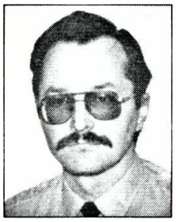

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Open-loop control of a twin-screw ferry

SUMMARY

In the paper the ferry and its simulation model are described and identification of its inverse steady-state characteristics is presented. Next results of the open-loop steering of the passenger ferry „Stena Germanica„ in longitudal and lateral directions and turning in a place are given and compared with results of real-ship trials and model ship experiments.

INTRODUCTION

In the recent years an increased interest in precise steering of ships during dead slow velocity movement has been observed. Many merchant ships are now equipped with the systems used only on drilling or searching ships so far. The systems called Dynamic Positioning Systems (DPS) permit to maintain the position and heading of the ship as well as to manoeuvre at any drift angle.

In order to properly steer the ship, active thrusters have to be applied. The simplest set of such equipment used on merchant vessels contains a few tunnel thrusters placed on bow and stern.

While bow thrusters are frequently installed onboard, stern thrusters are rare. Therefore, it was very interesting to find, if a twin-screw ferry equipped only with two bow tunnel thrusters could move perpendicular to its main longitudal axis or rotate without any drift. The study was performed on a simulation model of the passenger ferry „Stena Germanica„.

The paper is arranged as follows. At first, the ferry and its simulation model are described and identification of its inverse steady-state characteristics is presented. Next results of the open-loop ferry steering in longitudal and lateral directions and turning in place are given and compared with results of real-ship trials . Finally, concluding remarks are presented.

MATHEMATICAL MODEL OF THE „STENA GERMANICA"

Ferry

The ship built in Gdynia Shipyard was delivered to shipowner in 1987. Her main parameters are as follows :

Length overall	175.40 m
Breadth	28.50 m
Draught	6.25 m
Max. speed	21.5 kn
Deadweight	4500 t
Capacity	2455 passengers + 705 cars
Main engines	4 x 7355 KM, 500 rpm
Thrusters	2 x 1100 kW, 400 V
Electric power plant	5 x 1500 kVA + 1 x 570 kVA

A side view of the ferry is presented in Fig.1.

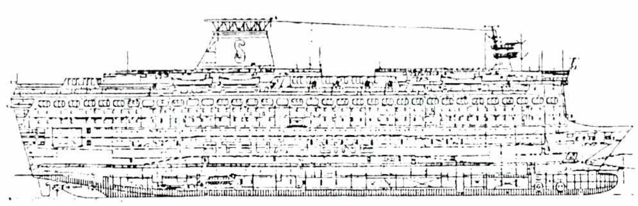

Fig. 1. The ferry „Stena Germanica"

Mathematical model

The mathematical model of the ferry, describing her dynamic and kinematic behaviour, was elaborated by J.Nowicki [3] in the form of a computer program. Two coordinate systems: the earth-fixed reference system $0\text{-}X_0\text{-}Y_0\text{-}Z_0$ and ship-fixed system $o\text{-}x\text{-}y\text{-}z$ presented in Fig.2 were used. It that the motion of the ferry was assumed in the restricted waters (close roads, harbours, navigation canals, etc.) where influence of sea waves is small.

The basic ship motion equations transferred from the earth-fixed reference system to ship-fixed one at the assumption : $w = p = q = o$ are as follows [1] :

