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Hydrodynamic aspects of the integrated ship movement control

SUMMARY

More and more ships are presently provided with propulsion systems consisting of two controllable pitch propellers and bow thrusters. Such systems are designed for improving manoeuvring characteristics of the ship in difficult passages, canals or areas of high traffic intensity. However their features are most effectively utilized if an integrated, computer-aided control of the whole propulsion system by means of joystick is applied.

The ship speed and movement direction, preset with the use of joystick, are not always exactly realized, especially if the ship is exposed to wind, wave and possible sea current effects. In such case the joystick software must include a hydrodynamic model of ship's movement. The paper presents a model of the joystick-effected control and exemplary results of its computer simulation.

INTRODUCTION

On the most frequented navigation routes, water regions (areas) occur of high traffic intensity. Even higher traffic intensity can occur in areas of big ports, rivers and inland canals. In the case of rivers and inland canals, their limited dimensions and presence of various structures, e.g. bridges, can form additional navigation obstacles.

Due to this reason ships and other watercraft (e.g. harbour craft) are equipped with special propulsion systems to improve their manoeuvring characteristics, e.g. the main propulsion system consisting of two propellers (often of controllable pitch), bow - and sometimes stern - thrusters and other additional propellers (e.g. of azimuth type). Conventional manual, individual control of each propulsion device, and control of the rudder requires good knowledge of dynamics of the ship and her reactions to operation of particular equipment items, to be used during simultaneous presetting of various control modes. The situation can be improved if the integrated computer-aided control (CAC) of the whole propulsion system, effected through joystick as the only presetting device, is applied [5], [6]. For many years such solutions have been used on special ocean engineering ships equipped with several propulsion units. By using the integrated CAC system it is possible to precisely keep the ship in a demanded position or to effect control of her motion precisely along the preset trajectory despite her exposure to marine environment effects (such as wind, waves, current).

However, the ship motion direction preset by means of the joystick is not always precisely realized by the propulsion system in operation. This depends not only on the assumed mode of joystick control, but also on hydrodynamic phenomena associated with the ship movement. Therefore the computer-aided operation of the integrated joystick control is wider and wider applied in order to realize more precisely the preset movement direction.

The paper presents the joystick control modes applied to a salvage ship and influence of relevant hydrodynamic phenomena on realization accuracy of the ship's movement direction.

INTEGRATED CONTROL THROUGH JOYSTICK

The integrated control through joystick consists in manual controlling the whole ship propulsion system by its operator in order to maintain the preset position or preset trajectory of movement (keeping her movement direction and speed). The operator, observing reaction of the ship or current ship's movement parameters on a display unit, makes necessary corrections by manipulating the joystick (Fig.1).

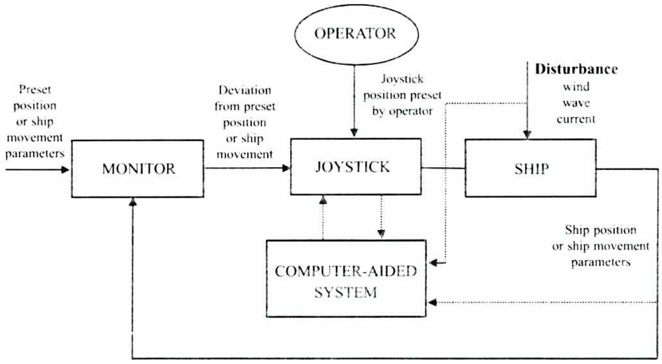

Fig.1. *Flowchart of the integrated control through joystick*
——— control not aided by computer
.... computer-aided control

The joystick deflection described by the angles φ and χ (Fig.2) generates the vector {K} of the components $\{K_x, K_y, K_z\}$. Direction of the vector {K} is defined by the angle φ and its value - by the angle χ.

