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Mathematical model of the stopping manoeuvre simulation

SUMMARY

This paper presents some aspects of active stopping manoeuvre simulation in which a mathematical model of ship motion is applied. Results of several simulations performed with the use of PC version of the authors' computer program are included and compared with some results of full scale trials. Both results are reasonably convergent.

INTRODUCTION

Stopping ability of ships is important from the safety point of view both for the operators and designers. Furthermore the stopping characteristics of a ship should meet the latest IMO requirements [15]. It means that ships must satisfy the safety standards and the ship manoeuvring performance has to be considered starting from the early design stage .

The idea of the skillful shiphandling used as a compensatory factor for the poor inherent manoeuvrability characteristics of a ship is somewhat haphazardous approach to ship manoeuvrability [13].

Recently several attempts have been undertaken to develop prediction methods that could be used in early stage design [1], [11]. It is possible to obtain main stopping parameters by using methods based on similar ships [11] with ready -to-use diagrams and empirical formula. In the advanced design a mathematical model of ship motion could be applied.

There are three main types of mathematical model in use, namely:

- holistic model
- hydrodynamic derivative model
- force mathematical model.

In this study the hydrodynamic derivative model, originally proposed by Pierszyc [14], was developed. Additionally the applied modular approach makes this model adaptable and versatile so a variety of modelling methods for each module can be selected.

Stopping seems to be the simplest manoeuvre to simulate when the simplest configuration of the system called a ship is considered and in this hull-propeller-rudder (HPR) system one part, the rudder, is neglected.

From the two stopping manoeuvres: inertial (when the engine is stopped and the ship stops inertially) and active (when the propulsion machinery works astern) the latter is more important for the safe ship operation. It is included in ITTC'75 Manoeuvring Trials Code as the *crash-stop* trial or the *stopping at a slow speed* trial and the IMO requirements concern the parameters of crash-stop trial. Furthermore the active stopping is more viable for the numerical analysis.

ACTIVE STOPPING MANOEUVRE

The active stopping manoeuvre can be described by using the following five periods [5] (Fig.1).

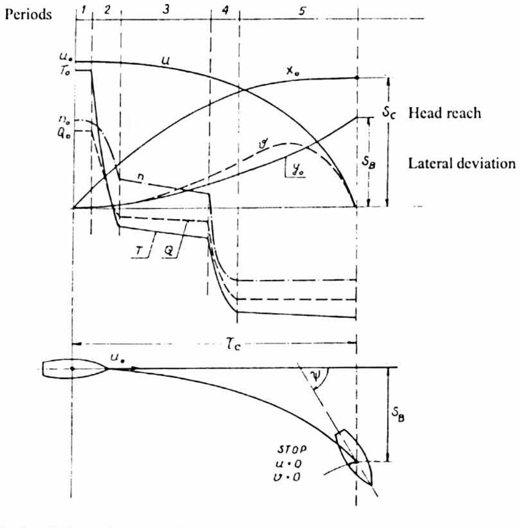


Fig. 1. Periods of the active stopping manoeuvre

- **1st period** starts when the order to stop the engine is given and it lasts up to its execution (fuel supply cut). It is very short, so that changes in the speed and the number of revolutions of the propeller can be neglected.
- **2nd period** starts when the fuel supply is cut and it lasts up to the moment when the propeller starts to work as a hydroturbine. That period is very short too so the speed can still be assumed unchanged but the propeller revolutions, thrust and torque decreasing.
- **3rd period** starts at the moment when the propeller rotates freely and it lasts up to the moment of its reverse action, which is allowed at the number of revolutions not exceeding the specified one for a given propulsion machinery. The greater the number of revolutions the shorter the third period.
- **4th period** starts when the engine is just reversed and it lasts until the required number of its revolutions astern is obtained. Flow conditions are then very unstable, but the ship's speed curves are quite even and regular.

