The influence of hydro-meteorological factors on the risk of harbour operations

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Abstract

The paper presents a study on the environmental impact on the risk of harbour operations. The hydro-meteorological elements have been recognised as the most important safety factors with regard to the ship entrance into the harbour and berthing inside the docks. They are identified as real time, short and long term factors and they all should be considered in the safety assessment of harbour operations. The risk of each operation should be determined on the basis of weather forecast and the modelled prediction of the total water level, surface currents and waves. Several topics have been discussed in the paper with regard to the safe ship approach and navigation inside the harbour. The application of different tools for the prediction of ship performance is presented. The stochastic method for the determination of probability that the ship will navigate within the boundaries of the required navigational width and low speed manoeuvring standards proposed by Panel H-10 SNAME have been considered. The real scale experiments carried out in Port of Gdynia and the several trials performed using the Full Mission Simulator convinced that the open water model tests are necessary for the proper prediction of ship performance during berthing. The program of the proposed open water investigations is presented in the paper. The experimental stand constructed for the tests of ship-berth interactions, in the lake Silm at the Ilawa Ship Handling Training and Research Centre facilities is described.

Keywords: *harbour operations, hydro-meteorological elements, model tests of self-berthing, real scale experiments, safety of navigation, ship motion simulation*

INTRODUCTION

The difficulty of navigation in restricted areas is closely connected with external conditions. The biggest influence of the hydro-meteorological elements on the ship safety is mainly observed for the ships approaching the harbour entrance and ships berthing inside the harbour. The most important influencing factors are wind, waves, current and under keel clearance. The changes in the bathymetry and extension of the breakwaters affect both wave propagation and current conditions in the harbour entrance and inside the docks. According to the evidence of harbour incidents caused by weather conditions, the information of the real time hydro-meteorological data is not sufficient. The short term and long term factors should also be considered [2].

The advanced environmental monitoring systems can integrate the measurements of several hydro-meteorological parameters: wind speed and direction, air pressure and humidity, rain fall and solar radiation, visibility, water salinity, sea current speed and direction, wave data and tide level. The collected data are stored and processed. The time lag between the wind forcing and the water level, surface currents and wave responses is considered. This allows to introduce the navigational warnings and restrictions via the vessel traffic system.

The implementation of the hydro-meteorological systems in port areas depends on local requirements. However in all cases the risk of operation should be determined at least on the basis of weather forecast and modelled prediction of water level and surface currents. Prediction of water level is the basic information. The lack of prediction of the surface currents parameters could become a very serious threat during the gusty wind conditions [2].

Evaluation of the safety of ships navigating near the harbour entrance and berthing inside the harbour is very important for big ships, but especially for self-manoeuvring ferries and passenger vessels. There are many studies conducted on this subject in the fields of sea traffic engineering and port facilities design [7], [11]. The most advanced investigations concern the port areas with long period waves (with the period of 60 s to 180 s).

The main tool used for the prediction of ship performance in particular weather conditions is the numerical simulation. To determine the wave and current conditions in the particular layout of a port area the hydrodynamic models are used. The implementation of external, hydro-meteorological conditions as the models of a stochastic nature gives the complex model of ship motions, quite close to reality.

Risk of ship entrance into the harbour

Permission of ship entrance into the harbour is dependent on the decision of the Harbourmaster. The decision can be consulted with the pilot and Ship Master. The bylaws and harbour Safety Management System procedures are used as the basic rules and guidelines. The vessel/harbour operational conditions are always considered. The assessment of the influence of hydro-meteorological elements on the safety is of the greatest importance.

The self-manoeuvring vessels like the passenger cruisers, ro-ro vessels and ferries usually get an exemption from the towage or tug assistance, up to a given wind force. However if the problems with keeping the vessel on the waterway appear due to the strong, transverse wind, the tug assistance is not always used and the ships very often navigate with the higher speeds then the allowable. This decreases the safety margin and can be the cause of an accident, when the wind parameters rapidly change [2]. Therefore the proper determination of the risk is necessary.

Harbourmaster may exempt from the towage any ship in any particular case and the economic reasons are always taken into account. To avoid too large or too small safety margins the personal experience and intuitional judging must be aided. In advanced applications of vessel traffic management systems (VTMS) the advisory systems are used.

Several tools are used to assess the risk. The sea traffic engineering statistical methods [7], based on computer simulation of ship motion as well as the measurements of the real ship performance are very reliable. However they need to collect a big set of data. The recently proposed probabilistic method, for the assessment of ship containment within the allowable navigational width [14], seems to be an alternative approach for the risk assessment. Also in some particular cases, one of the slow speed standards called MER (Minimum Effective Rudder) can be applied to assess the ship safety in the approach waterways.

