LESZEK MORAWSKI, Assoc.Prof.,D.Sc.,E.E.
JANUSZ POMIRSKI, M.Sc.,E.E.
ANDRZEJ RAK, M.Sc.,E.E.
Gdynia Maritime Academy
Department of Ship Automation

Ship course stabilization system with minimum effort controller

SUMMARY

Theoretical algorithm of ship steering with the use of an optimal controller based on minimization of the control effort performance index is presented. Possibility of its practical implementation is discussed in view of inaccuracies and simplifications involved. A modification of the controller is proposed to make it applicable in practice.

The modified minimum effort controller algorithm was implemented onto the real-time software environment SILME to verify correctness of its operation during steering tests of 1:24 scale model of a 145 000 dwt tanker carried out on a lake. The modified controller algorithm gives correct results at directional ship course stabilization and course changes less than 10 deg.

INTRODUCTION

Settings of the ship autopilot controllers for course stabilizing are often selected in such a way as to minimize a control quality economic index. It is formulated as an integral of the quadratic form of actual course deviation from an assumed course and the rudder angle amplitude, with appropriate weighing coefficients. Simultaneously, dead-zone nonlinear terms are introduced to steering algorithms to make switch-on frequency of the steering gear lower. Ship's course variance of such control systems is a function of external hydro-meteorological disturbances and applied dead-zone range. In this case control effort minimization seems to be more justified. The minimum effort controller is well known from publications, but it has not been applied to ship course stabilizing so far. It is very simple and easily tunable.

STEERING WITH THE USE OF THE MINIMUM CONTROL EFFORT

A typical minimum control effort problem with respect to moving objects can be defined as follows :

➲ for a ship described by the state equations which are linear in respect of steering (Norrbin's nonlinear model [4]) :

$$\begin{aligned} \dot{\psi}(t) &= r(t) \\ \dot{r}(t) &= -H\left[r(t)\right] + b \cdot \delta(t) + w \\ \dot{w}(t) &= 0 \end{aligned} \qquad (1)$$

where:

$\psi(t)$ - ship course
$r(t)$ - angular velocity
$w(t)$ - hydrometeorological disturbances
$\delta(t)$ - rudder angle
$H(r) = a_2 \cdot r|r| + a_1 \cdot r$ - nonlinear term which defines a ship directional stability type (the term $a_3 r^3$ is neglected in the polynomial and hull symmetry, $a_0 = 0$, is assumed for sake of simplicity)

the initial state $[\psi(t_0), r(t_0)]$, final set $[\psi(t_1), r(t_1)] = (0,0)$ and a set of the allowable steerings is assumed which constrain the maximum rudder angle $|\delta| \le \delta_m$.

The aim of steering is to transfer a system from the initial state to the final one in such a way as to minimize the steering effort performance index given in the following form :

$$J = \int_{t_0}^{t_1} |\delta(t)| dt \qquad (2)$$

where t_1 is the final steering time which is arbitrary It is assumed in the presented problem that the course is stabilized at the zero level (the course deviation $\Delta\psi = \psi_z - \psi,\ \psi_z = 0$).

It can be demonstrated by making use of the Pontriagin's maximum principle that the following rudder angle values : 0, $+\delta_m$, $-\delta_m$ can be selected out of the optimum steerings [1],[2]. In Fig.1 phase trajectories for the directionally stable ship ($a_1 \ge 0$, $a_2 \ge 0$) are presented which correspond to the above mentioned rudder angle values. In Fig.1d the switch-over curves γ^+, γ^- are shown as well as the exemplary phase trajectories which correspond to the optimum steerings with respect to the minimum effort. The following steering sequences : $\{+\delta_m, 0\}$ or $\{-\delta_m, 0\}$ correspond to the optimum steering, dependent upon course deviation. The zero-rudder-angle trajectories which pass through the phase plane origin (0,0) describe the curve of steering switch-over from ±δ_m to zero. A switch-over curve related to the ship dynamic model in question can be described by the following equation :

$$\frac{1}{a_2}\cdot\ln\left|\frac{a_1}{a_1+a_2|r|}\right| = \psi\cdot\mathrm{sgn}(r) \qquad (3)$$

