Scientific Journals
Maritime University of Szczecin

Zeszyty Naukowe
Akademia Morska w Szczecinie

2012, 30(102) pp. 126–131

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Assessment of ship steering gear load based on an analysis of rudder angle signal

Ocena obciążenia maszyny sterowej statku na podstawie analizy sygnału wychylenia steru

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Key words: automatic control of ship, steering engine of the ship, safety of the ship

Abstract
This paper presents observations and remarks on the work of ship's steering gear controlled by the autopilot in high seas. Attention is drawn to the insufficient power of steering gear operated by the autopilot in high waves and the consequent possibility of overloading and damage to the gear, creating a threat to the ship. Standard safeguards against damage are discussed. It is suggested that the alarm system should be extended to indicate the load of steering gears. The authors propose a method for assessment of the steering gear load by using a signal that is a nonlinear function of the actual rudder angle, based on the solution used in TS-type autopilot adaptation blocks. The results of computer simulations to obtain such signals for autopilot-controlled ship movement in irregular waves (sea state ranging from 3 to 6) are presented. The conclusion reached is that the signal can be used to assess the steering gear load, which may contribute to increasing ship's safety in high sea states.

Słowa kluczowe: automatyczne sterowanie statkiem, maszyna sterowa statku, bezpieczeństwo statku

Abstrakt
W artykule przedstawiono uwagi o pracy maszyn sterowych statków w wysokich stanach morza sterowanych autopilotem. Zwrócono uwagę na niewystarczającą moc maszyn sterowych dla pracy z autopilotem w tych stanach i możliwość ich przeciążania, uszkodzenia i wprowadzenia zagrożenia dla statku. Omówiono standardowe zabezpieczenia przed uszkodzeniem, wskazując na potrzebę rozszerzenia sygnalizacji alarmowej o układ wskazujący obciążenie maszyn sterowych. Przedstawiono propozycję wykorzystania do oceny obciążenia maszyn sterowych signal będącego nieliniową funkcją rzeczywistego kąta wychylenia steru bazującego na rozwiązaniu stosowanym w blokach adaptacji autopilota TS. Przedstawiono wyniki symulacji komputerowych uzyskiwania takiego signal dla realizacji prowadzenia statku autopilotem na nieregularnej fali przy stanie morza 3, 4, 5, 6. We wnioskach stwierdzono, że signal taki może służyć do oceny obciążenia maszyn sterowych, co może przyczynić się do zwiększenia bezpieczeństwa eksploatacji statku w wysokich stanach morza.

Introduction

The steering gear of a ship is one of the devices on which the reliable operation are made and of which depends the safety of people, cargo as well as the operating in different weather conditions. To achieve high reliability of such equipment the measures are being taken at the design stage, at the production phase, as well as on board – during a normal ship operation.

The steering gear, its energy systems (e.g. hydraulic), control systems (servo system and temporary), and energy supply systems should be designed in accordance with the rules of a classification society (e.g. PRS) that supervises the building and operation of the ship. Also, emergency and safety systems shall comply with these regulations. Details of these requirements are available in publications of classification societies.

In spite of compliance with the regulations, during the ship operation, there are cases when the alarm system reports some malfunctions of the steering gear. Among many different key mulfunctions (e.g. low levels of hydraulic oil in the tank pump unit caused by leaks in the hydraulic system, total or partial lack of electrical power, hydraulic lock due to damage of electro-hydraulic valves) the machine power overload is an important fault. The information about such situation is taken mostly from thermo-bimetallic relays that control the average current value of electric motors that, in turn, drive the main pump units, from the thermo-bimetallic relays or the thermistors placed inside the windings of electric motors, or from the thermostat controlling the temperature of the hydraulic oil in the unit. Continued work of an overloaded machine can lead to damage to electric motors or machines, leakage in the hydraulic system caused by lowered viscosity of the hot hydraulic oil, which may result in ship being not under command. In such cases, the steering gear should be quickly relieved by the helmsman.