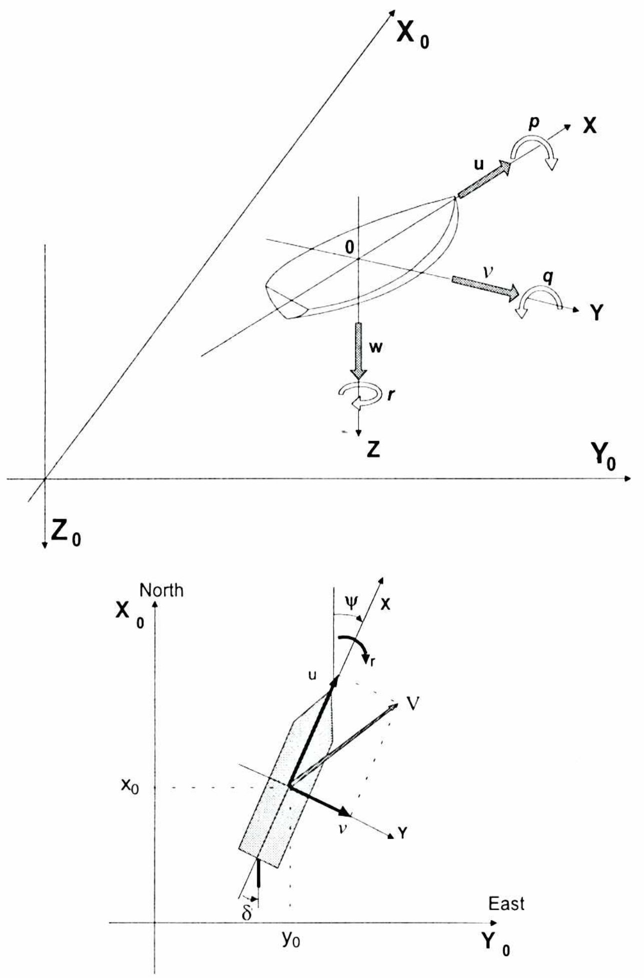

Fig. 2. The earth-fixed and ship-fixed reference coordinate systems

u,v,w	- linear velocity components
p,q,r	- angular velocity components
ψ	- heading angle
δ	- rudder angle
x_0,y_0	- ship position coordinates

$$
\begin{aligned}
m(\dot{u} - vr) &= X_{tot} \\
m(\dot{v} + ur) &= Y_{tot} \\
I_z\dot{r} &= N_{tot}
\end{aligned}
\qquad (1)
$$

where :

m	- ship mass
I_z	- ship moment of inertia about z-axis
X_{tot}, Y_{tot}, N_{tot}	- total forces and moment acting on the ship

The total forces and moment contain several components. For instance, the force X_{tot}:

$$X_{tot} = X_H + X_{rud} + X_{pr} + X_{thr} + X_w + X_c \qquad (2)$$

where :

X_H	- hydrodynamic force
X_{rud}	- force due to rudder
X_{pr}	- thrust due to propellers (main engines)
X_{thr}	- force due to tunnel thrusters
X_w	- force due to wind
X_c	- force due to sea current.

Current position coordinates and heading angle can be obtained from the following equations :

$$
\begin{aligned}
\psi(t) &= \psi_p(t_p) + \int_{t_p}^{t} r\,dt \\
x_0(t) &= x_p(t_p) + \int_{t_p}^{t} \left[u\cos(\psi) - v\sin(\psi)\right] dt \\
y_0(t) &= y_p(t_p) + \int_{t_p}^{t} \left[u\sin(\psi) + v\cos(\psi)\right] dt
\end{aligned}
\qquad (3)
$$

The model was rewritten from Turbo Pascal 6.0 to Matlab 4.2 as S-function (called „prom 8_of")and completed by external disturbance models (of wind and sea current). The models were based on the equations presented by Kallstrom [2]. Instantaneous wind velocity was obtained as a realization of the linearized Harris spectrum S(ω) [1] :

$$S(\omega) = k\frac{5286\,V_w^*}{\left[1+\left(\dfrac{286\,\omega}{V_w^*}\right)^2\right]^{\frac{5}{6}}} \qquad (4)$$

where :

V_w^*	- average wind velocity
k	- turbulence factor

The full block diagram of the model is presented in Fig.3.

IDENTIFICATION OF THE INVERSE STEADY-STATE CHARACTERISTICS

The inverse steady-state characteristics are functions of the surge, sway and yaw velocities and input command signals for steering ship devices (main engines, rudders, thrusters). They can be easily applied to open-loop control on condition that they are identifiable and univocal.

The ship model presented in Fig.4 has twelve outputs and ten inputs.

The outputs are as follows :

- the surge (u), sway (v), yaw (r) velocity components
- the heading angle (ψ)
- the actual ship position coordinates (x,y) in the earth-fixed reference system

and the actual values of the steering device signals, namely :

- the revolution of the left main engine (n_l) and the right one (n_r)
- the inclination angle of the left rudder (δ_l) and right one (δ_r)
- the relative pitch angle of the first thruster (thr1) and the second (thr2).

The inputs are as follows :

- the commands to the steering devices (n^*_l, n^*_r, δ^*_l, δ^*_r, thr1*, thr2*)

and the average values of the external disturbances, namely :

- the wind velocity (V^*_w) and its direction angle (γ^*_w)
- the sea current velocity (V^*_c) and its direction angle (γ^*_c)

The values n^*_l and n_l, δ^*_r and δ_r etc. can be different due to dynamic behaviour of the steering devices.

