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ASSESSMENT OF ESCORT TUG CAPABILITY AT FMBS

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ABSTRACT

The experiments performed at full mission ship's bridge simulator (FMBS) can form background for various safety assessments during harbours and waterways development leading to: design of harbour layout, establishing escort and assist tug requirements, establishing maximum wind and current limits, establishing rules for restricted traffic flow, detailed manoeuvring procedures, assessing risks, training pilots and tug masters on new procedures and familiarisation with new facilities. The paper presents research on escort tug capability for harbour-max ships performed at FMBS. The particular attention has been given to configuration of towing tugs, and tug's master control of three variables: the hull drift angle, the thruster angle and the thruster force value which essentially change with the speed of the assisted ship. The research conclusions in exemplary harbour have led to specification of tugs' number and bollard pull.

Keywords — full mission bridge simulation (FMBS), escort tug, ASD tug, bow-to-bow mode, stern-to-bow mode

1. INTRODUCTION

The specificity of tugs work requires their operation very close to an assisted vessel. It presents a risk to the tug and consequently also to the assisted ship. Additionally tugs should be used up to their fullest capabilities what can increase this existent risk even further. That is why experience of tug masters should be based on the various capabilities and limitations of the tugs they handle. This includes a good insight into manoeuvrability and handling of the specific tug, a tug master has under his / her command, with regard to hull design, rudders and propulsion, deck and wheelhouse equipment and finally selected mode of work. The harbour tug's mode of work can be classified into:

a) pushing;

b) rope aided pushing;

c) pulling as stern tug bow-to-stern;

d) pulling as stern tug stern-to-stern;

e) pulling as bow tug stern-to-bow;

f) pulling as bow tug bow-to-bow.

The problems of tugs' manoeuvrability and handling, dealt practically in [4], [5] and [11], cannot be neglected while evaluating tug assistance parameters as the result of Formal Safety Assessment (FSA) based on full mission bridge simulation studies leading to a new design or modernisation of harbour layout and fairway.

Generally, from assisted ship's captain or pilot point of view, the tug's output performance is indicated by the towing force (in terms of direction and magnitude) applied to the towed ship. This force is transferred by a hawser (towline) in pulling mode or a direct hull contact in pushing mode. To generate this force the tug master has to control three variables: the hull drift angle, the thruster angle and the thruster force which essentially change with the speed of the assisted ship. The research on the mechanism of equilibrium for an azimuth stern drive (ASD) tug in the pulling operation was presented in [2]. In this paper the author presents comparison of operational aspects, especially forces generated, in pulling as bow tug stern-to-bow and pulling as bow tug bow-to-bow during full mission bridge simulation (FMBS) studies based on ship mathematical models developed accordingly to [1] and [12].

2. MARITIME FORMAL SAFETY ASSESSMENT

The Guidelines for FSA for use in the IMO rule-making process were approved in 2002 by Maritime Safety Committee (MSC) and Marine Environment Protection Committee (MEPC) (MSC/Circ.1023/MEPC/Circ.392 [6]). These Guidelines have since been amended by MSC/Circ.1180-MEPC/Circ.474 [7], and MSC-MEPC.2/Circ.5 [8], and finally superseded by MSC-MEPC.2/Circ.12 [9] later amended by MSC-MEPC.2/Circ.12/Rev.2 [10]. The FSA in maritime industry is described as "a rational and systematic process for assessing the risks associated with shipping activity and for evaluating the costs and benefits of options for reducing these risks." It should be used as a tool to help evaluate new regulations or to compare proposed changes with existing standards. It enables a balance to be drawn between the various technical and operational issues, including the human element and between safety and costs. FSA consists of five steps [6] presented in the figure 1:

1) identification of hazards (a list of all relevant accident scenarios with potential causes and outcomes);

2) assessment of risks (evaluation of risk factors);

3) risk control options (devising regulatory measures to control and reduce the identified risks);

4) cost benefit assessment (determining cost effectiveness of each risk control option); and

5) recommendations for decision-making (information about the hazards, their associated risks and the cost effectiveness of alternative risk control options is provided).