To prevent the loss of ship control, during a machine failure the steering gear must have at least two pump units: primary and backup. In most cases the power part of steering gear (system of hydraulic actuators) is operated by one pumping unit, whose power is sufficient to turn the rudder with a required angular velocity (e.g. 3–4 degrees per second). The parallel operation of two pump units is applied only during maneuvers (this ensures increased rate of the rudder movement) or in waters where it is required by local maritime administration.

The reason for overloading the steering gear is its insufficient power in relation to the power of environmental disturbances (wind, waves). That is especially important when the ship proceeds in the automatic mode in high seas (only with automatic control of the ship there is an ‘overloading' alarm). It is estimated that the power of the steering gear is comparable to the forces acting on a ship at sea state 4. Above this state steering gear power is less than the power of disturbances. As the sea state increases, also the average amplitude of yawing rises, so does the average current of electric motors. Besides, the hydraulic oil temperature increases and consequently an alarm signal is released. During automatic stabilization of the ship course in heavy weather conditions the number of the reverse turns per hour rapidly grows. The gear designed for approximately 350–400 turns per hour makes about 2000 turns. This results in additional power loads of the mechanical and hydraulic systems that may cause damage to the steering gear.

The steering gear has less power than the forces of disturbances acting in high waves for economical reasons – to minimize the cost of ship operation in terms of fuel consumption. Using steering gear of higher power leads to decreased course stability of the vessel. On the other hand it leads to increased forces stopping vessel movement, reduced average speed and, as a result, increased fuel consumption to cover the whole route (for constant power of the plant). Installation of a more powerful machine is not advisable even if we consider the use of lower power of presently installed machine. The period of the gear operation in the automatic mode in high sea states (6–8) is only (20–30)% of the whole period of the ship operation. The remaining (70–80)% of this period accounts for the low and medium sea states, at which the machine operates with a small and very small load (e.g. the gear deflects the rudder to 5 degrees with the number of turns from a dozen to several dozen per hour).

It follows from the above considerations that the characteristic feature of ship steering gear is the risk of its overloading at high sea states while the vessel operates in the autopilot mode. Such overloading can cause damage to the gear and the ship control may be lost. Therefore, there is a need to extend the vessel alarm system by a subsystem monitoring the current load state of steering gear, so that the engine crew can take prompt relief action (e.g. change autopilot controller settings) before the alarm sounds. The paper presents possibilities of assessing the steering gear load on the basis of the available rudder deflection signal from the rudder stock in various sea states.

Assessment of steering gear load

The steering gear that in high seas may be overloaded has to be equipped with an overload alarm. Such signalling is in standard use as required by regulations. The overload signal is mostly generated due to exceeded average current of motors driving primary hydraulic pumps, excess temperature of the windings of motors operating variable delivery pumps or excessive hydraulic oil temperature. Additionally, the steering gear is equipped with an alarm system signaling that other parameters are exceeded (e.g. low tank level of hydrauic oil, increased drop of pressure at the oil filter, detected errors in electric supply to the power or control systems, hydraulic lock).

Alarm signals from the steering gear and procedures of operating pump and actuator units in an emergency situation allow to operate the steering gear safely. However, the monitoring of steering gear work based on alarm signals does not reveal its actual load. Alarm signals do not inform about speeds and accelerations of main mechanical parts during high sea states. There is no data on the torque developed at the rudder stock that would allow to determine the present power of the steering gear.

Average values of temperatures or electric motor currents do not reflect any information on properties in frequency domain of rudder deflection signal. Rudder reversals (change in the direction of rudder turns) are connected with a rapid direction change of oil discharge to the actuators and a sudden, short increase of the pressure in the hydraulic system that may cause its damage. Too many reversals in a short time is described by the engine personnel with the phrase "the gear jerks" often followed by requesting the OOW to change the operating condition of the steering gear (change the autopilot settings or switch it off). The actual change of steering gear working conditions takes place after "gear overload alarm" and chilling down the unit, which happens during manual steering until the alarm signal disappears.

Information on the frequency characteristics of rudder angle signal, that would illustrate more objectively both steering gear load and its reversals, can be created by processing the signal with function blocks [1], through an analysis of reversal times of electro-hydraulic port / starboard direction distributors or by analyzing other variable signals of the steering gear. It is worth noting that the constant value of rudder angle does not require a great power load because then hydraulic pumps work either in circuits outside the actuators (gear with constant delivery pumps), or with delivery equal to zero (gear with variable delivery pumps) absorbing a minimum power from the system. Therefore, essential information on the present power load of the steering gear is contained in the rudder angle signal, i.e. in the signal of rudder turning speed.