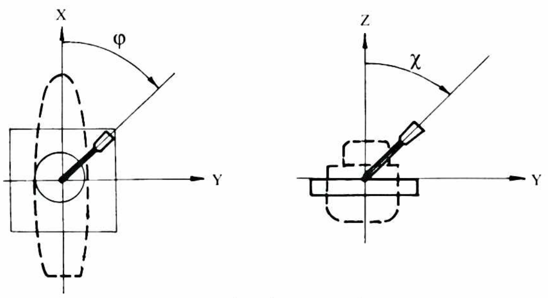

Fig.2. Joystick deflection angles

The control through joystick may consist in :

1st case : generation of the resultant thrust force of the propulsion system - the change of the joystick angular coordinate φ determines direction of the generated resultant thrust whose value is proportional to the change of the joystick angular coordinate χ. The resultant direction of the ship movement may be different from the direction of the joystick position change and from the preset direction of ship movement - then the operator so corrects the joystick deflection as to obtain the ship movement complying with that preset (required) ; the vector {K} is then the resultant vector of the thrust force {T} of the whole propulsion system :

$$\{K\}=\{T\}=\{T_x, T_y, M_{Tz}\}=f \text{ (thrusts of propellers)} \quad (1)$$

where :

- T_x, T_y - resultant propeller thrust components analog x - and y - axis, respectively
- M_{Tz} - resultant propeller torque around z - axis

2nd case : generation of the movement direction - the change of the joystick angular coordinate j corresponds to the required ship movement direction and the ship speed is proportional to the change of the joystick angular coordinate χ ; {K} is then the ship movement speed vector :

$$\{K\}=\{V\}=\{V_{Gx}, V_{Gy}, \omega_{vz}\} \quad (2)$$

where :

- V_{Gx}, V_{Gy} - ship speed components along x - and y - axis, respectively
- ω_{vz} - ship angular velocity around z - axis

Three cases are possible when generating the ship movement direction :

- ✦ generation without accounting for wind, waves, and current effects
- ✦ generation with accounting for wind, waves,and current effects
- ✦ generation with stabilizing the ship movement direction.

Irrespective of whether the thrust vector {T} or speed vector {V} is generated, the joystick must have its own software for calculating settings of the equipment performing the operation (thrusters, propellers).

In the first above defined case the software must additionally include a mathematical model of the ship. Such solution is obviously better but it ensures generation of the required (but approximate) ship movement on still water only. However, when the ship is exposed to exciting forces due to wind, current and waves, even *in the second considered case* the direction of joystick position change (φ) will not correspond to that of the ship movement, and the ship speed will not be proportional to the joystick deflection value (χ). In order to ensure generation of the movement direction even in the latter case an additional computer system is necessary of the similar software as that used in the dynamic ship positioning (DSP) system - Fig.1. The integrated CAC system permits keeping the ship movement direction in compliance with that of the joystick position change, despite the fact that the external forces due to marine environment effects act on the ship.

MATHEMATICAL MODEL OF SHIP MOVEMENT

General equations of ship movement

During the integrated control of ship propulsion system the ship movement only in the horizontal (water surface) plane is considered. Therefore the ship movement equations are identical with those describing the ship manoeuvring. Hence the movement is described by three non-linear differential equations defined in the coordinate system (G_{xyz}) associated with the ship (Fig.3) :

$$\begin{aligned}
&(m_v + m_{11})\ddot{x} - (m_v + m_{22})\dot{y}\dot{\psi} - m_{16}\dot{\psi}^2 = X_v \\
&(m_v + m_{22})\ddot{y} + m_{26}\ddot{\psi} + (m_v + m_{11})\dot{x}\dot{\psi} = Y_v \\
&(J_{66} + m_{66})\ddot{\psi} + m_{62}(\ddot{y} + \dot{x}\dot{\psi}) + \dot{x}\dot{y}(m_{22} - m_{11}) = M_v
\end{aligned} \quad (3)$$

where :

- m_v - ship mass
- J_{66} - ship inertia moment related to z - axis
- $m_{11}, m_{22}, m_{16}, m_{26}, m_{62}, m_{66}$, - added masses and their moments [1],[2]
- $x, \dot{x}, \ddot{x}$ - displacement, velocity and acceleration of longitudinal movement
- $y, \dot{y}, \ddot{y}$ - displacement, velocity and acceleration of transverse movement
- $\psi, \dot{\psi}, \ddot{\psi}$ - displacement, velocity and acceleration of rotary movement (around z - axis)
- X_v, Y_v, M_v - external forces and moment acting on the ship.