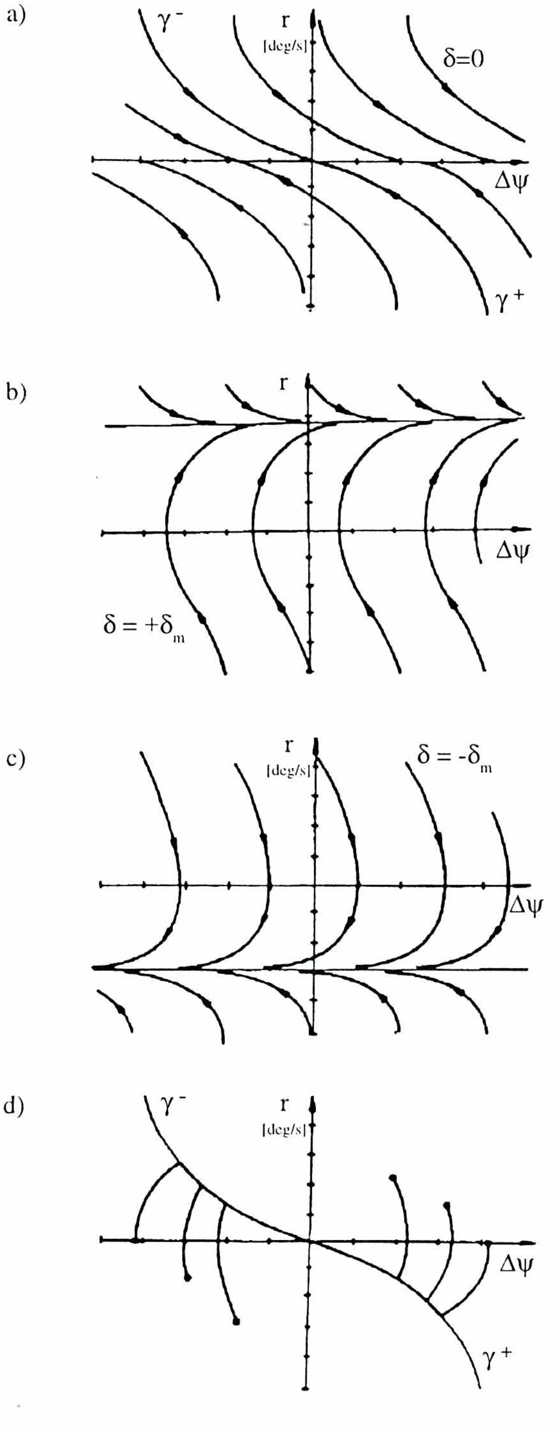

Fig. 1. Ship phase trajectories at the rudder angle values : a) 0 deg, b) +δ_m, c) -δ_m d) steering sequence {+δ_m, 0} and {-δ_m, 0}

The coefficient a_1 in the model (1) equations is of a negative value (a_1<0) for the directionally unstable ships and in consequence the final state (ψ, r)=(0,0) is not a stable equilibrium point. The trajectories which correspond to the constant rudder angles 0, +δ_m, -δ_m (δ_m is greater than the zone of directional instability on the Dieudonne spiral) are demonstrated in Fig.2.