Further in this study authors propose to use the adaptation block algorithm for creating a signal informing on steering gear operating condition. The algorithm is used in Polish TS type autopilots for determining conventional sailing conditions. The output signal of such block is used to lighten the steering gear load when navigating on autopilot in high waves. This is achieved by automatic increase of the controller P insensitivity (of the autopilot) and reducing the amplification of controller D when sea state rises. The block algorithm, modified by the authors, is shown in figure 1. It accounts for the fact that when the sea state increases, the average values of course deviation signal module and the angular speed module increase. The share of higher harmonics in the course deviation signal spectrum also increases. It can be proved [2] that the dispersion of output signal from the course controller PD (which enters the input of the steering gear) of that signal depends mainly on the dispersion of angular speed and squared amplification of element D of the controller (it can be assumed that steering gear overload is mainly caused by element D of course controller). An increase of signal dispersion at the steering gear input while sea state increases leads to increase of rudder angle signal module and the module of its derivative: rudder rate of rudder turn. Notably, the derivative module grows faster than the rudder angle signal module when sea state increases. Practically, the availability of output signal from the course controller is hampered because the technical control of the follow-up system of the steering gear takes place directly in the autopilot (its electronics may include a three-position controller, comparator, additional dynamic elements to achieve the proper statics and dynamics of the follow-up system). Authors propose to estimate the load of steering gear by taking a real signal from the rudder stock. This signal significantly differs from the course controller because it results from non-linear transformations of the controller signal

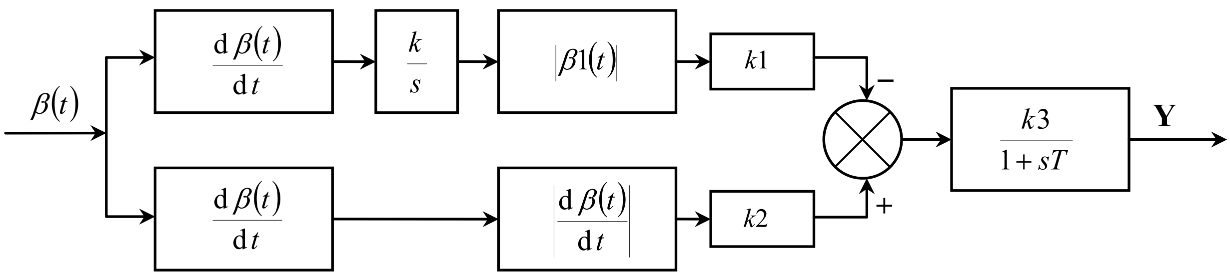

Fig. 1. Block diagram of the algorithm for determining the steering gear load
Rys. 1. Schemat blokowy algorytmu wyznaczania obciążenia maszyny sterowej

(e.g. through an additional three-position controller with dead zone and hysteresis). The differences are also due to restrictions of the hydraulic pumps delivery (restricted angular speed of the rudder) and maximum value of rudder deflection.

Nevertheless, the signal should reveal an increase of the module of rudder angular velocity and rudder angle module as the sea state rises. The place of system connection is illustrated in figure 2.

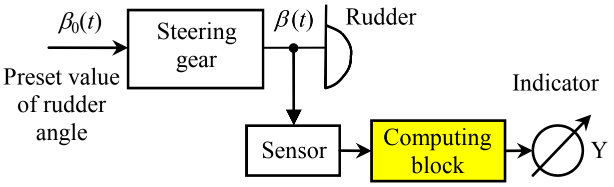

Fig. 2. The connection of the computing block
Rys. 2. Miejsce włączenia bloku obliczeniowego

The system input receives the signal $\beta(t)$ from the rudder angle sensor. The constant component, introduced by autopilot controller I, is eliminated from the signal. Then its module $|\beta 1(t)|$ is determined. At the same time the signal derivative ($d\beta(t)/dt$) and its module $|d\beta(t)/dt|$ are determined. After amplification of the signal modules, K1 and K2 times respectively, the signals are subtracted and the result is averaged by a first-order inertial system. The averaged output signal is a difference of respectively amplified modules of rudder angular speed signal and rudder angle signal without the constant component.