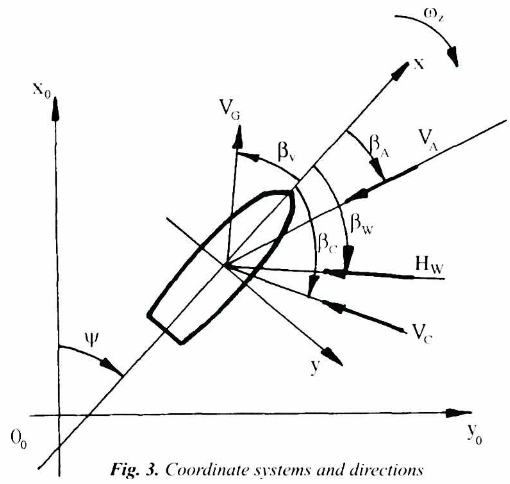

Fig. 3. Coordinate systems and directions

The solution of the equations (3) is position-described within the immovable reference system $Ox_0y_0z_0$ (Fig. 3), and speed-described within the system G_{xyz} associated with the ship.

External forces acting on the ship

The external forces acting on the ship are as follows:

$$\begin{aligned}
X_v &= X_P + X_T + X_H + X_D + X_A + X_W \\
Y_v &= Y_P + Y_T + Y_H + Y_D + Y_A + Y_W \\
M_v &= M_P + M_T + M_H + M_D + M_A + M_W
\end{aligned} \quad (4)$$

where the subscripts at particular forces stand for :

- P - main propulsion system propellers
- T - thrusters
- H - rudder (helm)
- D - water resistance and sea current effect
- A - air resistance and wind effect
- W - mean wave drift force.

When controlling the ship movement through joystick the rudder will not be used, so in equations (4) the rudder-related forces will be neglected.

In Fig.4 the propulsion system is presented of the salvage ship for which the simulation calculations were performed.

Thrust of the main propulsion system propellers

Thrust and moment of the propeller was determined from the formulae :

$$T_p = \rho_w \cdot n^2 D^4 K_T$$
$$Q_p = \rho_w \cdot n^2 D^5 K_Q \qquad (5)$$

where :

- ρ_w - water density
- n - propeller rotational speed [rpm]
- D - propeller diameter
- K_T - thrust coefficient
- K_Q - moment coefficient.

Propellers of the salvage ship are of controllable pitch, therefore the coefficients K_T and K_Q depend on the advance coefficient J and pitch ratio (P/D); the coefficients can obtain both negative and positive values (4 cases of the propeller operation) [7].

An effective available value of the propeller thrust was calculated in the compliance with the following condition :

$$Q_p \le \frac{N_e}{n} \qquad (6)$$

where N_e is the effective power output of the driving engine at the propeller rotational speed n_p.

For the nominal power output of the engine N_n and nominal rotational speed of the engine n_n the condition obtaines the following form :

$$Q_{pn} \le \frac{N_n}{n_n}$$

The components of the thrust resultant force due to two propellers of the main propulsion system are as follows :

$$X_P = T_{LP} + T_{RP}$$
$$Y_P = C_{PY}\left(T_{LP} - T_{RP}\right) \qquad (7)$$
$$M_P = b_P\left(T_{LP} - T_{RP}\right)$$

where :

- T_{LP}, T_{RP} - thrust of left-hand and right-hand side propeller, respectively
- C_{PY} - propeller transverse force coefficient [10]
- b_P - distance of the propeller axis from the ship centre line (Fig.4).

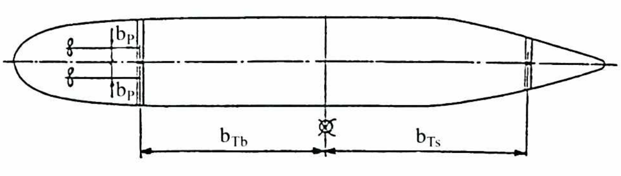

Fig.4. Salvage ship propulsion system

Thrust of tunnel thrusters

Thrust of the tunnel thruster was obtained from the formula :

$$T_T = C_{TV} \cdot C_{TT} \cdot C_{TH} \cdot \alpha_T \qquad (8)$$

where :

- C_{TV} - correction factor related to the ship speed
- C_{TT} - thrust coefficient of free thruster (i.e. not interacting with the ship hull, and of a value specified by its manufacturer)
- C_{TH} - correction factor accounting for shape of the tunnel and its outlet from the ship hull (of a value determined during thruster tests on the ship)
- α_T - deflection angle of the propeller blades.