In identification experiments only one model output (surge, sway or yaw) was unequal zero during the test, and others were held as close to zero as possible in every simulation run. The lateral movement or turning demanded different commands for the left and right main engine (i.e. value and sign). A simulation scheme in Simulink, shown in Fig.4, was elaborated for identification process.

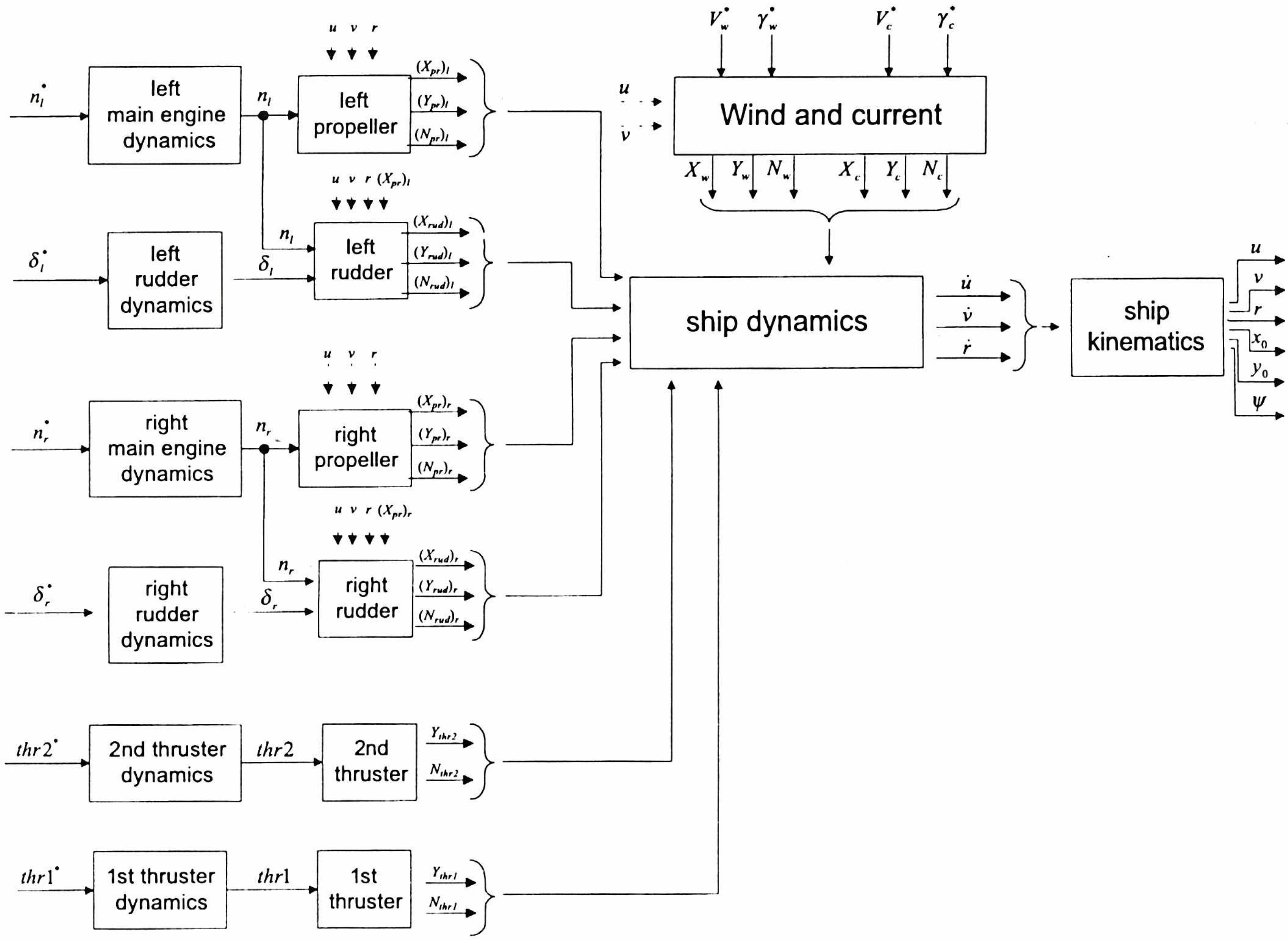

Fig.3. Block diagram of the ferry mathematical model

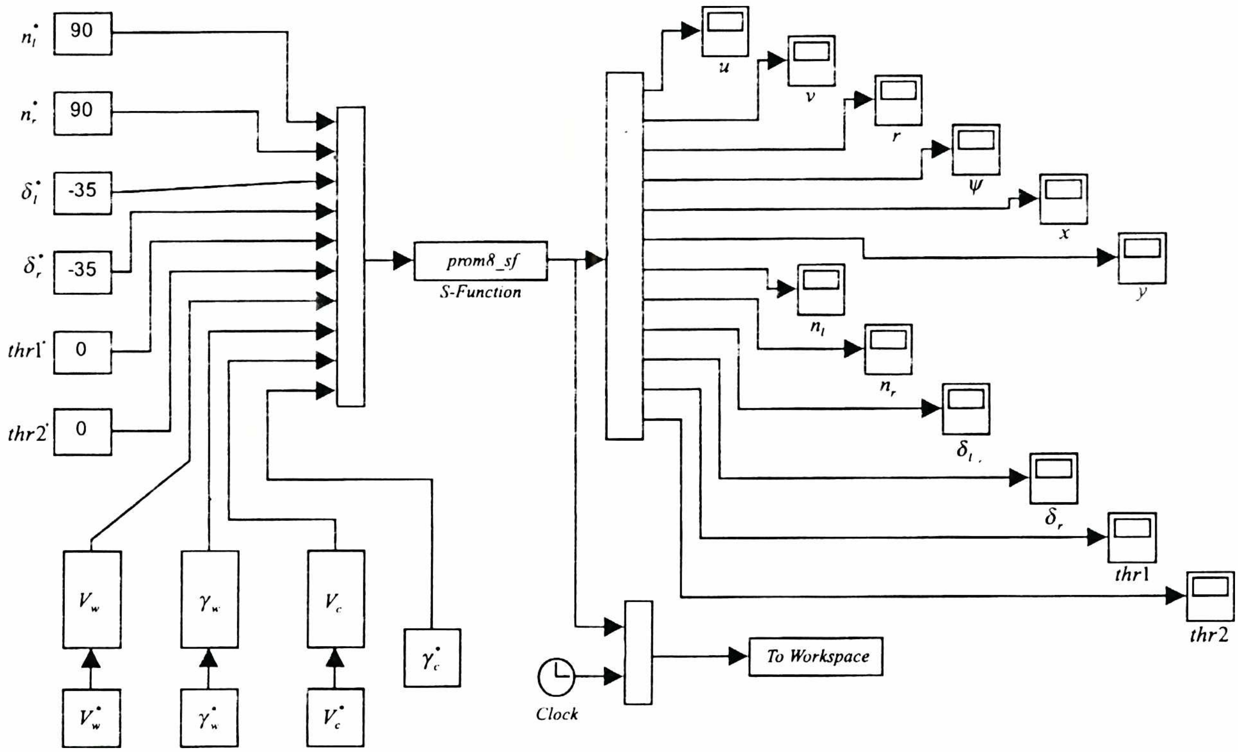

Fig.4. Simulink identification block diagram

Relationships between the surge (u) and commands for both main engines (n^*_l and n^*_r) are simple:

$$n^*_l = 13.8113 \cdot u \quad \text{for } u \geq 0$$
$$n^*_l = 22.5224 \cdot u \quad \text{for } u < 0 \qquad (5)$$
$$n^*_r = n^*_l$$

with the commands for other devices : δ^*_l, δ^*_r, thr1*, thr2* equal zero.

