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On the overloading of the steering gear controlled by automatic pilot at high seas

SUMMARY

The problem of the overloading of steering gears controlled by an automatic pilot is presented. The paper also describes basic causes of the phenomenon, applied methods of limiting the signals sent to the steering gear under such conditions and prospects of solving the problem by introduction of an optimum multicriterion control system.

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INTRODUCTION

An important functional imperfection of the automatic ship's course stabilizing system is that beginning at some high sea state (e.g. over 6°B) the system must be switched off and course keeping must be executed by a helmsman. Such decision is taken usually when receiving a signal from steering gear about its overloading.The intensive steering gear action, manifested by rise of temperature of working medium, electric motors and pumps, induces quick tear-and-wear of its elements, and leads to failures and loss of ship's manoeuvrability, which can be dangerous for the ship while navigating in rough weather.

The problem, known to ship designers for a long time, is not yet solved satisfactorily enough. Modernization of steering algorithms, carried out by different automatic pilot producers, solves the problem partially by making it possible using automatic pilot to navigate a ship at higher sea states at the expense of a substantially lower course-keeping quality and ship's speed drop.

The algorithm improvements concern mainly with limitation of amplitude of signals sent to steering gear, by filtrating some steering signal components (e.g. regulation error derivative signal), limiting and cutting-off signals by means of elements with insensitiveness and saturation characteristics, lowering amplification factors etc. It should be noted that a helmsman, who takes over ship's steering duties from an automatic pilot because of steering gear overload, can control the ship with an accuracy comparable to that of the automatic pilot and radically lowered (several times) steering gear load. It may evidence that there are still vast possibilities in searching for improvements of automatic steering algorithms aiming at a satisfactory solution of the problem of steering gear overloading in high seas.

MAIN CAUSES OF STEERING GEAR OVERLOADING

There are many causes of the overloading of the steering gear controlled by an automatic pilot. The most important are the following:

- too low steering gear power necessary for automatic steering
- load disturbance spectrum (due to waves, wind, ice impacts) is located outside steering gear transmission band
- incomplete knowledge of steering process (in most of automatic pilots steering control is carried out on the basis of error signal)
- inadequate steering algorithms resulting from either incomplete information about the process or/and lack of information about dynamic motion characteristics of a given ship considered as a control object
- steering quality criteria, assumed while designing an optimum steering system, do not sufficiently account for steering gear overload

Some of these problems are solved successfully in adaptive automatic pilots, but steering gear overload problem still remains unsolved.

METHODS TO COPE WITH STEERING GEAR OVERLOADING

Steering gear power, determined for a given ship, should ensure her an appropriate manoeuvrability, sufficient course-keeping ability, sufficiently high angular velocity rate when putting rudder on side, all to provide ship's navigation safety. The rudder area and the time of putting rudder from one side to the other side, regulated by rules, are selected in such a way as to obtain these aims. The increasing of rudder putting-over speed or rudder area could better ship manoeuvrability but worsen her course-keeping ability which in consequence could lead to a greater energy loss when steering in good navigating conditions.

It is assessed that steering gear power margin can cover a disturbance power up to 3÷4°B sea state. Over that, disturbance power is higher than that of steering gear.

The broadening of steering gear transmission band is connected with the increasing of rudder putting-over speed, therefore the limitations, similar to those above stated, appear.

While course-keeping in high seas it is impossible to measure directly the forces and moments due to wave and wind action against ship's hull. Nonetheless statistical characteristics of such disturbances (e.g. power spectral density) is known, but their current identification (of e.g. variance) is difficult; thus precluding them from any direct use in steering.

Usually, steering is based on error signal processing, but an averaged information about external conditions intensity is used to returne course regulator PID coefficients or to control nonlinear elements which limit signals to steering gear.

To analyse external conditions intensity the following signals are usually applied:

- yawing angular velocity
- pitching angular velocity
- maximum yawing angle

When analysing helmsman's performance in the difficult conditions it seems that the gaining of additional information on ship's environment is the area where possible solutions of the problem could be found. The information can be gained by measuring magnitudes, other than the above mentioned, e.g. wind direction in respect of ship's course, wave height, wave encounter frequency, and used to form steering algorithms.