Nominal and effective thrust values of the tunnel thrusters measured on the salvage ship are published in [8].
Components of the thrust resultant force of the tunnel thrusters are described as follows :

$$X_T = 0$$
$$Y_T = T_b + T_s \qquad (9)$$
$$M_T = b_{Tb} \cdot T_{Tb} - b_{Ts} \cdot T_{Ts}$$

where :

- T_b, T_s - thrust of bow and stern thruster, respectively
- b_{Tb}, b_{Ts} - position coordinate of the bow and stern thruster, repectively (Fig.4).

MARINE ENVIRONMENT FORCES

The marine environment reaction forces are the ship manoeuvring resistance as well as exciting forces due to effects of wind, waves, and possible sea current.

Resistance and current effect

The components of the resultant resistance and current effect force are expressed by the formulae (10) :

$$X_D = \frac{1}{2}\rho_w L d V_{rG}^2 C_{Dx}(\beta_{rG})$$

$$Y_D = \frac{1}{2}\rho_w L d V_{rG}^2 C_{Dy}(\beta_{rG}) \qquad (10)$$

$$M_D = \frac{1}{2}\rho_w L d V_{rG}^2 C_{DM}(\beta_{rG})$$

where :

- ρ_w - water density
- L,d - ship length and draught, respectively
- V_{rG} - relative ship speed (including the current velocity V_C)
- β_{rG} - relative ship drift angle (including the current direction angle β_C)
- C_{Dx}, C_{Dy}, C_{DM} - coefficients of the wetted hull resistance during manoeuvring at any drift angle β.

The resistance and current effect forces calculated for the salvage ship [9] are shown in Fig.5.

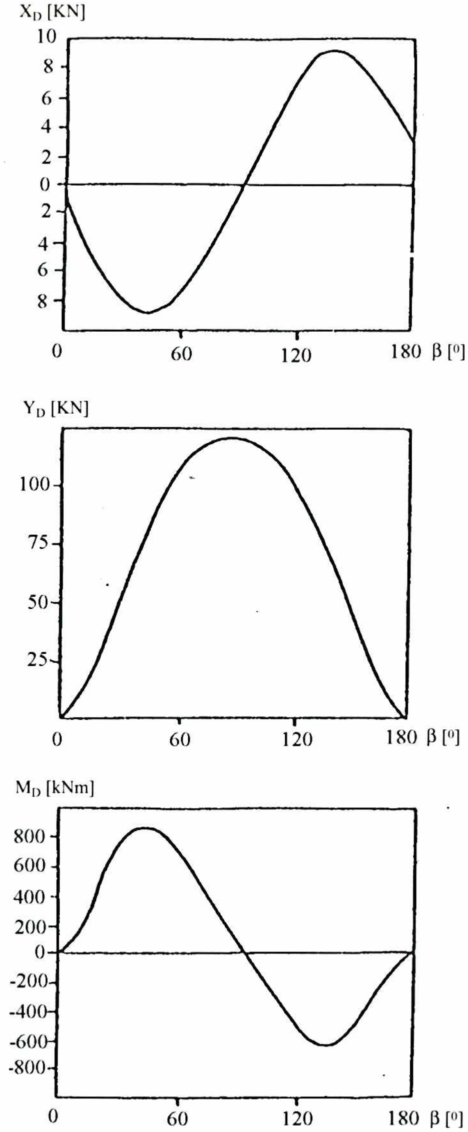

Fig.5. *Resistance and current effect forces calculated for the salvage ship at the ship speed V_G=1 m/s*