The question of whether a ship can be stopped more quickly by operating at reduced torque is not the point here, because the propeller in reversal is in a state of extreme cavitation and the thrust for stopping the ship is a function of the torque developed in reversal.

The stopping effect will be the greatest at the highest number of revolutions, therefore the main propulsion machinery should be reversed as quickly as possible.

- **5th period** starts when the propeller rotates with the required number of revolutions astern and it lasts until the ship is stopped.

A sketch of manoeuvre nomogram for a ship with diesel engine working from full ahead to full astern is presented in Fig.2.

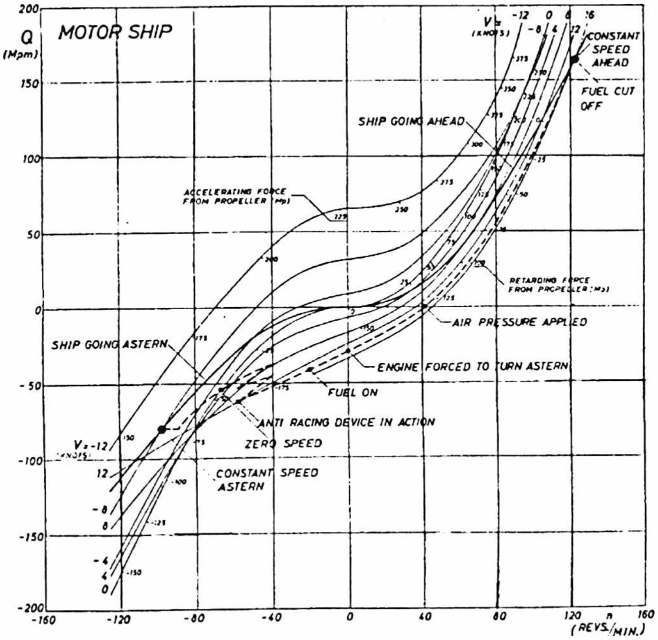


Fig. 2. Sketch of manoeuvre nomogram for a ship with diesel engine working from full ahead to full astern

MATHEMATICAL MODEL AND ITS MODIFICATIONS

The most effective way to describe numerically a ship as the hull-propeller system is to use a modular approach which makes modification and experimentation easy. The mathematical model used is based on the deep-water model with the introduced correction coefficients for confined waters effects.

The ship's centre of gravity is assumed as the origin of the coordinate system and only three planar motion components: surge, sway and yaw are considered .They are represented by the following set of equations:

surge:

$$X = m(\dot{u} - vr) = X_H + X_P$$

sway:

$$Y = m(\dot{v} - ur) = Y_H + Y_P \tag{1}$$

yaw:

$$N = I_Z \dot{r} = N_H + N_P$$

Notation is attached in the end of this paper. The subscripts H and P refer to ship's hull and propeller respectively

The basic form of the model modules of hull and propeller, used in this study, are as described in [3] and [14].The introduced modifications concern wake and thrust deduction coefficients originally assumed as:

$$w = \begin{Bmatrix} const \neq 0 & \text{for } u > 0 \\ 0 & \text{for } u \leq 0 \end{Bmatrix} \tag{2}$$

$$t = \begin{Bmatrix} const \neq 0 & \text{for T} > 0 \\ 0 & \text{for T} \leq 0 \end{Bmatrix} \tag{3}$$

To get more proper values of w and t it is necessary to have a complete picture of the propeller capacity in ahead and astern motions at various number of revolutions and different ship speeds. A considerable number of experiments in this area was carried out by Kempf, Nordstrom (1948), Miniowicz (1954÷56), Harvald (1967), Van Lameren (1969), Bernitsas (1971). Additionally Bakajew and Lawrientiew (1955) developed a calculation method of the propeller characteristic curves especially applicable in the case of ship retardation, when K_T and K_Q are equal to infinity at n=0 and therefore can not be used in calculations.