If amplifications K1 and K2 are chosen so that K1/K2 is equal to the basic frequency of signal $\beta(t)$ for calm water sailing, then signal Y at the output will assume the zero value. When the sea state rises, higher harmonics appear in signal $\beta(t)$ and increase the value of signal Y. A theoretical relation between the average value of signal Y and signal $\beta(t)$ frequency for its constant amplitude and averaging of ½ period is linear. That linear relation does not occur in the presented system due to dampening action of the inertial element along with frequency increase. The value Y also grows when the average amplitude $\beta(t)$ increases. Observing the value Y with an indicator it can derive conclusions concerning the spectrum of signal $\beta(t)$.

By setting a maximum value of signal Y for a given ship (and its steering gear) it can estimate the operation of steering gear in the range of higher frequencies on the basis of present value of the signal.

If necessary, engine personnel may then request the deck personel to change the algorithm of course controller to eliminate higher harmonics in signal $\beta(t)$. Also, the bridge personnel, seeing indications of the value Y, may introduce changes of the algorithm in advance and lighten the gear, before the overload alarm sounds.

To verify the effectiveness of steering gear monitoring at various sea states by means of the modified algorithm a model was made of course stabilization system with a PID controller (without parameters adaptation) – figure 3.

Authors adopted a simplified linear model of ship's dynamics with transmittance defined by the formula:

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

The steering gear was modeled by a 1st order inertial element with an assumption that its follow-up system for slight rudder deflections is a linear system (the steering gear will not turn the rudder to the limits). PID controller settings were selected to give 10% overshot when the ship alters course.

A random signal was applied at the input, corresponding to forces and moments acting on the ship's hull due to waves. The random output signal had a spectrum density of power in this form:

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

where β – is a resonance frequency of the spectrum, $\alpha = 0.21\beta$, Dr – dispersion of the process. The function block was tuned to a frequency $\omega = 0.1$ (X = 0). Figure 4 shows the results of simulated operation of the system for sea states 3 to 6.

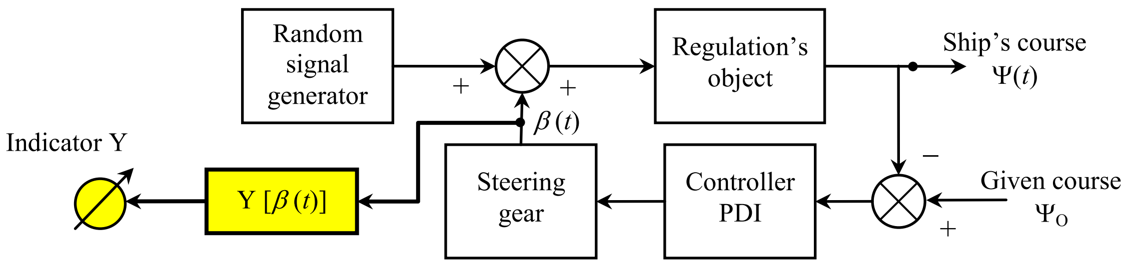

Fig. 3. A model of course stabilization system with steering gear load monitoring
Rys. 3. Model układu stabilizacji kursu z monitorowaniem obciążenia maszyny sterowej