Dynamic behaviour of a ship, considered as a control object, changes along with sea state changes. Linear dynamic equations assumed for still water condition (and low sea states) do not entirely describe ship's behaviour in high seas. Many causes contribute to that, e.g. equation coefficients depend upon rudder inclination amplitudes (which increase as sea state grows), and on ship's speed (which drops at constant propulsion power as sea state grows).

Some research results suggest to assume modelling ship's dynamic behaviour in waves by equations with periodically changeable coefficients. In most cases, however, it is rather impossible to identify directly ship's dynamic behaviour at sea for many practical reasons.

Selection of course regulator settings is made rather in a subjective way basing on comparative information gained from previous voyages and taking into account the following conditions:

- to keep ship's course within yawing amplitude not greater than permissible (e.g. it is required in the rules that maximum yawing amplitude at a set course do not exceed ±1° in a sea state up to 3°B and ±4° in a sea state up to 5°B and at ±45° relative ship course angle in respect of wave direction
- to ensure angular velocity damping sufficient for automatic course change with overshoot not greater than 10% of a set course correction.

The selection of settings in that way does not ensure often an optimal operation of steering system even in good weather conditions. Steering is far from optimal in bad weather when it is necessary to retune a course regulator in consequence of steering gear overloading.

Therefore, in the classical automatic pilot systems in view of lack of reliable data on actual ship dynamic behaviour it is difficult to achieve a steering quality which satisfies minimum steering quality criteria (e.g. minimum speed loss) at a low number of rudder put-overs per hour in high seas.

SEARCHING FOR OPTIMAL COURSE REGULATOR STRUCTURE

Searching for an optimal course regulator structure can be carried out with the use of calculus of variations if linear behaviour of a steering object is assumed and the economic quality criterion, such as minimum speed loss of a ship when going on a given course is, adopted.

However, when proceeding in this way difficulties appear in accounting for limitations imposed by steering gear power. The quality criterion expressed by the following functional (1):

$$\Delta v \cong \lim_{T\to\infty} \frac{1}{T}\int_0^T \left(m^2\Delta\psi^2 + \beta^2\right)dt \qquad (1)$$

where:

Δv	-	speed loss
$\Delta\psi$	-	course deviation
β	-	rudder inclination angle
t, T	-	time variable and instant of time, respectively

contains the coefficient m^2 which is not Lagrange's multiplier determined from steering limitations, but is a constant value equal to:

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

where:

B_1	-	hydrodynamic coefficient dependent on the shape of immersed part of ship's hull
B_2	-	hydrodynamic coefficient dependent on rudder size and shape.

The coefficient m^2 is contained, for contemporary ships, within the 4÷16 range and it can be determined for each given ship.

Having assumed a simplified dynamic equation of ship steering as follows:

$$T_1^2\frac{d^2\Delta\psi}{dt^2} + T_2\frac{d\Delta\psi}{dt} = \beta(t) + \varphi(t) \qquad (3)$$

where:

T_1, T_2	-	constant values
$\varphi(t)$	-	disturbance function assumed in a form of white noise

(This is justified by very fast decreasing square of frequency characteristics module of a closed system).

One can obtain an optimal steering regulator, satisfying the quality criterion described earlier, which can be expressed as follows (4):

$$\beta(t) = -\left[m\Delta\psi + \left(\sqrt{2mT_1^2 + T_2^2} - T_2\right)\frac{d\Delta\psi}{dt} + 0{,}005\int \Delta\psi dt\right] \qquad (4)$$

The regulator provides the following steering quality values:

- mean square course error value	0,67°
- mean square rudder inclination angle	1,86°
- nominal speed loss	0,1%

for a ship with the following parameter values:

$T_1^2 = 400\ s^2$ $\quad T_2 = 20\ s$ $\quad m^2 = 4$

under disturbance with an input function of the power spectral density (5):

$$S_\varphi(\omega) = 0{,}279\frac{1}{\left(1{,}04 + \omega^2\right)^2 - 4\omega^2} \qquad (5)$$

where:

ω - disturbance frequency

and the mean square disturbance amplitude $\sqrt{\langle\varphi^2\rangle} = 10°$.

