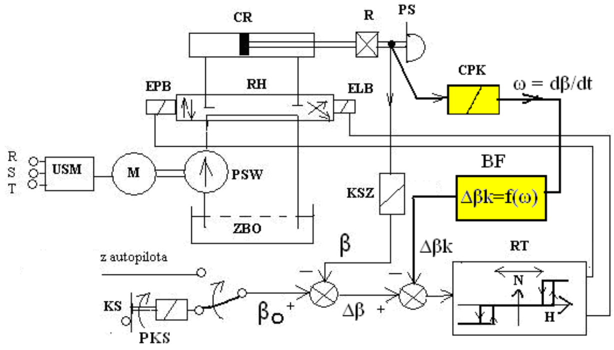

Figure 1. Simplified diagram of steering gear control using a constant delivery pump. The notations: CR – working cylinder, R – gear, PS – rudder, RH – electrohydraulic distributor, EPB, ELB – coils controlling oil flow direction moving the rudder to, respectively, starboard or port side, PSW – constant delivery hydraulic pump, M – electric motor driving the pump, USM – control system of electric motor drive, ZBO – oil tank, KS – steering wheel, PKS – steering wheel transducer, βo – rudder deflection setting signal, β – actual rudder angle signal, $\Delta\beta$ – rudder setting error signal, RT – three-position controller, N – controller insensitivity, H – hysteresis of the controller, KSZ – rudder angle signal transducer in feedback, CPK – proposed rudder angular velocity sensor, ω – rudder angular velocity, BF – proposed block executing the function $\Delta\beta_k = f(\omega)$, $\Delta\beta_k$ – signal correcting the error $\Delta\beta$

The system without the proposed correction works as follows. A change of the rudder angle value βo, which results in a value $\Delta\beta$ greater than the operational limit of the three-position controller, causes one of electrohydraulic distributor coils to be fed (e.g. starboard coil). Consequently, the pump is connected to the working cylinder (power unit) and the rudder turns towards starboard. Each rudder actuation causes a change in signal β of real rudder angle, which reduces error signal $\Delta\beta$. After $\Delta\beta$ is lowered to a value below controller switch-off limit, feeding of the EPB distributor coil stops, and further rudder deflection movement (stopping) takes place due to kinetic energy of the system. The angle at which the rudder will eventually stop in most cases is not equal to the angle setting. The higher the kinetic energy of the system, the greater the rudder run-out angle will be.

The solution proposed herein makes use of an appropriate correction of error signal $\Delta\beta$ by a value $\Delta\beta_k$. The correction yields a rudder rundown at which the static error of the machine is close to zero (i.e. the difference between the setpoint and real angle at which the rudder stops).

Figure 2 illustrates an example of various static error values occurring during rudder deflection angle settings made without error correction. It has been assumed that the power unit of the steering gear can be presented as a real integrating term, whose steady rate of integration is 3.5°/s, while the time constant of inertia is one second. Switch-on limit of the starboard distributor coil $\Delta\beta_z = 1.6°$, switch-off limit of that coil $\Delta\beta_w = 1.5°$ (for the port side coils: $\Delta\beta_z = -1.6°$, $\Delta\beta_w = -1.5°$).

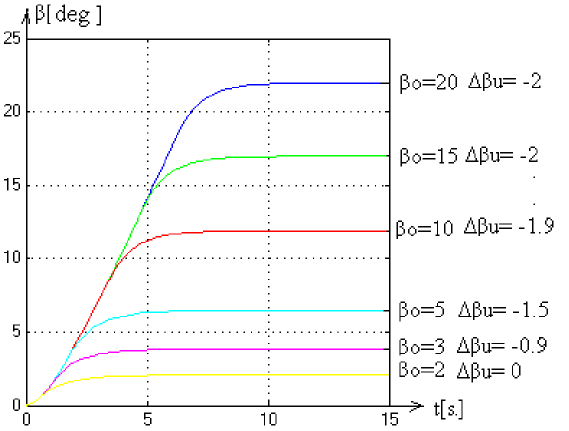

Figure 2. Rudder deflection angles in the control without correction; ($\Delta\beta u$) – static errors of the system for various setpoint values

It follows from Figure 2 that static errors of the steering gear increase along with an increase of angle setpoint, then become steady. This is strictly related to the rudder angular velocity obtained at the moment of pump disconnection and instantaneous kinetic energy of the system. At small angle settings, the steering gear does not reach full velocity and maximum kinetic energy – hence the gear movement (rundown) after the pump has been disconnected is small. This is compared to changing the rudder by a relatively large angle wherein the gear develops full velocity, maximum kinetic energy and substantial rundown.