More complex relationships are between sway (v) and yaw (r) and input signals.

for $v \geq 0$:

$$\begin{aligned} & n^*_r = 93.6058 \cdot v \\ & n^*_l = -1.0625 \cdot n^*_r \\ & thr = 2.8704 \cdot v^2 - 0.0398 \cdot v \\ & thr1^* = thr, \text{ and } thr2^* = 0 \quad \text{for } thr \leq 1 \\ & thr1^* = 1, \text{ and } thr2^* = thr - 1 \quad \text{for } thr \leq 2 \\ & \delta^*_l = -\delta^* r = -35° \end{aligned} \qquad (6)$$

for $v < 0$:

$$\begin{aligned} & n^*_l = -93.6058 \cdot v \\ & n^*_r = -1.0625 \cdot n^*_l \\ & thr = -2.8704 \cdot v^2 - 0.0398 \cdot v \\ & thr1^* = thr, \text{ and } thr2^* = 0 \quad \text{for } thr \geq -1 \\ & thr1^* = -1, \text{ and } thr2^* = thr + 1 \quad \text{for } thr \geq -2 \\ & \delta^*_l = -\delta^* r = -35° \end{aligned} \qquad (7)$$

where : surge (u) expressed in m/s
sway (v) expressed in m/s
revolutions (n) expressed in min^{-1}

