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Port basin as a waterway system component

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Abstract
The system of port waterways has been defined herein as a composition of three subsystems: approach area (port basin), quay and its equipment, navigational (determination of ship position and speed). Besides, the author defines the state vector of conditions for safe operation of berthing ships. Described are interrelations between parameters of port waterway system and the state vector of safe operation of berthing ships. Differences have been specified between sea waterway systems (fairways, harbour entrances, turning basins, anchorages) and systems of port waterways (port basin, lock).

Introduction

Marine traffic engineering divides waterways depending on the type of ship's manoeuvres. The following types of waterway and associated manoeuvres are distinguished [1]:

Waterway type	**Manoeuvre type**
1. Fairway: • straight section • bend	− fairway passage
2. Port entrance	− entry into port
4. Turning basin	− turning
3. anchorage	− anchoring
5. Port basin	− berthing, unberthing
6. Lock	− entry into and departure from the lock

Research into sea waterway systems including fairways (open, approach channels, port channels / canals, etc.), port entrances, turning basins and anchorages, has resulted in the determination of the dependence of system components on conditions of safe operation of ships within the system [2, 3]. The research has led to the development of methods of system component parameter optimization. Such system of sea waterways (fairways, port entrances, turning basins and anchorages) can have the following matrix notation [4]:

$$\begin{bmatrix} \mathbf{A_i} \\ \mathbf{N_{in}} \\ \mathbf{Z_{im}} \end{bmatrix} = f(\mathbf{W_i}) \tag{1}$$

where:

$\mathbf{A_i}$ – waterway subsystem;
$\mathbf{N_{in}}$ – navigational subsystem;
$\mathbf{Z_{im}}$ – traffic control subsystem;
$\mathbf{W_i}$ – conditions of safe ship operation on a waterway;

while

$$\mathbf{A_i} = \begin{bmatrix} t_i \\ l_i \\ D_i \\ h_i \end{bmatrix} \tag{2}$$

where:

t_i − type of i-th waterway section;
l_i − length of i-th waterway section;
D_i − width of navigable area of i-th waterway section;
h_i − minimum depth of i-th waterway section;

$$\mathbf{N_{in}} = \begin{bmatrix} d_{in} \\ m_{in} \\ n_{in} \end{bmatrix} \tag{3}$$

where:

d_{in} – accuracy of n-th navigational system in i-th waterway section (standard deviation);

m_{in} – availability of n-th navigational system in i-th waterway section (dependent on system operator, for terrestrial navigational systems on day/night time and visibility);

n_{in} – reliability of n-th navigational system in i-th waterway section (technical reliability);

$$\mathbf{Z_{im}} = \begin{bmatrix} r_{im} \\ o_{im} \end{bmatrix} \tag{4}$$

where:

r_{im} – type of m-th traffic control system in i-th waterway section;

o_{im} – type of m-th hydrometeorological information system (hydro-meteorological support) in i-th waterway section.

The existing systems of sea waterways (fairways), where manoeuvres performed include straight passages of a fairway section, port entry, or turning, are imprecise in describing the process of ship berthing or mooring in a lock.

Taking into consideration such limitation, this author has developed a system of port waterways, within which quay or lock approaching and berthing manoeuvres are performed. Studies of port waterway system allow to identify relations between system components and conditions of safe ship handling during berthing or mooring manoeuvres.

System of port waterways

Navigational risk (manoeuvring risk) is the criterion of manoeuvre safety while a ship is berthing (unberthing). The risk of berth approach and berthing itself can be represented as this function:

$$R_p = f(A, K, S, N, H, M) \tag{5}$$

where:

R_p – risk of approach and berthing;

A – parameters of approach area (e.g. port basin);

K – parameters of the quay and its equipment;

S – ship parameters;

N – parameters of navigational system (determination of ship position and speed);

H – hydrometeorological parameters;

M – parameters of a manoeuvre being performed.

The risk of approach and berthing manoeuvre R_p is a variable dependent on independent variables A, K, S, N, H, M. These represent a number of factors describing the ship – approach area – quay and its equipment – navigational system in use – prevailing hydrometeorological conditions – manoeuvring tactics.

Port basins and quays have manoeuvring restrictions for approaching ships. These restrictions are referred to as conditions of safe operation of berthing ships (W^p) and relate to:

- parameters of berthing ships;
- hydrometeorological conditions, at which approach, berthing and unberthing manoeuvres can be performed;
- conditions of ship manoeuvring during its approach, berthing and unberthing.