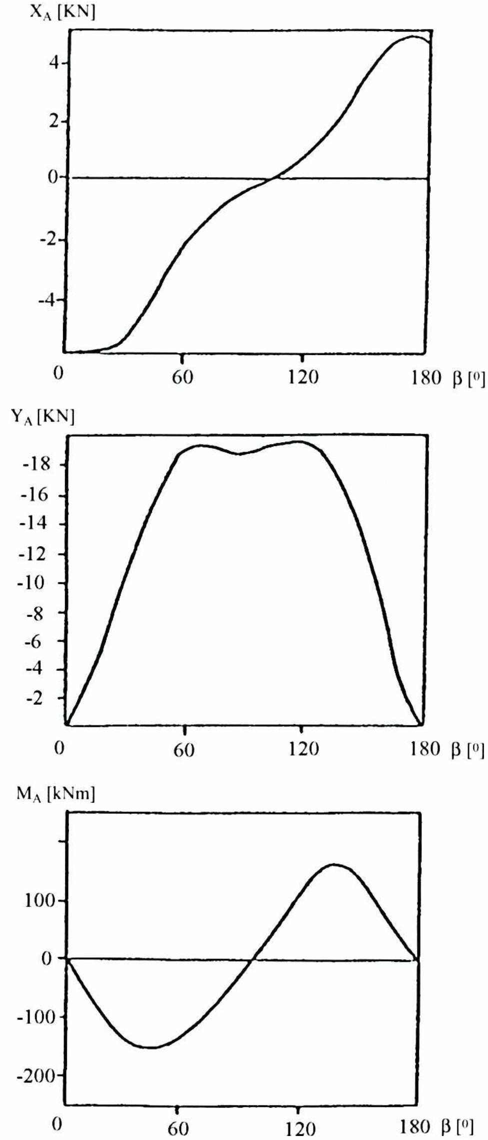

Fig.6. *Wind effect forces calulated for the salvage ship at the wind speed V_A=10 m/s*

Wind effect

The components of the resultant force of the wind effect are expressed by the formulae (11) :

$$X_A = \frac{1}{2}\rho_A F_x V_{rA}^2 C_{Ax}(\beta_{rA})$$

$$Y_A = \frac{1}{2}\rho_A F_y V_{rA}^2 C_{Ay}(\beta_{rA}) \qquad (11)$$

$$M_A = \frac{1}{2}\rho_A F_y L V_{rG}^2 C_{AM}(\beta_{rA})$$

where :

- ρ_A - air density
- F_x,F_y - front and side windage area of the above-water ship's part, respectively
- V_{rA} - relative wind velocity (including the ship speed V_G), (Fig.6)
- β_{rA} - relative wind direction angle (including the drift angle β of the ship)
- C_{Ax}, C_{Ay}, C_{AM} - aerodynamic resistance coefficients of the above-water ship's part.

Wind effect forces calculated for the salvage ship [4] are presented in Fig.6.

Wave effect

The components of the irregular wave drift force are expressed by the formulae (12) :

$$X_w = 2\rho_w g \frac{B^2}{L}\int_0^\infty C_{wx}(\omega) S_{\varsigma\varsigma} d\omega$$

$$Y_w = 2\rho_w g \frac{B^2}{L}\int_0^\infty C_{wy}(\omega) S_{\varsigma\varsigma} d\omega \qquad (12)$$

$$M_w = 2\rho_w g B^2 \int_0^\infty C_{Mx}(\omega) S_{\varsigma\varsigma} d\omega$$

where :

- B - ship breadth
- g - acceleration of gravity
- $C_{wx}(\omega)$, $C_{wy}(\omega)$, $C_{wM}(\omega)$ - coefficients of the mean wave drift force due to regular waves
- $S_{\varsigma\varsigma}$ - functions of the wave energy spectral density
- ω - regular wave frequency.

Wave drift forces calculated according to [3] for the salvage ship are shown in Fig.7.

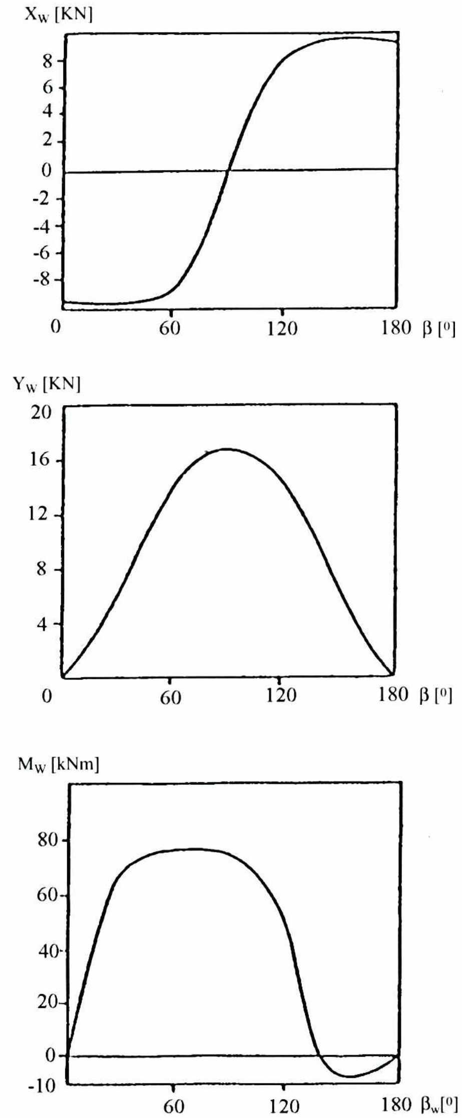

Fig. 7. Wave drift forces calculated for the salvage ship at the wave height H_W=0.85 m