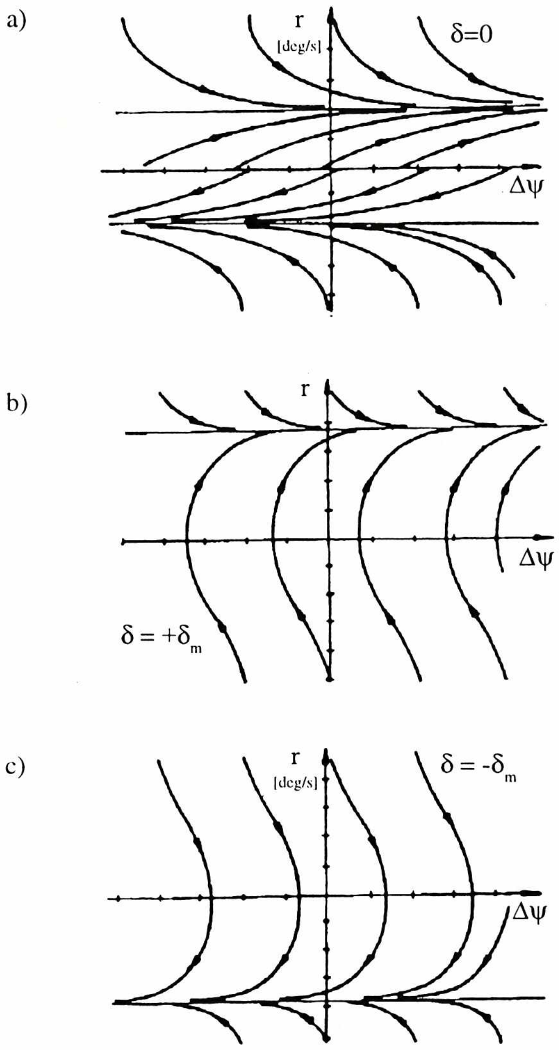

Fig. 2. Phase trajectories of the directionally unstable ship a) 0 deg, b) +δ_m, c) -δ_m

Two alternative solution methods of the steering problem of directionally unstable ship are available. The first of them consists in the analytical synthesis of the minimum effort controller where other, more complex conditions of steering switching-over can be expected. Only the trajectories which correspond to the rudder angles +δ_m, -δ_m lead to the point (0, 0), but this is a transient state. The second approach consists in compensating the zone of ship's directional instability by using the velocity feedback : linear or nonlinear, which compensates the negative value of the coefficient a_1. In the steering process the additional rudder angle component δ_k is generated and added to the angle value generated by the minimum effort controller. Thus the total rudder angle in the steering system can be expressed as follows :

$$\delta_c = \delta + \delta_k$$

$$\delta_k = \frac{1}{b}\left(a_{1k} r + a_{2k} r|r|\right) \qquad (4)$$

The state (1) equations of the steering process model are now of the following form :

$$\dot{\psi}(t) = r(t)$$

$$\dot{r}(t) = -H[r(t)] + b\cdot\delta_c(t) = \qquad (5)$$

$$= -(a_2 + a_{2k})\cdot r|r| - (a_1 + a_{1k})\cdot r + b\cdot\delta(t)$$

The compensating feedback values are so assumed as to fulfil the conditions : $(a_1+a_{1k}) > 0$ and $(a_2+a_{2k}) \cong 0$. In result an object of nearly linear directional stability characteristics is obtained. The principle of Dieudonne's characteristics compensation of the directionally unstable ship is explained in Fig.3.

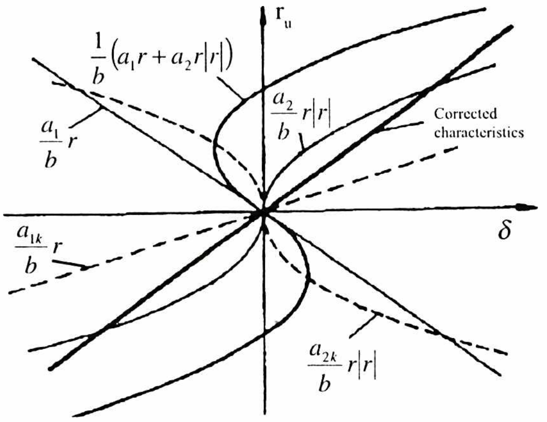

Fig.3. Compensation principle of ship's directional instability

IMPLEMENTATION OF THE MINIMUM EFFORT CONTROLLER

The minimum effort ship course controller of the presented form cannot be applied in practice. Description inaccuracies of real object dynamics connected with the model for which the controller synthesis was performed, neglecting the steering gear dynamics, approximate form of the switch-over curves (γ^+, γ^-), disturbances appearing in the process which result in short-time deviations of the rudder out of an assumed course, will cause that the rudder deflection process will be of a high switch-over frequency.