Bearing this in mind, if we wish to bring static errors down to zero, the pump should be disconnected from the power unit earlier, at a smaller rudder angle.

A simulation method was used to determine the necessary correction of error signal at the moment of pump disconnection, resulting in a static error close to zero. In addition, the value of angular velocity at that moment was determined. Simulations were performed for angles set at 2, 3, 5, 10, 15, 20 degrees.

The simulation results are given in a Table 1.

Table 1. Values of rudder angular velocity and necessary correction of error signal ($-\Delta\beta_k$) at the moment of pump disconnection giving a static error close to zero

βo set value of rudder deflection angle [°]	ωp angular velocity of rudder at moment of pump disconnection [°/s]	$-\Delta\beta_k$ necessary correction of error signal $\Delta\beta$ to reduce static error towards zero [°]
20	3.48	2.02
15	3.45	2.0
10	3.30	1.8
5	2.65	1.2
3	2.05	0.55
2	1.50	0.037

Based on the data from the table, a functional relationship $(-\Delta\beta_k) = f(\omega p)$ was established using the approximation by polynomial function. For a linear function, the approximation has this form:

$$(-\Delta\beta_k) = 1.00443\ \omega p - 1.48264$$
(movement towards starboard side)
$$(-\Delta\beta_k) = 1.00443\ \omega p + 1.48264$$
(movement towards port side)

While for a quadratic function the relation is:

$$(-\Delta\beta_k) = 0.01217\ \omega p^2 + 0.94236\ \omega p - 1.41083$$
(movement towards starboard side)
$$(-\Delta\beta_k) = -0.01217\ \omega p^2 + 0.94236\ \omega p + 1.41083$$
(movement towards port side)

The linear function modified by cutting off negative values for starboard and positive values for port side was used for further investigation. The shape of a function enabling correction to be made is shown in Figure 3.

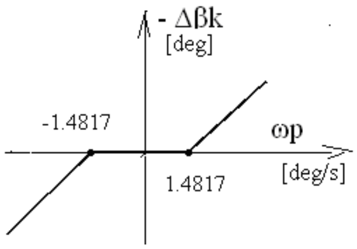

Figure 3. Diagram of the function adopted for correction of the steering gear system

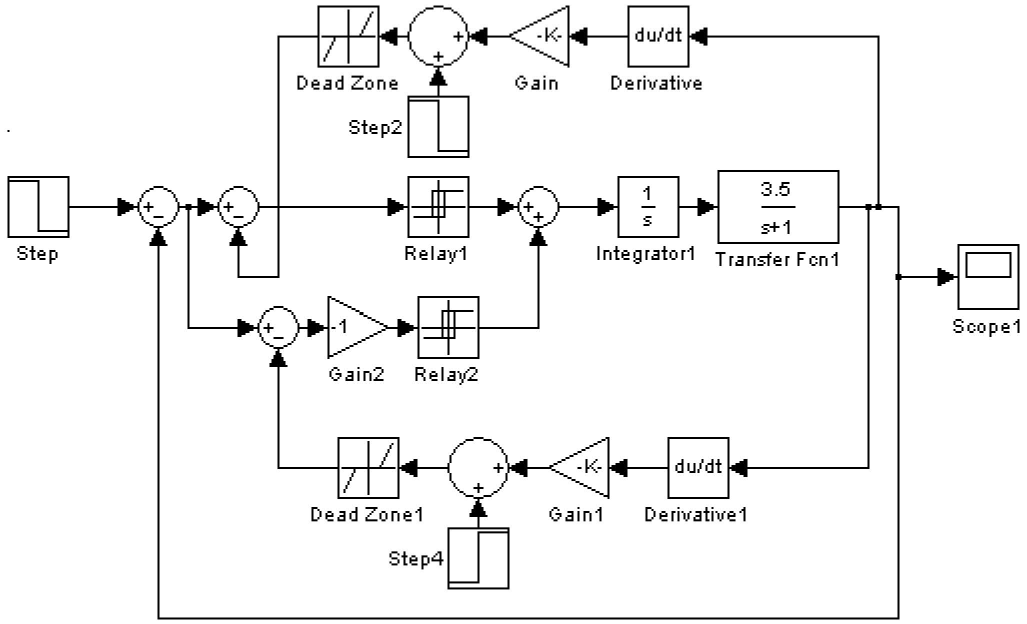

Figure 4. A model of steering gear control with rudder angular velocity correction

An upgraded control diagram was modelled in the Matlab Simulink program.