RESULTS OF SIMULATION TESTS

Simulation tests of the salvage ship control realized by means of a joystick were performed for the following cases :

1st case : the joystick generates ***the resultant thrust force*** of the propulsion system (Fig.4) proportional to the joystick position change; the ship movement was simulated under the following conditions :

- the ship moves in calm water : V_A= 0 V_C= 0 H_W= 0
- the ship is exposed to wind effects.

2nd case : the joystick generates ***the ship movement direction*** proportional to the joystick position change, without any help of CAC system; the ship movement was simulated under the following conditions :

- the ship moves in calm water : V_A= 0 V_C= 0 H_W= 0
- the ship is exposed to wind effects.

3rd case : the joystick aided by CAC system generates ***the ship movement direction*** proportional to the joystick position change; the ship is exposed to wind effects.

During the simulation tests three components of the propulsion system thrust force, T_x , T_y , M_{Tz} or three components of the ship resultant movement, V_{Gx} , V_{Gy} , ω_{vz} were preset. Simulation of the ship movement was carried out by solving the equations (3) and (4) in the time domain.

During the simulation of the ship movement the parameters preset by means of joystick were not changed, i.e. the joystick deflection was kept constant in each investigated case.

Generated resultant thrust force

In this case the resultant thrust force vector {T}, preset constant by means of the joystick, had the following components :

$$\{T\}=\{50.0\ ;\ 20.0\ ;\ 0.0\}\ [kN]$$

The joystick deflection angle φ=21.8°. During the ship movement in calm water the resultant resistance direction, at the initial movement stage, was deflected from the ship centre line by the angle of 18.5°, and the ship drift angle β = 347.4° (i.e. 12.6° starboard from the ship centre line). The difference between the thrust force direction angle φ and the drift angle β caused that the ship did not move in line with the direction of the preset resultant thrust force - Fig.8.

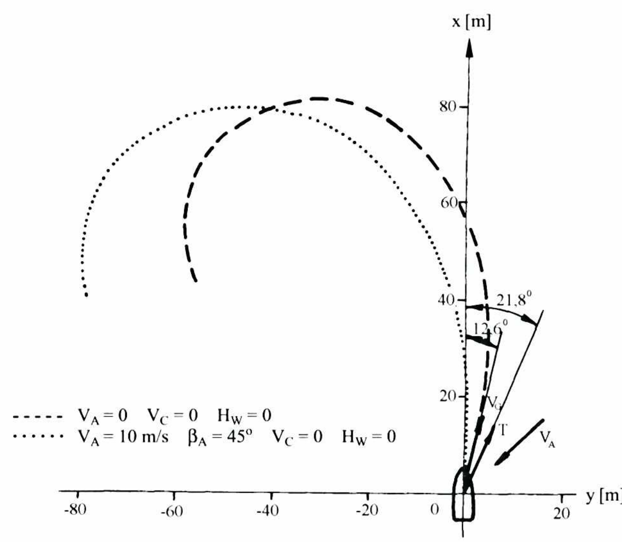

Fig.8. Ship movement during thrust force generation

In the case of the included wind effects, the ship movement direction changed even faster. In such case the thrust force direction must be corrected through the joystick over and over again in order to maintain the fixed movement direction; the ship can move in line with the preset thrust force direction during generation of only the thrust force longitudinal component {T_x} with no external disturbances due to marine environment.

Generated ship movement direction

In this case the ship movement resultant speed vector {V} preset constant by means of the joystick :

$$\{V\}=\{2.31\ ;\ -4.0\ ;\ 0.0\}\ [m/s]$$

was so assumed as to obtain the ship drift angle β=60° (Fig. 9). In the case of the ship movement in calm water, it coincided with the generated movement direction, these differences are caused by non-linear characteristics of the ship resistance force components, as it results from (10) and Fig.5. In the case of the wind effects acting on the ship the running ship movement direction immediately become different from the preset one, Fig.9.