Risk of ship entrance into the harbour – Application of the stochastic method to the risk assessment

In 2005 Vorobyov [13] presented the model of the probability that a ship can navigate within the boundaries of a fairway, of the navigational width equal to Bn (figure 1). The probability has been proposed as a new representative characteristic of the assessment of ship dynamics controllability. The influence of wind, regular waves and constrained waters on a vessel has been considered as a stochastic process. If it is assumed that the yawing angle, drift angle and rate of turn are small (1) the solution of the system of differential equations describing the ship motion, during her navigation along the fairway, is a multidimensional Markov process and the joint density function of probability of this process satisfies the equation of Fokker - Plank -Kolmogorov.

$$|\psi| \le 0.4 \ , \ \ |\beta| \le 0.2 \ , \ \ \mathrm{rot} \le 0.1 \qquad (1)$$

where:

$$\mathrm{rot} = \left| \dot{\psi} \frac{\mathrm{L}}{\mathrm{u}} \right|$$

L – length between perpendiculars [m],
u – ship velocity [m/s].

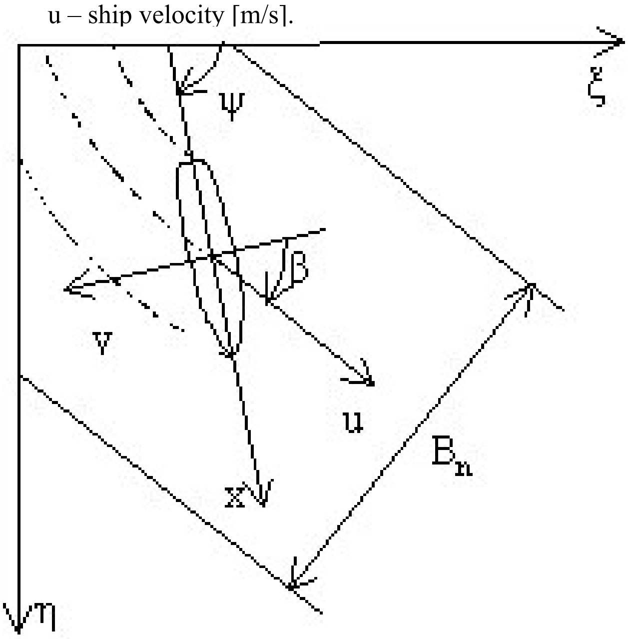

Figure 1. Trajectory of the VLCC2 during the MER trials in the training area of Ship Handling Research and Training Centre of the Foundation for Safety of Navigation and Environment Protection in Ilawa-Kamionka and MER trial results.

Probability P of the fact that a vessel will never cross (or even touch) the boundaries of the fairway of navigational width equal to B_n can be determined from the Chebyshev inequality proposed by Vorobyov in the form (2) [14].

$$P\left(\left| \left(\frac{1}{2} - \bar{x}_f \right) X_{13} + X_{15} \right| \ge \frac{|B_n - B|}{2L} \right) < 4L^2 \frac{\left(\frac{1}{2} - \bar{x}_f \right)^2 k_{13,13} + 2\left(\frac{1}{2} - \bar{x}_f \right) k_{13,15} + k_{15,15}}{\left(B_n - B\right)^2} \qquad (2)$$

where:

P – probability that the vessel will navigate within the boundaries of the fairway of navigational width equal to B_n,
B – vessel breadth,
B_n – navigational width of the fairway,
x_f – longitudinal centre of floatation,
$\bar{x}_f$ – x_f/L,
X_{13} – random function describing ship yaw angle, ψ - component of the vectorial Markov process ,
X_{15} – random function describing ship sway ç - component of the vectorial Markov process,
$k_{i,j}$ – correlation coefficients for the assumed value of B_n
L – length between perpendiculars [m],
u – ship velocity [m/s].

The risk of the ship entrance into the harbour can be determined, as a risk R of crossing the boundaries of a fairway (3), using the probability P (2).

$$\mathrm{R} = (1 - \mathrm{P}) \cdot \mathrm{S} \qquad (3)$$

where:
P – probability that the vessel will navigate within the boundaries of the approach fairway,
S – consequences.

The probability (2) that the vessel will navigate within the boundaries of the navigational width, should be determined for a particular distance of the approach fairway or for a given interval of time. This is caused by the unstable form of the matrix, of the system of stochastic equations of ship motion, for some combinations of wind disturbance and vessel velocity values.