The proposed universal characteristics based on the universal advance coefficient [5] are defined as:

$$K_1 = \frac{K_r}{\left(1 - J^2\right)} \qquad K_2 = \frac{K_Q}{\left(1 - J^2\right)}$$

and:

$$J = \frac{v_p}{\sqrt{v_p^2 + n^2 D^2}} \qquad \text{(instead of } J_p = \frac{v_p}{Dn} \text{)}$$

As the lasting time of the first and second periods of the above described stopping manoeuvre is very short the engine reverse time highly influences ship active stopping characteristics as it is shown in Fig. 4.

The first (v>0 and n>0) and third (v>0 and n<0) quadrants of the propeller characteristics diagram as well as the wake and thrust deduction coefficients in these quadrants are the most important for stopping manoeuvre description . When the number of propeller revolutions approaches 0 w is tending to -∞ , therefore at large negative values of the advance coefficient J_p, the wake deduction coefficient w can be estimated close to the values given in the first quadrant [4], say within 10% range of the values.

The thrust deduction coefficient t varies between ±∞ within a rather narrow range of J_p . The variation of the thrust deduction coefficient is rather small [4] provided this area of very unstable flow is disregarded.

The contribution of the thrust force T in the total lateral force Y at positive and negative thrust,originally assumed as $Y_p=0,05T$ was modified as suggested by Norrbin [9]:

$$Y_p = 0,04\,T \quad \text{for } T > 0$$

and

$$Y_p = 0,06T \quad \text{for } T < 0 \tag{4}$$

The drift angle β influence on Y_p and its variation with the drift angle was approximated according to the functional relationship developed by Fujino, Kagemuto [10] for β<35°:

$$Y_p(\beta) = c_\beta\, Y_p \tag{5}$$

where:

$c_\beta = 1$ *for* $\beta \leq 0,2$ [rd]

$c_\beta = 8,75\beta(1-\beta)+3,1$ *for* $0,2 < \beta \leq 0,7$ [rd]