The results correspond well to those obtained from measurements [3].

However, the number of rudder put-over per hour n, calculated from the expression (6):

$$n = \frac{3600}{\pi}\sqrt{\frac{\langle\dot{\beta}^2\rangle}{\langle\beta^2\rangle}} \tag{6}$$

where:

$\langle\dot{\beta}^2\rangle$ - mean square value of the rudder put-over velocity

$\langle\beta^2\rangle$ - mean square value of the rudder inclination angle

is n = 380, which is a symptom of the intensive steering gear work.

From (6) it results that the decrease of the mean square value of the rudder put-over velocity $\langle\dot{\beta}^2\rangle$ is necessary to lower steering gear loading.

In order to keep ship's yawing at a low level, synthesis of an optimal steering regulator can be based on the following quality criterion (7):

$$J = \lim_{T\to\infty}\frac{1}{T}\int_0^T\left[\lambda_0 \Delta\psi^2 + \left(\frac{d\beta}{dt}\right)^2\right]dt \tag{7}$$

where:

λ_0 - constant value

This optimal steering regulator makes it possible to obtain now:

- mean square course error value	1,22°
- mean square rudder inclination angle	1,48°
- nominal speed loss	0,15%

at λ_0 = 0,01 and the same conditions as stated above, but with the number of rudder put-overs per hour n = 76 , which is five times lower value than the previous one.

It can be observed that ship speed loss increased moderately (by 0,005% of the nominal speed), but steering gear loading decreased substantially without any need of limiting signals to the steering gear, by means of filtering or cutting them off .

The switching-over of a regulation structure from that based on the first quality functional described to that based on the other one could be executed in dependence on a value of steering gear load (overload signal) and ship personnel decision.

CONCLUSIONS

A mathematical model of ship's motion in high seas is not quite identified. Therefore, the optimal regulation algorithms, elaborated on the basis of a simplified model, are surely not optimal ones at high sea states. However, a change of the quality criterion from that given by (1) to that given by (7) may be of importance for ship safety at the expense of some economic loss.

The problem of quality criterion change during ship's operation at a given course may be considered as that of synthesis of an adaptive regulator, in which search for steering that fulfils minimum of a quality criterion, is crucial.

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Miscellanea

KORAB

KORAB serves as an acronym of the organization which has associated students and graduates of shipbuilding studies at Technical University of Gdańsk since 1924.

20 Polish students studied shipbuilding from the very beginning of this university,being then under German administration, with an intention to contribute in developing Polish maritime economy on the Baltic Sea just after I World War. Unfortunately they were then badly treated by their German nationalistically oriented colleagues and university administration which forced them to resign studying. In order to defend their rights Polish students organized „ the Scientific Circle of Polish Shipbuilding Students KORAB „ which changed its name to „ the Association of Polish Shipbuilding Students of Technical University in Gdańsk „ in 1929.

Association's activities were then focussed on representing interests of its members in relations with the university administration and helping them in studies by making available different scientific instruments, books, lectures, excursions to and proffesional training in shipyards abroad, as well as shipboard training etc. The Association was substantially supported by the Polish Navy.

Just before II World War the Association had about 50 members at each year of studies, but in February 1939 all Polish students were dismissed out of the University and the war years scattered them all over the world.

After the war, already in 1945, KORAB started again its activity first of all taking care of subsisting matters of its members and taking part in rebuilding destroyed university acomodations.

It was Korab's tradition giving joyful fancy-dress balls devoted to a.o. introducing new members. Korab's activity has been step by step transformed to more scientific one and it has maintained this character till now.

In 1991 KORAB organized XII International Waterbike Regatta i.e. the competition of unconventional floating objects with man propulsion, designed and built by competitors from different technical universities.

Nowadays apart from the student association, the Polish Association of Shipbuilding Engineers KORAB, grouping shipbuilding graduates who work in this country, has been established, as well as KORAB INTERNATIONAL which associates several dozen Polish shipbuilding engineers living and working abroad.