It is scarcely probable that the phase trajectory of the system would attain the final point (0, 0) and stay in it for a given, non-zero time period. Such steering result is usually acceptable in which the final deviation of course regulation $\Delta\psi(t_1)$ is achieved with some accuracy. The similar assumption can be accepted for the conditions after which, when satisfied, a steering sequence minimizing its effort takes place. The minimum effort controller is switched off as long as an absolute value of course deviation does not exceed an assumed threshold value. The mechanism of algorithm modification corresponds to introducing the dead zones to the regulator, which should be retuned dependent on an external disturbance level, in the same way that is usually applied to ship autopilots. The two dead zones : of initial steering sequence ($\Delta\psi_2$) and of hitting accuracy ($\Delta\psi_1$) may be different but the first should be greater than the second.

In Fig.4 the phase plane is demonstrated on which a working principle of the modified minimum effort controller is explained.

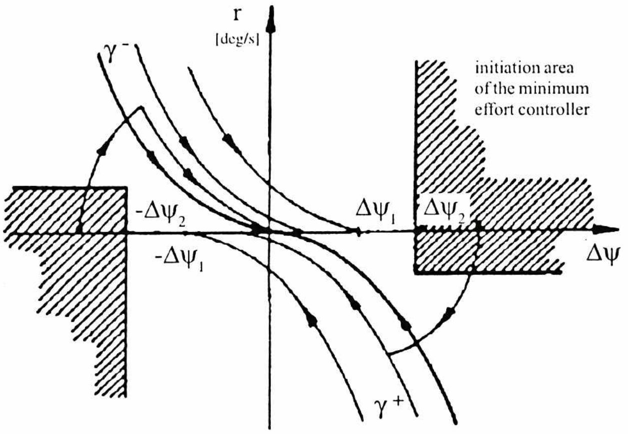

Fig. 4. Phase trajectories of course stabilizing process of the ship with the modified minimum effort controller

The course deflection will attain an average value in result of the system droop with respect to wind disturbances and due to existence of a small moment dependent on the direction of propeller revolutions (in the case of single propeller propulsion system). It will be compensated by rudder deflections on one side. An astatic controller is additionally introduced after application of the minimum effort controller that enlarges astatic characteristics of the steering system and compensates the average value of disturbances affecting the process, to make switch-over frequency of the rudder gear lower. Measuring the wind direction and power and applying an additional corrector to compensate gusts of wind is an effective method. A general block diagram of the ship course stabilizing system with the modified minimum effort controller is shown in Fig.5.

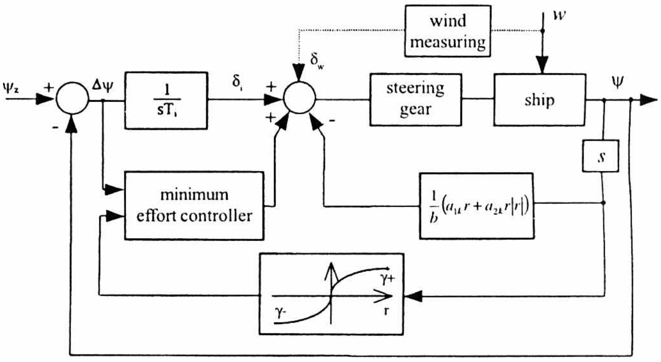

Fig.5. Block diagram of the ship course stabilizing system with the modified minimum effort controller

In the case when a linear model of ship's dynamics or its linearized characteristics are applied by means of the velocity feedback, the nonlinear switch-over characteristics located in the feedback loop is replaced by the straight line of the slope inversely proportional to a negative time constant value of the ship.