The consequences S are dependent on the ship and harbour operational conditions – for example: distance to the breakwaters and navigational obstructions, close proximity to the dangerous and sensitive areas or dangerous cargo on board the vessel.

Practical aspects of MER trial implementation to the safety assessment of a ship approaching the harbour

The main reason to introduce the low speed manoeuvring standards [8] was the assessment of the manoeuvring performance of a particular ship in the restricted areas. The standard trial proposed by Panel H-10 SNAME (The Society of Naval Architects and Marine Engineers) called Minimum Effective Rudder (MER) has been developed to decide whether a vessel has got the sufficient controllability to navigate in the narrow channels and waterways. This standard information can be the most required for the big vessels, to decide whether the tug assistance is required.

The proposed standard is a combination of the pull out and limited spiral trials. It is performed starting from the steady speed and the 30° helm to port side, when the rate of turn gets the constant value, the helm is put to zero and kept midship until the yawing speed becomes constant again. The helm is changed consecutively 2°, 4° and 6° to starboard until the value of constant rate of turn is zero or gets the opposite sign. This rudder angle is defined as MER. The collected constant values of the rate of turn, at the rudder angles of 30°, 0° and if necessary 2°, 4° or 6° allow to assess ship course stability. The trial should be performed to port side and to starboard. Although this characteristic does not give any advice regarding the whole range of ship controllability, it is a big help to a Ship Master and pilot in narrow waterways. The example of the MER trial results for the deep water conditions is presented in table 1 [8].

The proposed trial has been tested in the way of its application to the assessment of the ship controllability during her navigation in approach waterways.

The tests were conducted for VLCC vessels using Full Mission Simulator of Gdynia Maritime University - VLCC1 [6] and self-propelled man manned model - VLCC2, at the training area of Ship Handling Research and Training Centre of the Foundation for Safety of Navigation and Environment Protection in the Silm lake in Ilawa-Kamionka. The parameters of the tested vessels are presented in table 2.

The simulator runs of the trial, in different conditions, show the dependence of the yaw rate on the vessel speed, observed for the deep water – table 3. In shallow water conditions there was almost no dependence of the rate of turn on vessel speed, also the influence of the propeller side force was not observed during manoeuvres in shallow water. Figure 2 presents the non-dimensional rate of turn (4) for MER to starboard.

$$rot = r \cdot L / u \tag{4}$$

where:
r – rate of turn [rad/s]
L – length between perpendiculars [m].

TABLE 1. *The example of the MER trial results for the deep water conditions [hwang].*

Approach Speed [kts]	5 (DSAHD)		10 (HAHD)		16 (FAHD)	
Initial Rud [°]	30 L	30 R	30 L	30 R	30 L	30 R
Initial Yaw Rate r*L / U	-0.594	0.592	-0.616	0.614	-0.603	0.602
Rud Sequence #1						
Rud Angle [°]	0R	0L	0R	0L	0R	0L
Initial Yaw Rate r*L / U	-0.229	0.222	-0.200	0.193	-0.161	0.152
Swing direction changed?	no	no	no	no	no	no
Ship is directionally	unstable	unstable	unstable	unstable	unstable	unstable
Rud Sequence #2						
Rud Angle [°]	2R	2L	2R	2L	2R	2L
Yaw Rate r*L / U	-0.212	0.205	-0.181	0.174	0.000	0.000
Swing direction changed?	no	no	no	no	almost	almost
Rud Sequence #3						
Rud Angle [°]	4R	4L	4R	4L	4R	4L
Yaw Rate r*L / U	0.000	0.000	0.000	0.000	0.279	-0.283
Swing direction changed?	almost	almost	almost	almost	*yes*	*yes*
Rud Sequence #4						
Rud Angle [°]	6R	6L	6R	6L		
Yaw Rate r*L / U	0.335	-0.337	0.338	-0.341		
Swing direction changed?	*yes*	*yes*	*yes*	*yes*		

TABLE 2. *Main parameters of tested models VLCC1 and VLCC2.*

Vessel	VLCC1	VLCC2
Displacement [t]	291,154	232,660
Length [m]	315.00	324.00
Breadth [m]	56.00	57.00
Draft [m]	19.36	20.60
C_B	0.787	0.83

The performance of the proposed trial is very much dependent on the accuracy of the mathematical model used for the simulation, especially in the shallow water conditions. The open water model tests performed on the self-propelled man manned model