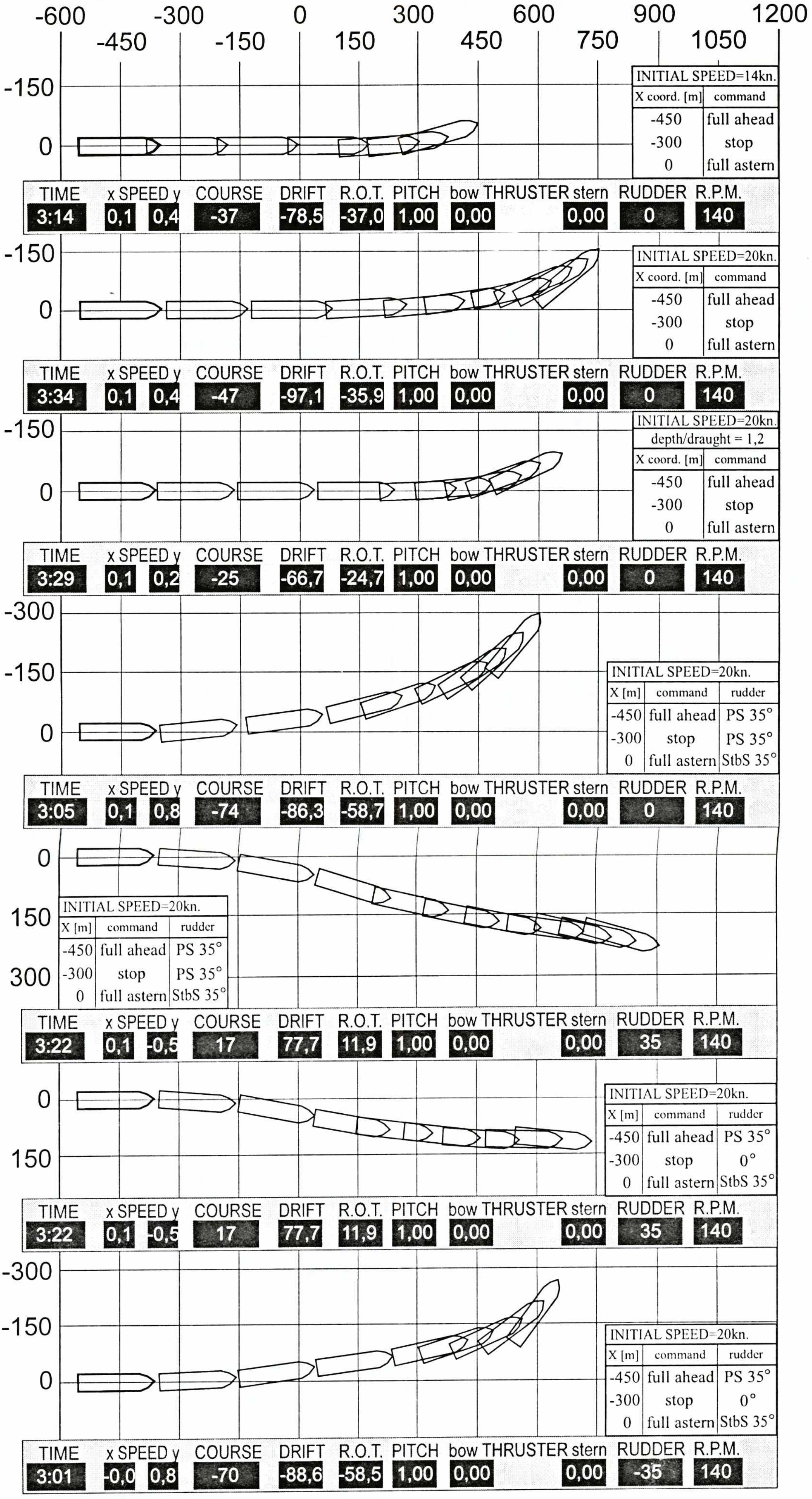


Fig. 5. Ro-ro vessel active stopping manoeuvres simulated for the different conditions of ship's initial speed, water depth, with and without rudder action taken into account

ESTIMATION OF SHIP ADDED MASSES IN ACTIVE STOPPING MANOEUVRE

A simple example of the way used to estimate the ship added masses in active stopping is given below.. Lets consider the ship just before the propeller rotates astern, which moves along the x coordinate axis (i.e. before the active stopping manoeuvre is analysed). The motion may be described as follows:

$$(m+m_{xx})\frac{du}{dt}=X_P-X_H \qquad (6)$$

where :

m - ship mass

m_{xx} - added mass

As wind and wave forces are not accounted for X_H describes resistance of ship with the working propeller and X_P represents propeller thrust (Fig. 3)

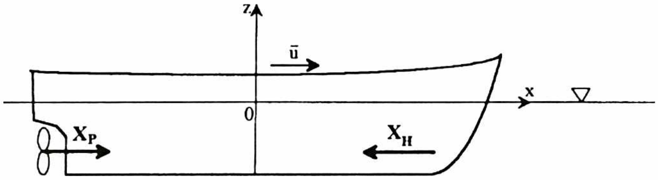


Fig. 3. The ship in motion along the x axis

When:

X_P-X_H>0 then the ship accelerates,

X_P-X_H<0 the ship begins to stop and ship's speed decreases.

If the ship's speed decreases the propeller thrust may satisfy each of the following relationships:

$$X_P > 0 \quad or \quad X_P = 0 \quad or \quad X_P < 0$$

The relationships fully describe the periods of active stopping manoeuvre. Therefore the added mass m_{xx} can be expressed by the following equation:

$$m_{xx}=\frac{X_P-X_H}{\frac{du}{dt}}-m \qquad (7)$$

If the bare hull resistance curve is known it is possible to estimate the hull-propeller resistance from the X_P thrust function given in the following form [8]:

$$X_P(\tau)=Xu(\tau) \qquad (8)$$

where: X - constant thrust

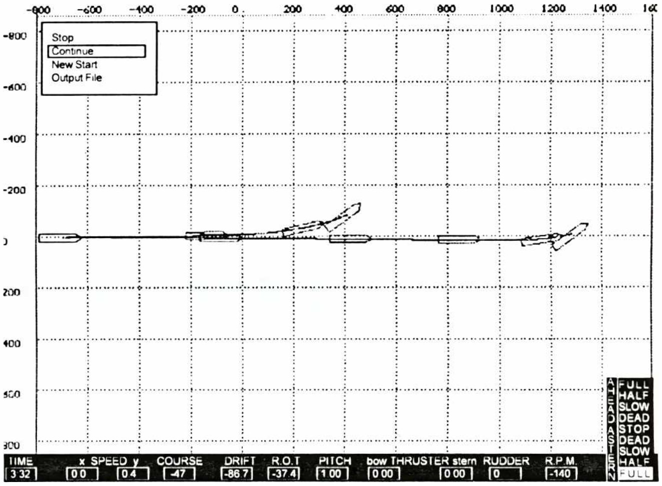
$u(\tau)$ - step function

τ - time

The derivative $du/d\tau$ can be calculated from the speed variation in time. Generally when the t and w coefficients are assumed constant the m_{xx} estimation is straightforward.

COMPUTER SIMULATION - RESULTS OF CALCULATIONS

The results of the active stopping manoeuvre simulation carried out with the use of PC computer program version are shown in Fig. 4 and 5 where several different trials are presented. Fig.4 shows the trajectory of the ro-ro vessel with full load, and corresponding displacement of 28 950 t , simulated with the assumed different engine reverse time of 1 min and 3,5 min.



TIME 3 32
x SPEED y 0 0 0 4
COURSE -47
DRIFT -86 7
R.O.T -37 4
PITCH 1 00
bow THRUSTER stern 0 00 0 00
RUDDER 0
R.P.M. -140

Fig. 4. Ro-ro vessel active stopping trajectories simulated for two different engine reverse time intervals

Simulation results of seven manoeuvres of the ship, performed in different conditions of ship's initial speed, water depth, with and without rudder action taken into account, are shown in Fig. 5.

The comparison of the stopping distances and times obtained in full scale trials and the computer simulation is given in Tab. 1.

Tab. 1. Comparison of the stopping distances and times obtained in full scale trials and the computer simulation

Trial	Full scale trials		Simulation	
	S_C [m]	τ_C [s]	S_C [m]	τ_C [s]
Initial speed = 20 kn, Full Ahead - Dead Astern	1 310	300	1 250	348
Initial speed = 9 kn, Slow Ahead - Dead Astern	525	210	510	247
Initial speed = 9 kn, Slow Ahead - Full Astern	225	90	270	92

The differences of the values given in Tab. 1 are quite reasonable. Generally they result from differences in the environmental forces, those acting in full scale trials and modelled, as well as by simplifications assumed in the mathematical model.

CONCLUDING REMARKS

Quality of the results obtained from a mathematical model depends on the available input data. Generally it is known which factors are significant for a satisfactory accuracy of calculations. The available input data are dependent upon the design stage of a ship or on the data which can be obtained from ships in operation (the data are usually scarce). Even sophisticated DP (dynamic positioning) systems based on mathematical models require on-board tuning, cost of which reaches about 1/3 of the total system cost.

In ship design, mathematical model application is preferable in comparison with any empirical or semi-empirical method because all the data generated during simulation process are available at any time as they can be stored for further use.

It is also possible to examine the ship's performance in a high risk situation by using a manoeuvre simulation program installed in the personal computer which is the most safe and comfortable approach.