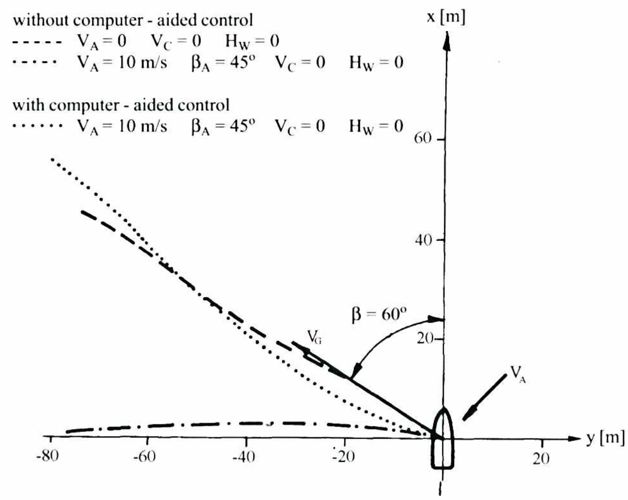

Fig. 9. Ship movement during movement direction generation

Only the generation of the movement direction through the computer-aided joystick (for the measured wind parameters V_A and β_A) caused the ship to move approximately in line with the preset movement direction, Fig.9.

Hence the best compatibility of the ship movement direction generated through joystick and the actual one was obtained (even with the wind effects included) when the joystick was aided by CAC system with the actual, marine environment effects included.

But also in this case some differences exist between the preset and real movement directions. They result from non-linearity of the resistance force components and from possible in accuracy in the measurement of the marine environment parameters. The differences can be considerably reduced by including a computer-aided system for stabilization of the preset movement direction into the software.

Acknowledgment

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Appraised by Jan Szantyr, Prof.,D.Sc.

NOMENCLATURE

b_P	-	distance between axes of propellers
b_T	-	location coordinate of tunnel thruster
C	-	coefficients and factors (generally)
d	-	ship draught
D	-	propeller diameter
F	-	area of overwater part of the ship
G	-	ship mass centre
H	-	height
K_T, K_Q	-	coefficient of propeller thrust and torque, respectively
L	-	ship length
m	-	hydrodynamic added mass
m_v	-	ship mass
M	-	moment
n	-	propeller revolutions
N	-	propulsion engine output
P	-	propeller pitch
Q	-	propeller torque
T	-	propeller thrust
V	-	linear velocity
x, y, ψ	-	displacement components of the ship in planar motion
$\dot{x}, \dot{y}, \dot{\psi}$	-	velocity components of the ship in planar motion
$\ddot{x}, \ddot{y}, \ddot{\psi}$	-	acceleration components of the ship in planar motion
X,Y,M	-	external force components and moment, respectively
α	-	inclination angle of thruster propeller blades
$\beta_A, \beta_C, \beta_W$	-	direction angle of wind, current and wave, respectively
β_v	-	ship drift angle
ρ_w	-	water density
φ, χ	-	joystick deflection angles in the ship plane of symmetry and midship plane, respectively
ω_v	-	ship angular velocity

Indices

A	-	of air or wind
b	-	of bow
C	-	of current
D	-	of water resistance
e	-	effective
G	-	of ship mass centre
H	-	of typical rudder (helm)
L	-	left
n	-	nominal
P	-	of ship propulsion system or propeller
r	-	relative
R	-	right
s	-	of stern
T	-	of tunnel thruster
v	-	of ship
W	-	of wave or sea water
x	-	of longitudinal component
y	-	of lateral component
z	-	of vertical component

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Conference

MCMC 2000

On 23÷25 August this year 5th IFAC Conference on :

Maneouvring and control of marine craft

was held in Aalborg, Denmark. Among others five papers of Polish scientists (as authors or co-authors) were presented during the conference :

- *AUV path planning for navigational constraints by evolutionary computation* – by M. Kwiesielewicz and W. Piotrowski of Technical University of Gdańsk, R. Śmierzchalski of Gdynia Maritime Academy and R.Sutton (UK)
- *On the design of a high precision track keeping system for a containership* – by A.Łozowicki of Technical University of Szczecin, and A.Tiano (Italy)
- *Dynamic optimisation of ship's safe trajectory in collision situations* – by J.Lisowski of Gdynia Maritime Academy
- *Computer simulation of risk assessment for a ship with a novel arrangement of internal spaces in damage condition* – by M.Gerigk of Technical University of Gdańsk
- *Hydrodynamic related problems when controling a ship behaviour in the port area* – by T.Abramowicz-Gerigk of Gdynia Maritime Academy.