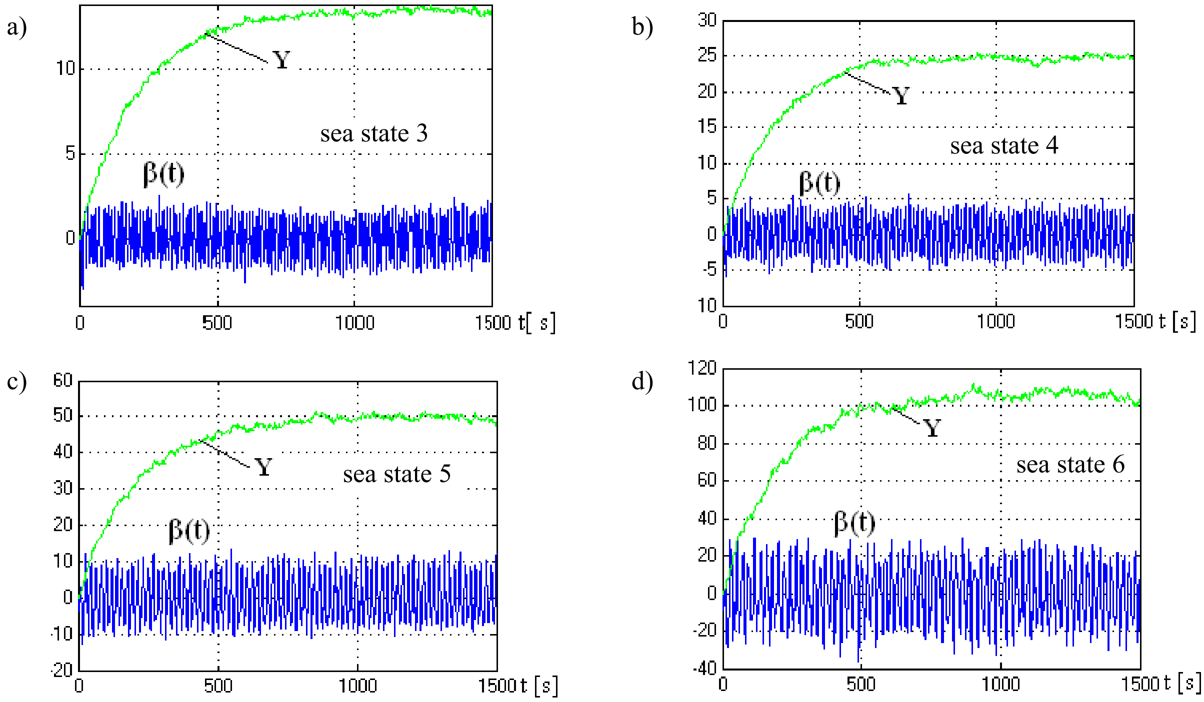

Fig. 4. The change of signal Y of the function block at sea states: a) 3, b) 4, c) 5, d) 6.
Rys. 4. Zmiana sygnału Y bloku funkcyjnego w stanach morza: a) stan morza 3, b) stan morza 4, c) stan morza 5, d) stan morza 6

One can see from an analysis of changes of function Y block output signal that along with an increase of sea state the signal Y also increases and stabilizes. The stabilization time is about 10 minutes. Therefore, the stable value of signal Y can be used for assessing sailing conditions and the associated load of the steering gear.

A limit value of the signal not to be exceeded can be adopted for a specific ship and its steering gear power. When the limit value is exceeded, settings of the autopilot course controller should be changed, so that signal Y is brought down to an allowable value. If such reduction of the signal Y is not possible, the autopilot should be switched off and the ship steering should be taken over by a helmsman.

Conclusions

Based on the conducted simulation results it can be concluded that the proposed solution of the steering gear load assessment, that has been accomplished via the processing a signal of the rudder angle deflection, by means of the presented algorithm is characterized by encouraging qualities wherein:

- it can be used to assess the load of the steering gear – especially in co-operation with the autopilot equipment in high sea states;
- it has a very good resolution – the changes in sea state produce significant changes in the settling output value Y;
- it is characterized by a relatively short time to achieve a settled value Y, i.e. to obtain the information about the steering load (approx. 10 min.);
- this solution allows the realization of the algorithm with simple technical means and may be applied on ships that do not have computer systems;
- it is characterized by ease of visualization of the signal Y using standard measuring instruments.

Simulation study was carried out with the use of simple models of the ship and its steering gear hence the results may not be adequate for vessels described, e.g. by nonlinear models, the scaled noise spectra for various angles of the direction of the ship’s and wave propagation, etc. Follow-up studies need to conduct simulation research for more complex models of objects and disturbances, as well as to collect the performance results of the algorithm based on the rudder angle signal that is taken from the real steering gear operated in different sea conditions.

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