Figure 4 shows the created model.

The simulation results for angle settings: 2, 3, 5, 10, 15, 20 degrees using the model presented in Figure 4 (with the same object dynamics and the same setpoints of the three-position controller as in a system without correction) are given in Figure 5.

Figure 6 reproduces rudder angle settings in the form of rectangular and sinusoidal waves of low frequency. Very good accuracy can be observed, where the static error is very small (reproduction of sinusoids at the controller switching thresholds of 0.5° "switch on" and 0.4° "switch off" and a new corrective function).

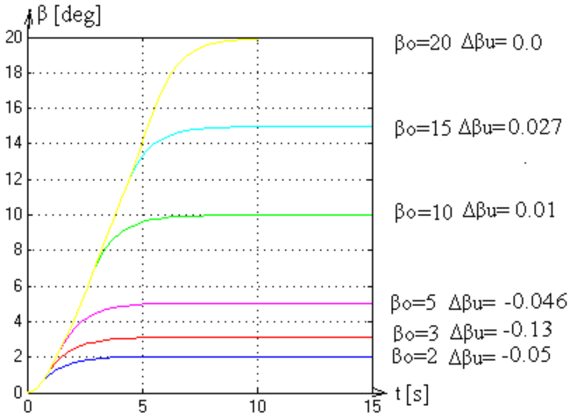

Figure 5. The results of simulated rudder angle changes to 2, 3, 5, 10, 15 and 20 degrees after the introduction of correction signals into the control system

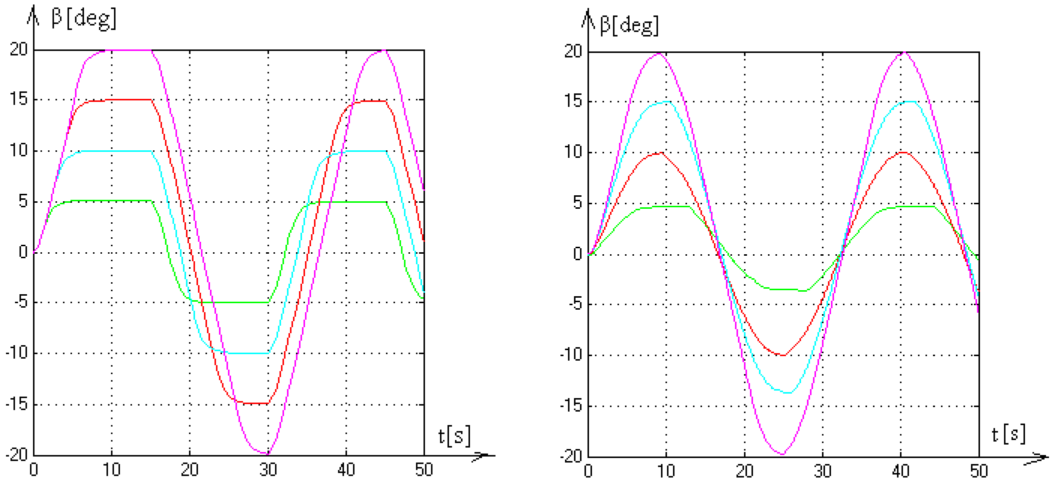

Figure 6. Reproduction of rectangular and sinusoidal waves signals by the upgraded system

Conclusions

The introduction of the corrective signal into the control system of a steering gear with a constant delivery pump, leads to the improvement of static properties of the system, depending on the rudder angular velocity. The corrective signal critically reduces overshoots relative to setpoints. These overshoots can require the gear to move in the opposite direction. Such characteristics of the system make it possible to shift the levels of the three-position controller switching close to zero (e.g. $\Delta\beta = 0.5°$ – switch on, $\Delta\beta = 0.4°$ – switch off). This increases the system sensitivity and enables good reproduction of low-amplitude periodic signals (e.g. one degree). The accuracy of sinusoidal signal reproduction depends on the frequency of the set signal and the level of controller switching. To limit the frequency of switching the electromagnetic distributors, the controller hysteresis has to be carefully selected.

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