Equations for yaw (r) characteristics are as follows:

for $r \geq 0$:

$$\begin{aligned} & n^*_l = 81.4093 \cdot r \\ & n^*_r = -1.0625 \cdot n^*_l \\ & thr = 1.3083 \cdot r^2 - 0.0144 \cdot r \\ & thr1^* = thr, \text{ and } thr2^* = 0 \quad \text{for } thr \leq 1 \\ & thr1^* = 1, \text{ and } thr2^* = thr - 1 \quad \text{for } thr \leq 2 \\ & \delta^*_l = -\delta^*_r = -35° \end{aligned} \qquad (8)$$

for $r < 0$:

$$\begin{aligned} & n^*_l = -81.4093 \cdot r \\ & n^*_r = -1.0625 \cdot n^*_l \\ & thr = -1.3083 \cdot r^2 - 0.0144 \cdot r \\ & thr1^* = thr, \text{ and } thr2^* = 0 \quad \text{for } thr \geq -1 \\ & thr1^* = -1, \text{ and } thr2^* = thr + 1 \quad \text{for } thr \geq -2 \\ & \delta^*_l = -\delta^*_r = -35° \end{aligned} \qquad (9)$$

where : yaw (r) expressed in deg/s

Open-loop steering

Results of the identification experiments by using equations (5)÷(9) with added logical conditions for all inputs were modelled as three S-functions: „surge„, „sway„ and „yaw„. The Simulink block diagram is presented in Fig.5.

After setting any input command (eg. u^*= 4 m/s or r^* = -0.7 deg/s, etc) one can observe realization of the control on Simulink scopes. Exemplary simulation results for commands given to all in-