TABLE 3. *Main parameters of tested models VLCC1 and VLCC2.*

Speed	ROT [°/min]			MER [°]		
	Deep water	h/T=1.2	h/T=1.1	Deep water	h/T=1.1	h/T=1.1
HALF	-8.6	-2.8	-2.1	-2	-2	-2
SLOW	-6.7	-2.4	-2.5	-2	-2	-2
DEAD SLOW	-7.4	-2.5	-1.9	-2	-2	-2

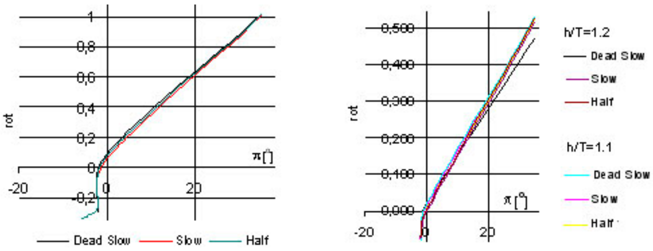

Figure 2. *Results of VLCC2 MER trial simulation in deep and shallow water conditions.*

of VLCC confirmed that the trial is very sensitive to wind. The big manoeuvring area is necessary to conduct the trials. There are five runs presented in figure 3. Only two of them can be used for MER assessment due to the wind disturbances. The results of the MER trials to port and to starboard side, for the deep water conditions are presented in figure 3.

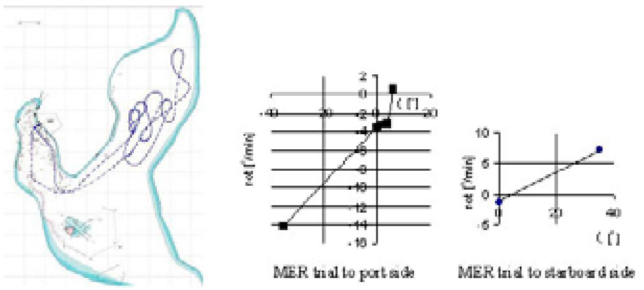

Figure 3. *trajectory of the VLCC2 during the MER trials in the training area of Ship Handling Research and Training Centre of the Foundation for Safety of Navigation and Environment Protection in Ilawa-Kamionka and MER trial results.*

Risk of berthing operations

The safety of berthing operations in particular conditions can be assessed on the basis of model tests carried out during the ship design. The results are mainly used for the determination of the necessary power of the bow and aft thrusters for the self-berthing vessels. The prediction of the real ship performance is difficult to determine because of the scale effect. Mathematical modelling of the self-berthing operation is still not solved due to the small model scale and the complicated interactions. The mathematical models used for berthing simulation still need further, usually heuristic, tuning.

The methods used to determine the safety of berthing operations, applied in port design and planning of harbour manoeuvres, are mainly based on the stochastic models. The multiple runs of the same manoeuvre in different environmental conditions are performed. The ship motion simulations are usually applied but the observations and measurements of real ships performance are also used [7]. The methods are very reliable, but need much effort and their accuracy is also dependent on the accuracy of the mathematical models used for the simulations.

The accepted safety measures used in berthing and deberthing operations are the allowable impact force and sufficient power of tug boats. For self-berthing vessels, the safety measure is also the available thrust of ship propellers and thrusters in the particular external conditions [3].

The basic factor of the safety of berthing operations is the berthing energy. This is the energy to be absorbed by the fenders and is usually calculated by multiplying the vessel total kinetic energy by the berthing coefficient c:

$$E_k = \frac{1}{2} c \cdot D \cdot V_s^{\,2} \qquad (5)$$

where
E_k - impact energy [MJ],
D - vessel displacement [t],
s - vessel speed [m/s],
c - berthing coefficient.

The coefficient c is the product of several factors. The eccentricity factor accounting for ship's rotation, berth configuration factor which represents the portion of energy absorbed by the cushion effect of water between the approaching vessel and the quay wall, softness factor which represents the portion of energy absorbed by deformation of fender and ship hull, friction coefficient between the fender and ship side and mass factor which depends on the momentum transferred from the ship to surrounding water are considered. The mass factor depends on the water depth to ship draft ratio and a type of berth, fender stiffness, berthing velocity and the deceleration of ship. Usually all the above factors are defined by simple empirical formulas or constant values. For large vessels the approaching speed should not exceed 0.1 – 0.2 m/s and for the high performance fender systems, used in some of the cruise vessels terminals, the available contact speed could be 0.15 m/s. For this berthing operations conducted on DP (Dynamic Positioning) system the reliability of this system is an important safety factor. The DP systems require very reliable mathematical models of ship motions. Training of the navigators based on Full Mission Simulators is now a very efficient way to prevent the accidents.