The presented controller algorithm was implemented into the real-time software environment SILME elaborated for isomorphous steering the sea-going ship models on the Silm lake, at the Centre of Ship Safety and Environment Protection Foundation, Iława-Kamionka. Investigations of the steering algorithm were carried out with the use of 1:24 model of 145 000 dwt tanker, ZAWRAT, shown in Fig.6.

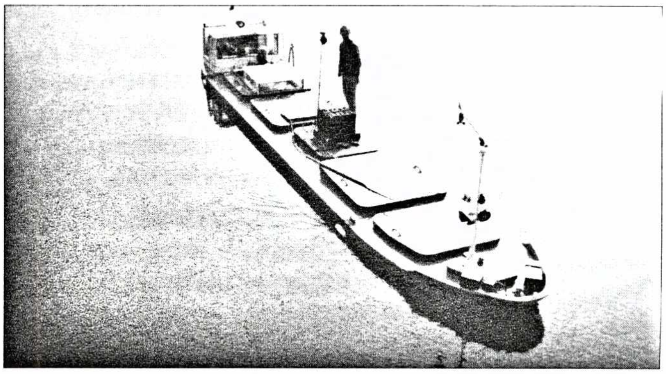

Fig.6. Model of 145 000 dwt tanker, ZAWRAT

The IBM PC connected to NAVIGAT VI gyrocompass through RS422 terminal (of 9600 bands transmission speed at 0.2 deg course indicating accuracy) and to a steering gear through an additional Z-80 microprocessor system with 10 and 12-bit d/a and a/d convertors, was the main element of the measuring-steering system of the model. A pictorial scheme of the model instrumentation is presented in Fig.7.

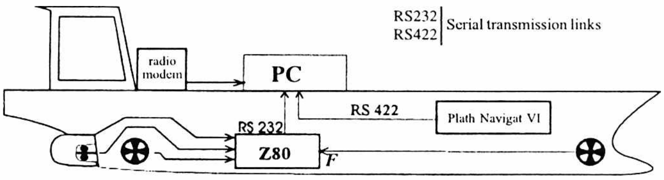

Fig.7. Instrumentation scheme of ZAWRAT tanker model

0.5 s process sampling period was assumed in the research. It results from the process scaling principle that the model time scale is $\sqrt{\lambda}$ times more „speedy" (λ- model scale) in comparison with that of the real object, and linear and angular velocities are as many times smaller [3].

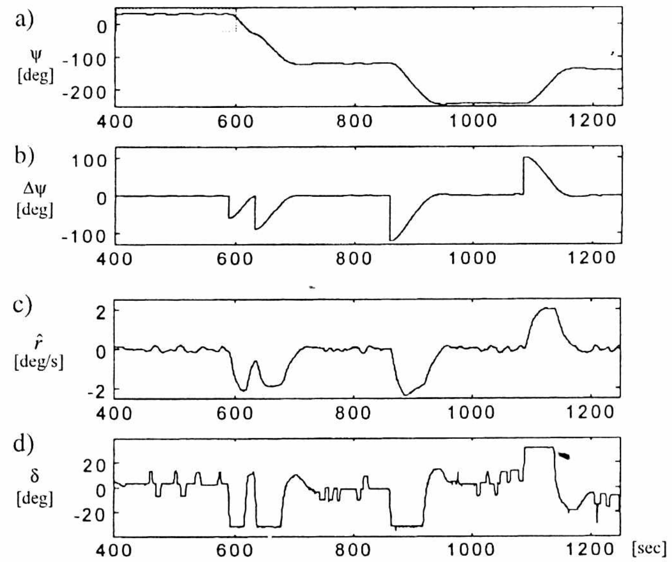

Fig.8. *Records of: a) course angle, b) deviation from an assumed course, c) estimated angular velocity, d) rudder angle, for ZAWRAT tanker model at 1.23 m/s speed (full speed), full load, external disturbances corresponding to 15 m/s wind speed from 330 deg direction, at ± 0.5 deg dead- zone of the controller*

The presented minimum effort controller was supplemented, in result of successive modifications and upgradings, by Kalman stationary filter in view of smoothing the irregularly quantized ship course (0.1, 0.2 deg) and estimating the non-measured angular velocity of the ship. The average disturbance value was compensated by the applied astatic controller as it could not be reproduced by the filter used.