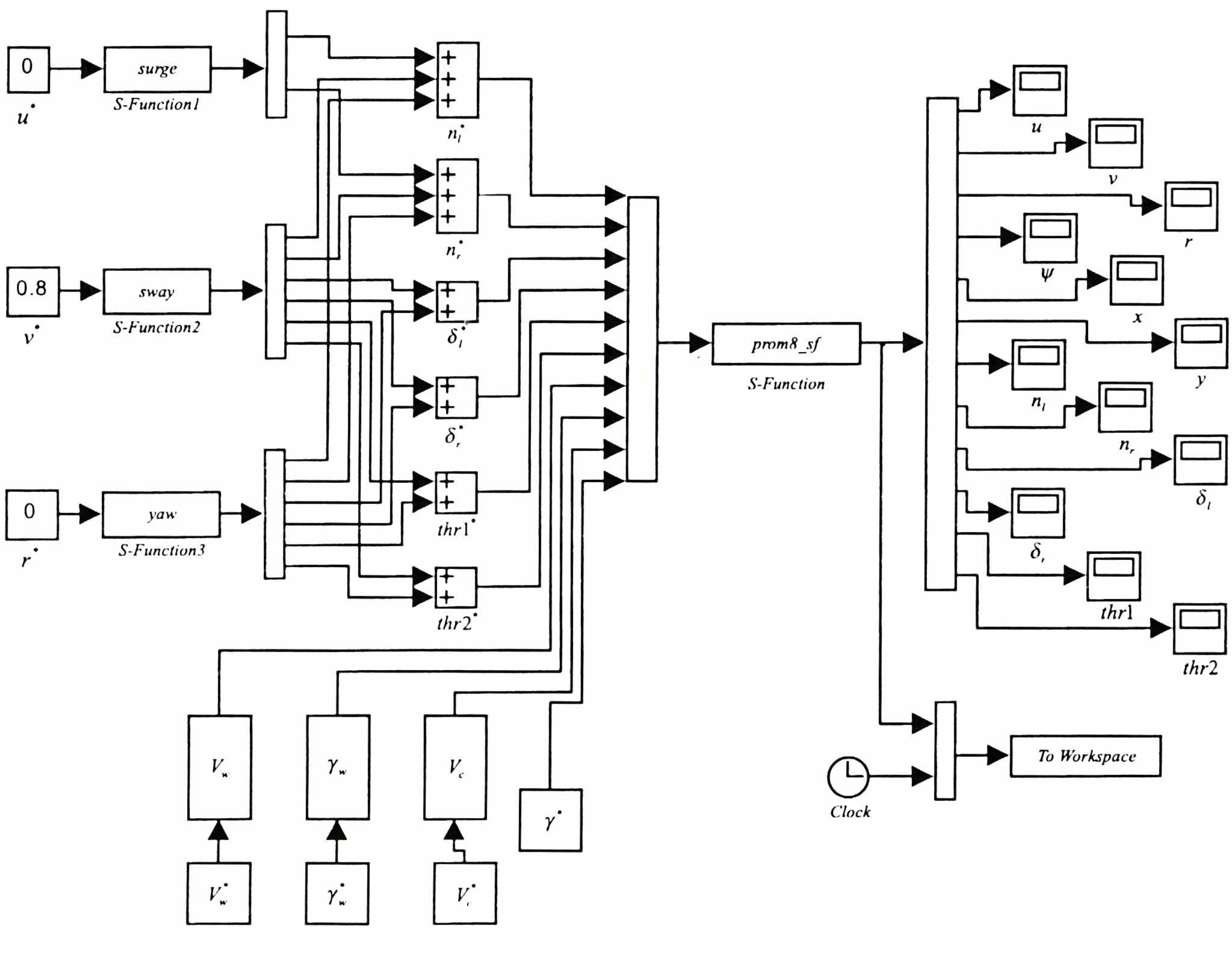

Fig.5. Simulink block diagram for open-loop control model of the ferry

puts: surge, sway or yaw are presented in Fig.6,7 and 8 respectively. A controlled quantity is presented on the left-hand side diagram and two other quantities in the centre and on the right-hand side diagram of each a.m. figure. The non-controlled quantities are presented in the same scale.The experiments were performed in the absence of any external disturbances.

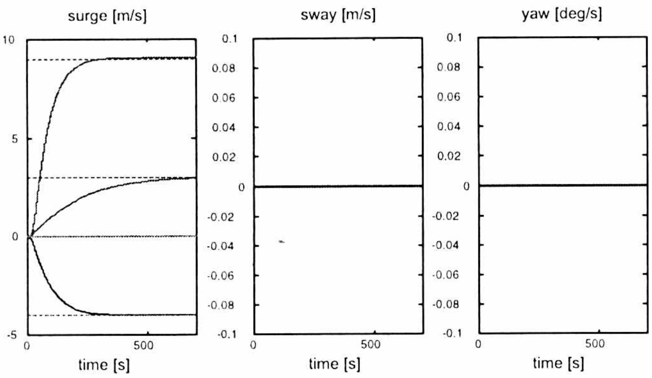

Fig.6. *Three experiments for surge open-loop control. Dotted lines denote the command values of : 9 , 3 and – 4 m/s.*

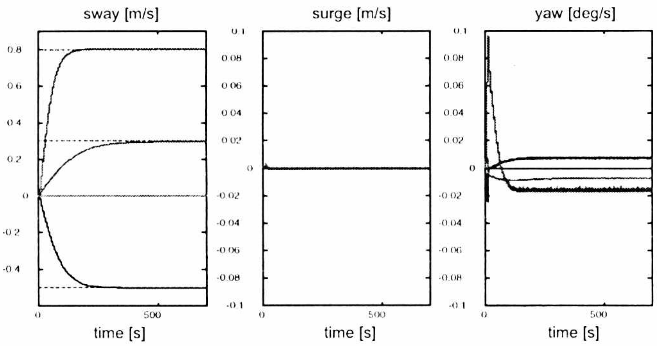

Fig.7. *Three experiments for sway open-loop control. Dotted lines denote the command values of : 0.8 , 0.3 and – 0.5 m/s*

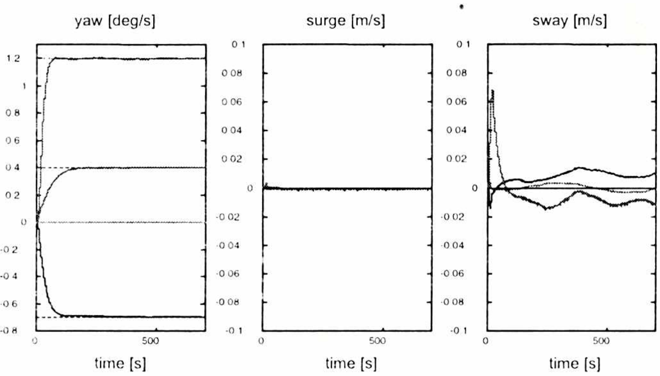

Fig.8. *Three experiments for yaw open-loop control. Dotted lines denote command values : 1.2 , 0.4 and – 0.7 deg/s*