NOMENCLATURE

c_β - ship drift angle influence coefficient (on the propeller lateral force)

D - propeller diameter

I_z - moment of inertia of ship with respect to z-axis

J - universal advance number

J_P - advance number

K_1 - universal thrust coefficient

K_2 - universal torque coefficient

K_T - thrust coefficient

K_Q - torque coefficient

m - mass of ship

m_{xx} - added mass

n - number of propeller revolution

N - total yaw moment

N_H - yaw moment acting on ship hull

N_P - yaw moment induced on ship hull by propeller action

Q - propeller torque

r - turning rate

S_C - lateral deviation

S_B - head reach

τ_c - stopping time

t - thrust deduction coefficient

T - propeller thrust

u - ship speed in x-axis direction

v - ship speed in y-axis direction

v_P - propeller advance speed

w - wake fraction

x_o, y_o - ship surge and sway, respectively

X, Y - surge and sway total forces, respectively

X_H, Y_H - longitudinal and lateral forces acting on ship hull, respectively

X_P, Y_P - propeller thrust and lateral force, respectively

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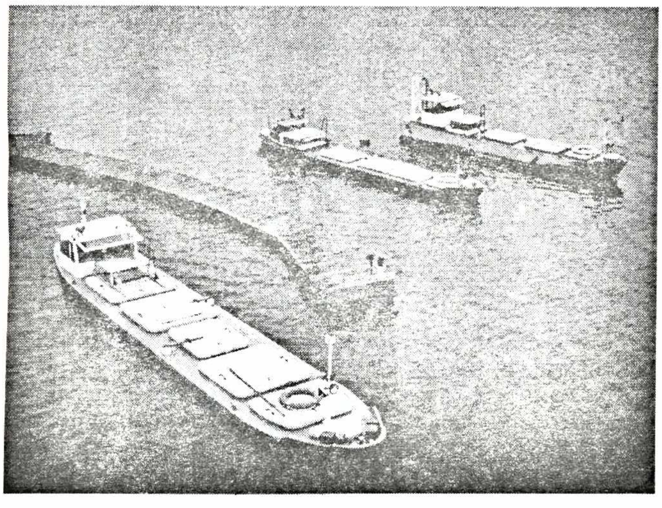
Appraised by Wiesław Wełnicki, Assist.Prof.,D.Sc.,N.A.



Conferences

A hundred years of marine radiocommunication

Under this slogan a symposium on historical development and recent technical problems of marine radiocommunication was held from 27 to 29 September 1995 in Gdynia, being organized by Chair of Marine Radioelectronics, Merchant Marine Academy, Gdynia.

Prof. Józef Lisowski, Rector of Merchant Marine Academy, Gdynia, gives an inaugural address while opening the symposium

During the symposium it was presented 20 papers devoted a.o. to the following topics:

- Analysis of the nonlinear digital teletransmission systems
- Multifunctional module for radiocommunication establishing
- The antenna theory and techniques applicable to ship's radio-systems
- Polish marine radiocommunication in the inter-war period
- Radio wave propagation in satellite radiocommunication
- Fundamental limitations in piezoelectric frequency stabilisation
- VSAT satellite telecommunication systems: performance, applications, development trends
- INMARSAT - B - the latest option in marine satellite radiocommunication
- Computation method of operational range estimation in the land mobile communication systems

This symposium was given a solemn character due to its jubilee date - prof. Józef Lisowski, Rector of Merchant Marine Academy in Gdynia, gave an inaugural address while opening the symposium, stressing an important role of radiocommunication for safety at sea and necessity of its continuous improvement.

Repesentatives of Maritime Institute in Constanca, Romania, who presented a paper, were also among about 100 participants of the symposium. The remaining papers were prepared and read by radiocommunication scientists and experts from seven Polish technical universities and institutes, especially those of Technical University in Gdańsk.

The symposium participants were given an opportunity for visiting GDYNIA - RADIO Telecommunication Centre and a ship, being built in a shipyard in Gdynia, fitted with equipment complying with GDMSS requirements, as well as for taking part in a short voyage on board DAR MŁODZIEŻY, a training tall-sail ship.

The symposium proceedings are published in one, concise volume.