Modelling of ship self – berthing manoeuvre

The accuracy of the mathematical models used for the simulation depends on the available experimental data because it is still very difficult to model the manoeuvres when the transient, turbulent flow is induced.

The model tests results are strongly influenced by the scale effect. The CFD (Computational Fluid Dynamics) methods still need further development with regards to the accuracy of turbulence models.

To obtain the realistic performance of simulated manoeuvres, the heuristic tuning of the mathematical models is mainly implemented in ship handling simulators, used for training and research purposes. Although the experienced masters and pilots can report an unusual performance of the modelled ships, the accuracy of modelling is much more important for the research and design applications.

To improve the accuracy of mathematical models the investigations on modelling of the different interactions have been carried out in many research centres - mainly based on the towing tank tests [9], [10],[12], [13]. Full scale trials of the assisted berthing were successfully performed and used as the validation data for a numerical model of ship parallel berthing based on CFD methods [4]. However, the conclusions following from the real scale tests, conducted at Gdynia Maritime University, for the training vessel Horyzont 2 (figure 4) [1], convinced that due to the very strict experimental conditions, model tests would be a much more efficient method to evaluate the mathematical model of ship self-berthing.

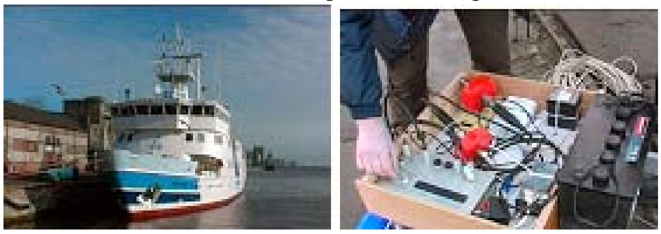

Figure 4. *Real scale tests of BATHING – research and training vessel of Gdynia Maritime University "Horyzont " at "Indyjskie" Quay in Port of Gdynia.*

Good results could be achieved using a big model and open water experimental facility. A program of experiments based on the open water model tests has been developed for the self-propelled model of a car-passenger ferry of model scale 1:16. The experiments will be conducted at the Ship Handling Training and Research Centre of the Foundation for Safety of Navigation and Environment Protection in Ilawa-Kamionka.

The experimental stand under construction and the man manned scale model of the car-passenger ferry during the tests in the research area of the Ship Handling Research and Training Center of the Foundation for Safety of Navigation and Environment Protection in Ilawa-Kamionka is presented in figure 5.

Figure 5*. Experimental stand under construction and the man manned scale model of a ferry during the tests in the research area of Ship Handling Research and Training Center in Ilawa-Kamionka.*

The experiments will involve force measurements. The changes in forces with the following parameters will be accounted:

- water depth,
- ship distance to the quay,
- ship approach angle,
- rudder angle,
- propeller power,
- bow thruster power,
- berth type.

Conclusions

The hydro-meteorological elements are the most important safety factors with regard to the ship entrance into the harbour and berthing inside the docks. Both linear and neural network models are used to improve significantly short-term and long term predictions of the environmental parameters. To determine their influence on the risk of harbour operations they can be subsequently implemented in the real-time simulator for the purpose of pilots training or evaluating the new designs under the real environmental and structural conditions.

Application of the stochastic method proposed by Vorobyov [14] can give very promising results, but it is necessary to include current parameters in the stochastic model and find out the effective method of combining the values of risk, determined for the particular parts of the approach fairway and harbour entrance, into the total risk.

MER trial is a very useful tool to predict ship controllability in narrow channels and approach fairways. However it is very difficult to perform due to the wind sensitivity and big manoeuvring area necessary to conduct the trials. It could be assumed that the real scale MER test would be very difficult to perform in normal sea conditions and as it was proved the simulations were very much dependent on the mathematical modelling of shallow water effect.

The model tests of different kinds of interactions are necessary for practical applications in mathematical models used in ship handling simulators as well as for the validation of CFD methods. The available model scale, and possible accuracy of measurements are of the greatest importance for the accuracy of modelling.

The open water model tests of ship-berth interaction will allow to recognise the dependence of the interaction forces on several parameters. Further research will focus on the formulation of the interactions.

Acknowledgement

The presented open water model tests have been carried out in collaboration with the Shiphandling Research and Training Centre of the Foundation for Safety of Navigation and Environment Protection in Ilawa, Poland. The research regarding the influence of a ship distance from the quay on the efficiency of the ship propellers and thrusters is currently conducted according to the research project No. 4T12C01029 sponsored by Polish Ministry of Education and Science.

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