If eg. wind velocity was low, the open-loop control was still achievable, but at medium value of this velocity (eg. 15÷20 m/s) the steering was unsatisfactory. In the case of surge the non-zero wind precluded achievement of the set ship speed, but in general the control was realizable. However, in this situation, the ship became non-controllable for sway and yaw. Fig.9 presents surge steering at the wind speed of 20 m/s from bow, Fig.10 sway steering at the wind speed of 10 m/s from starboard and Fig.11 yaw steering at the wind speed of 20 m/s from the same direction.

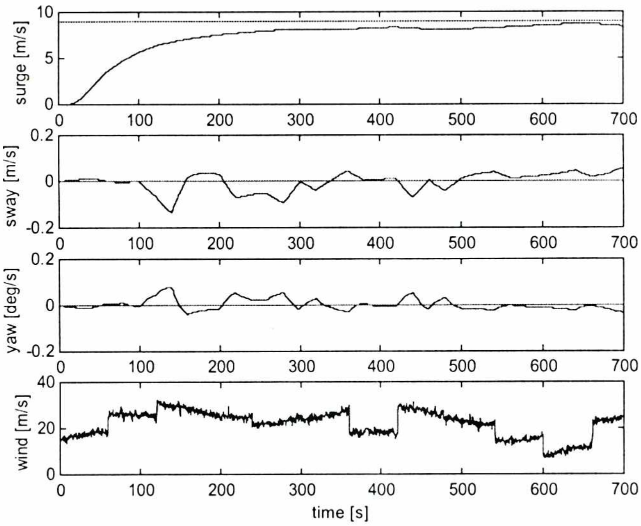

Fig.9. *Surge open-loop conrol at the average wind speed of 20 m/s from bow*

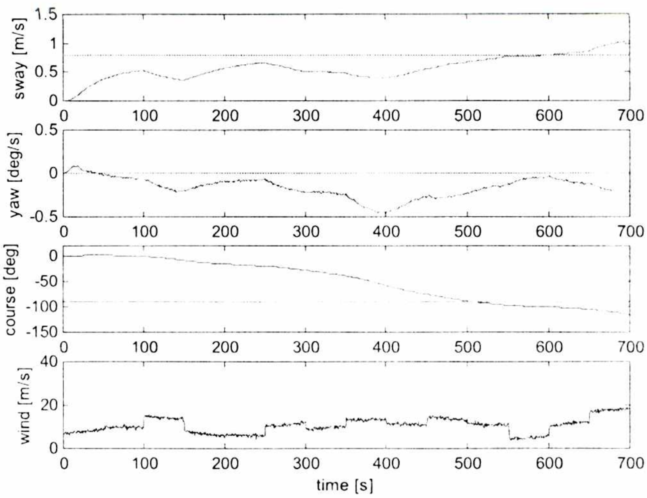

Fig.10. *Sway open-loop conrol at the average wind speed of 10 m/s from starboard*

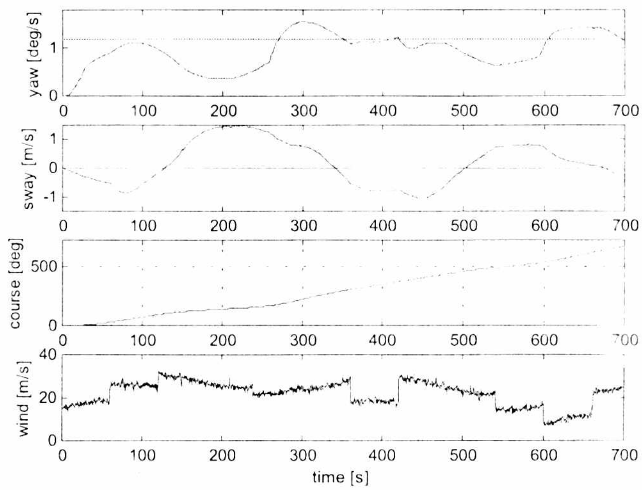

Fig.11. *Yaw open-loop conrol at the average wind speed of 20 m/s from starboard*

CONCLUDING REMARKS

- The presented simulation model was verified by the real-time experiments. The „Stena Germanica„ was tested during shipyard trials in August 1986.Two kinds of manoeuvres were performed:

- turning with ±35° rudder put-over angles
- crash-stop.