Therefore:

$$W^p = f(S, H, M) \tag{6}$$

Taking into consideration the conditions of safe ship operation during approach and berthing, it can present navigational risk for a specific ship performing a specific manoeuvre in preset hydrometeorological conditions as a simplified function:

$$R_{SMH} = f(A, K, N) \tag{7}$$

The port waterway system consists of three components, or subsystems:

1. Approach area (port basin).
2. Quay and its equipment.
3. Nawigational subsystem determining ship position and speed.

These components are interrelated and essentially affect the system properties.

The primary function of the port waterway system is to allow a ship with specific characteristics to perform planned approach and berthing manoeuvres. The input quantity is a planned approach / berthing manoeuvre to be performed by a ship with specific characteristics, while the output quantity is the actual manoeuvre performed by that ship. A cybernetic definition of the system is used in marine traffic engineering [5]. These are relatively isolated systems, in which a separate whole is coupled with the environment through input and output quantities [6]. The waterway system is built by man and the boundaries between the system and its model are somewhat fuzzy. Figure 1 presents a general model of port waterway system.

The system of port waterways is defined by parameters of its components (subsystems). Three components of port waterway system are a function of the vector of safe 'maximum ship' operation conditions. In this connection, the system of i-th quay in the port (port basin) has this form in the matrix notation:

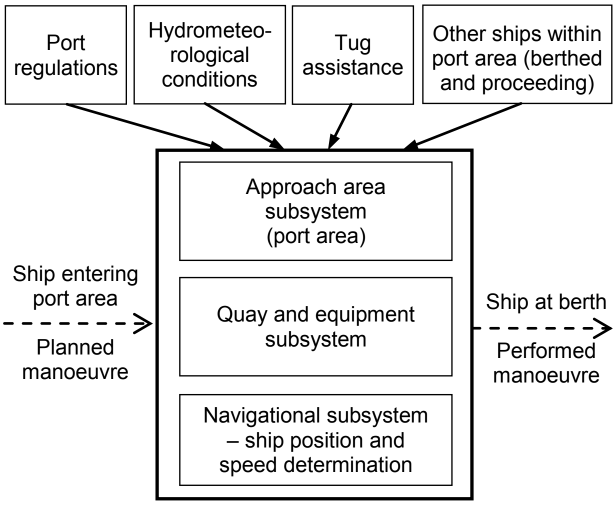

Fig. 1. A general model of port waterway system – berthing manoeuvre

$$\begin{bmatrix} \mathbf{A}_i^p \\ \mathbf{K}_i^p \\ \mathbf{N}_{in}^p \end{bmatrix} = f\left(\mathbf{W}_i^p\right) \tag{8}$$

where:

$\mathbf{W}_i^p$ – state vector of safe operation conditions for a 'maximum ship' approaching i-th quay.

The following matrix notations have been adopted for the respective subsystems:

- **Approach area (port basin)**:

$$\mathbf{A}_i^p = \begin{bmatrix} r_i \\ l_i \\ D_i \\ h_i \\ \upsilon_i \end{bmatrix} \tag{9}$$

where:

r_i – type of approach area to i-th quay;
l_i – length of approach to i-th quay;
D_i – width of navigable approach to i-th quay;
h_i – minimum depth of approach to i-th quay;
υ_i – allowable propeller stream speed at the bottom of approach area [m/s].

The following quay approach types are distinguished (approach area):

- mooring alongside:
  - approach parallel to the quay;
  - approach at an angle to the quay ($\beta > 30°$);
  - approach to the quay with a ship's turn.
- stern-to or bow-to ramp mooring:
  - approach parallel to the quay (at right angle to the ramp);
  - approach at an angle to the quay ($\beta > 30°$);
  - approach to the quay with a ship's turn.

- **Quay and its equipment**:

$$\mathbf{K}_i^p = \begin{bmatrix} T_i \\ k_i \\ b_i \\ E_i \\ p_i \end{bmatrix} \tag{10}$$

where:

T_i – construction type of i-th quay;
k_i – length of line of mooring of i-th quay [m];
b_i – length between fenders on i-th quay [m];
E_i – maximum kinetic energy absorbed by fender of i-th quay [kNm];
p_i – maximum reaction force per 1 m^2 of fender front surface area of i-th quay (maximum unit thrust on the hull) [kN/m^2].

The following types of quay structures are distinguished:

- solid – mooring alongside;
- pier – mooring alongside;
- dolphins – mooring alongside;
- ramp – stern-to or bow-to mooring.

- **Navigational subsystem of ship position/speed determination**:

$$\mathbf{N}_{in}^p = \begin{bmatrix} d_{in} \\ m_{in} \\ n_{in} \end{bmatrix} \tag{11}$$

where:

d_{in} – accuracy of n-th navigational system during approach to i-th quay (directional error of ship position and speed, perpendicular to the quay);
m_{in} – availability of n-th navigational system during approach to i-th quay waterway section (dependent on type of navigational system, for optical system – on day/night time and visibility);
n_{in} – reliability of n-th navigational system during approach to i-th quay.