Characteristic records of tanker model course obtained from its testing on the Silm lake, are presented in Fig.8 and 9.

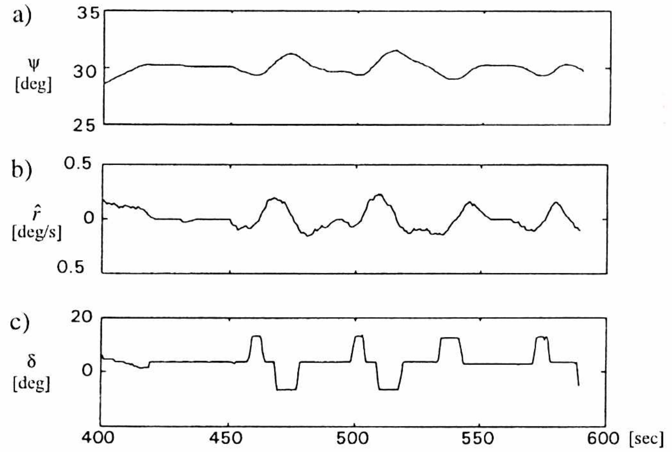

Fig.9. *Records of : a) course angle, b) estimated angular velocity, c) rudder angle, taken within the course stabilization time period of ZAWRAT tanker model (Fig.8)*

CONCLUSIONS

The investigation results of the steering algorithm make it possible to formulate the following conclusions :

● The steering algorithm provides correct steering results at course stabilizing; it is simple and can be characterized by the following features :

- low rudder deflection frequency that depends to a large extent on an applied dead-zone of the regulator
- regulator dead-zone influence on steering accuracy; the obvious conviction was confirmed about decreasing the steering gear switch-over frequency and worsening the steering accuracy along with enlarging the controller dead-zone.
- a very low number of simply tunable controller parameters; for instance, the rudder angle amplitude of the controller is selected inversely proportional to square of the linear speed, and the dead-zone of the controller with respect to external disturbance level. Nonlinear switch-over curve of the controller can be replaced by the comutation straight line of a constant slope. The investigations demonstrated that after tuning its slope at one model speed it was not necessary to change the slope at other model speeds.

● The steering algorithm does not provide correct steering results at course changes greater than 10 deg. Large wind influence on model manoeuvring characteristics was observed. Therefore PID standard controller was used for course changes greater than 10 deg.

Conditions of switching-over the minimum effort controller were established by controller's dead-zone and the angular velocity $|r| < 0.5$ deg/s.

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NOMENCLATURE

a_0, a_1, a_2, a_3	-	coefficients of H term of the ship dynamic model
a_{1k}, a_{2k}	-	coefficients of the term compensating ship's directional instability
b	-	coefficient of the ship dynamic model
H	-	nonlinear term determining the type of ship directional stability
J	-	steering performance index
r	-	ship angular velocity
$\hat{r}$	-	estimated value of the ship angular velocity
r_u	-	stabilized angular speed of the ship during circulation
s	-	Laplace operator
t	-	time
t_0, t_1	-	initial and final steering time point, respectively
T_i	-	integration constant of time
w .	-	hydro-meteorological disturbances
γ^+, γ^-	-	switch-over curves
δ	-	rudder angle
δ_c, δ_k	-	total and corrective deflection angle of the rudder, respectively
δ_i	-	rudder angle component at the integrating controller effort
$\pm\delta_m$	-	extreme rudder deflection angles
δ_w	-	rudder angle component compensating the hydrometeorological disturbances
λ	-	model scale
ψ	-	ship course
ψ_z	-	assumed ship course
$\Delta\psi$	-	course deviation
$\Delta\psi_1, \Delta\psi_2$	-	controller dead-zone values: of „hitting" accuracy and minimum effort controller initiation, respectively

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Appraised by Józef Lisowski, Prof.,D.Sc.,E.E.