The main difficulty in reconstructing conditions of the real ship trials was suitable modelling of the non-stationary wind. During the trials the wind state of 7°B and the sea state of about 4° (of rather low importance) was noted. This problem could be the reason of the observed discrepancies between the results of the simulation experiments and real ship trials. The comparison of the results is presented in Tab.1a and 1b. Experiments on the scale model of the ferry in question carried out on the Silm Lake near Iława were another way to verifying the mathematical model. All their results confirm that the model rightly represents the real ship properties and therefore it can be used as a convenient tool in ferry control research.

Tab.1a. Comparison of the results obtained from the real ship trials and simulation experiments of the ferry during turning manoeuvres

Turning circle to starboard		
Time to achieve : ψ=...[deg]	ψ_{real}	ψ_{sym}
[s]	[deg]	[deg]
68	90	90.5
127	180	185.5
190	270	284.0
258	360	394.0
Distance to achieve : ψ=...[deg]	x_{real}	x_{sym}
[deg]	[m]	[m]
90	405	407.2
	y_{real}	y_{sym}
	[m]	[m]
180	418	423.5

Turning circle to port		
Time to achieve : ψ=...[deg]	ψ_{real}	ψ_{sym}
[s]	[deg]	[deg]
65	90	85.3
115	180	166.2
173	270	257.1
237	360	361.4
Distance to achieve : ψ=...[deg]	x_{real}	x_{sym}
[deg]	[m]	[m]
90	445	400
	y_{real}	y_{sym}
	[m]	[m]
180	518	451

Tab.1b. Comparison of the results obtained from the real ship trials and simulation experiments of the ferry during crash-stop manoeuvre

		Ferry	Model
Time to stop	[s]	110	121.9
Distance	[m]	602	632
Course changing	[deg]	+50	+38.4

- The merchant, single-screw ships equipped with bow thrusters are only able to shift their bow laterally or to perform close turn. Ships with two main propellers can generate the force perpendicular to the main ship axis, applied to the ship afterbody. It can be obtained by generating reverse thrust by both screws. Owing to this capability, one can move the ship laterally or turn it in a place. However, this kind of movement requires very precise setting the rotational speed of the main screws and the pitch angle of the bow thrusters.
- The identification experiments proved that the moving with „crossed„ rudders (ie. the left rudder set on –35° and right one on +35°) was more effective.
- From Fig.7 and 8 it can be observed that it is impossible to get perfect sway or yaw velocities, nevertheless the remaining, non-conrollable quantities are rather small due to the adequate inverse steady-state characteristics.
- Appropriate steering, mainly for sway and yaw, is achievable only at low external disturbances.This restriction is not serious beacuse this kind of movement is mainly required in harbours during alongside passing and sailing into or out of ports.

NOMENCLATURE

I_z	-	ship moment of inertia about z-axis
k	-	turbulence factor
m	-	ship mass
n	-	main engine revolution
N	-	moment acting on the ship
p	-	roll velocity
q	-	pitch velocity
r	-	yaw velocity
t	-	time
thr1, thr2	-	relative pitch angle of the first and second thruster, respectively
u	-	surge velocity
v	-	sway velocity
V	-	velocity
w	-	heave velocity
x, y, z	-	ship coordinates in the ship-fixed reference system
X	-	force on the ship in x-direction (eq.1,2)
X_0, Y_0, Z_0	-	ship coordinates in the earth-fixed reference system
Y	-	force on the ship in y-direction (eq.1,2)
γ	-	direction angle
δ	-	inclination angle of the ruder
ψ	-	heading angle

Indices :

c	-	sea current
H	-	hydrodynamic
l	-	left
p	-	starting point
pr	-	propeller
r	-	right
rud	-	rudder
thr	-	thruster
tot	-	total
w	-	wind
*	-	set value (input command)

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

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ERRATA

In Polish Maritime Research No 2 (June 1999), p.10, the reviewer name of the paper by Dr L. Kyziol was wrongly given. In fact the paper was appraised by **Prof. Andrzej Sawicki**, but not by Assoc.Prof. Henryk Zaradny. The Editor apologize to all involved persons and readers for the error.