Systems of ship position and speed determination during berthing manoeuvres can be dividied into:

- terrestrial systems, using methods of optical and radar navigation;
- based on electronic navigational chart technology: pilot navigational system (PNS) and pilot navigation and docking system (PNDS).

Taking into account the availability and reliability of navigational subsystems, they have to be designed for three different visibility and night/day conditions:

- day-time (good visibility);
- night-time (good visibility);
- restricted visibility.

Navigational subsystems of position/speed determination for each type of visibility conditions have to be doubled (redundant), and the whole system of port waterways should be designed for a navigational subsystem that has a lower accuracy of ship position and speed determination.

Conditions of safe ship operation in the port waterway system

Conditions of safe operation of ships berthing to i-th quay are described by the state vector of safe operation of a 'maximum ship' in the herein considered port waterway system, written in this form:

$$\mathbf{W}_i^p = \left[t_{yp}, L_c, B, T, H_{st}, F, M, M_{st}, n_h, P_h, \mathbf{H}\right] \quad (12)$$

where:

t_{yp} – type of a 'maximum ship';
L_c – length overall of 'maximum ship';
B – breadth of a 'maximum ship';
T – 'maximum ship' draft;
H_{st} – 'maximum ship' airdraft;
F – windage area of 'maximum ship';
M – main propulsion power of 'maximum ship';
M_{st} – bow thrusters power;
n_h – tugs assisting the berthing of 'maximum ship';
P_h – total bollard pull of tugs assisting the berthing;
$\mathbf{H}_\mathbf{i}$ – vector of hydro-meteo conditions acceptable for 'maximum ship' berthing to a given quay.

$$\mathbf{H}_\mathbf{i} = \left\lfloor d/n, \Delta h_i, V_{wi}, KR_{wi}, V_{pi}, KR_{pi}, h_{fi}, KR_{fi} \right\rfloor \quad (13)$$

where:

d/n – day/night time (day or no restrictions);
Δh_i – maximum drop of water depth;
V_{wi} – critical wind speed at i-th quay (maximum wind speed, at which a ship can safely berth or unberth);
KR_{wi} – wind direction restriction (if any at i-th quay);
V_{pi} – maximum current speed at i-th quay;
KR_{pi} – current direction restriction (if any at i-th quay);
h_{fi} – maximum wave height at i-th quay;
KR_{fi} – wave direction restrictions (if any at i-th quay).

For the determination of vector of safe ship operation in the port waterway system the following ship types are distinguished:

- twin-propeller ships with bow thrusters – berthing unassisted;
- single propeller ships with bow thrusters – berthing unassisted;
- single propeller ships without bow thrusters – berthing unassisted;
- ships berthing with tug assistance.

The state vector of safe operation conditions of a maximum ship at i-th quay of port waterway system unequivocally defines:

- underkeel clearance (Δ_i);
- width and shape of safe manoeuvring area of approach to berth (d_i);
- kinetic energy of first contact of a maximum ship with the quay (E_i) and distribution of first contact points;
- propeller stream speed at the bottom (υ_i) and their distribution.

Hence we get:

$$\begin{aligned} \Delta_i &= f_1\left(\mathbf{W}_i^p\right) \\ d_i &= f_2\left(\mathbf{W}_i^p\right) \\ E_i &= f_3\left(\mathbf{W}_i^p\right) \\ \upsilon_i &= f_4\left(\mathbf{W}_i^p\right) \end{aligned} \quad (14)$$

Conclusions

Interrelations between parameters of port waterway system and conditions of safe operation of ships berthing to quays of the system permit to perform two reversed tasks:

1. Determination of parameters of basic components of port waterway system built or modernized (approach area, quay, navigational subsystem). Parameters of a port waterway system are a function of designed (assumed) conditions of safe ship operation (state vector of safe ship operation):

$$\begin{bmatrix} \mathbf{A}_i^p \\ \mathbf{K}_i^p \\ \mathbf{N}_{in}^p \end{bmatrix} = F_1\left(\mathbf{W}_i^p\right) \quad (15)$$

2. Determination of conditions of safe ship operation in the existing port waterway system whose parameters are known. Then, the state vector of safe ship operation conditions is a function of port waterway system parameters:

$$\mathbf{W}_i^p = F_2 \begin{bmatrix} \mathbf{A}_i^p \\ \mathbf{K}_i^p \\ \mathbf{N}_i^p \end{bmatrix} \quad (16)$$

The basic problem is to identify the vector of conditions of safe 'maximum ship' operation in the examined system of port waterways. In both tasks the vector is identified in a different way.

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