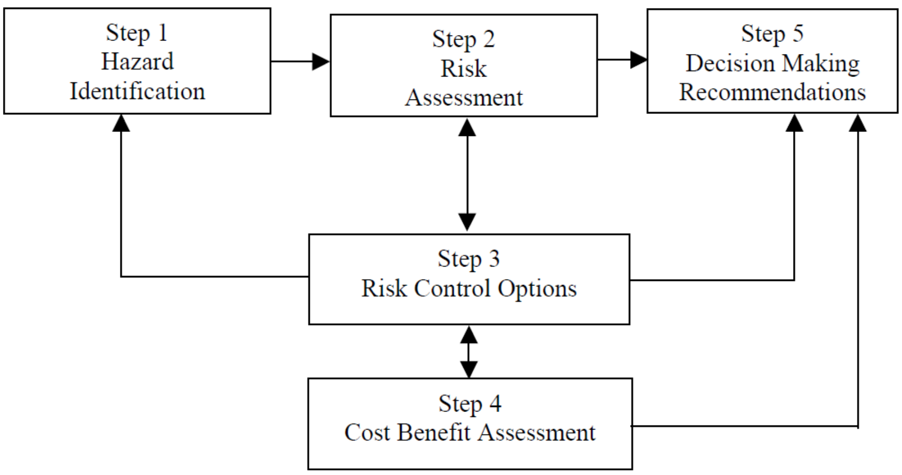

Fig. 1. FSA methodology [6]

Performing FMBS in order to identify and minimize the risks existing during manoeuvres of ships with tugs' assistance in newly designed or modernised water areas is the preferred option. On the basis of data recorded in simulations the complex safety criterion – waterway manoeuvring risk – and the cost of its achievement can be assessed. In particular the requirements for the navigation systems, supporting systems (pilot service, towing assistance, vessel traffic management and service – VTMS) and the dimensions of the safe manoeuvring area at the confidence level assumed via risk calculation [3] can be determined. In the figure 2 the manoeuvring area evaluated by means of acceptable risk criterion in FMBS of Kongsberg Polaris type in Maritime University of Szczecin is presented. It is an example of a safe manoeuvring area for an LNG QFlex type vessel (315m in length, 12.5m of draft) in Świnoujście outer harbour, obtained on the basis of registration of 20 simulated passages with 4 tugs assistance. The area includes the deepening of the basin to 14.5m marked in dark blue, and to 6m marked in violet. 6m safe isobath limits manoeuvring area available for ASD-tugs of 5m draft.

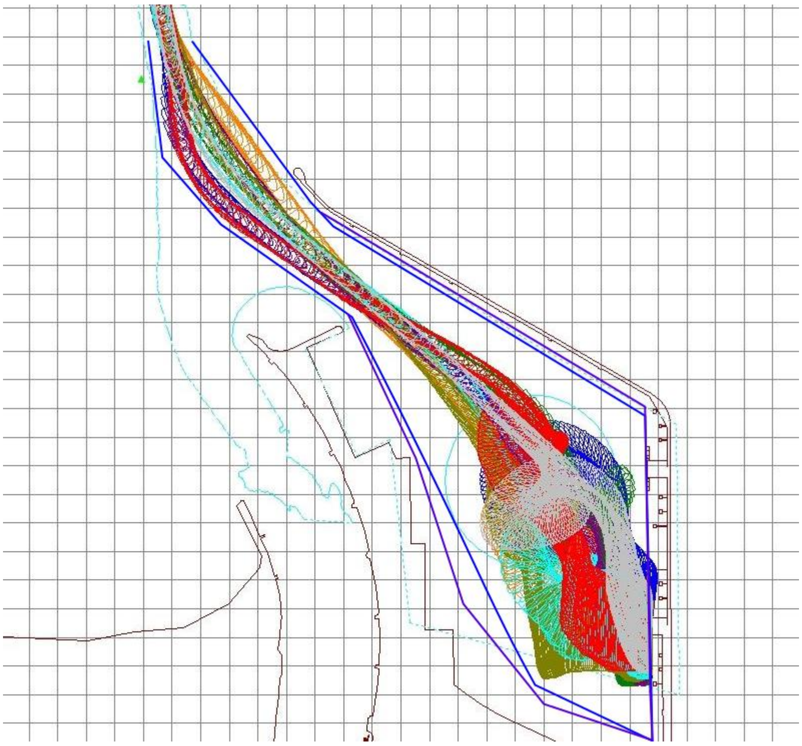

Fig. 2. Manoeuvring area evaluated by means of an acceptable risk criterion during FSA in FMBS (own study)

3. MATHEMATICAL MODELS OF SHIPS IN FMBS

Simulation of towing assistance in full mission bridge simulators, consisting of several separated ship bridges with the computer based vision of the environment and realistic navigational equipment, can be carried out in three variants. The first option assumes control of tugs' excitations by the instructor's application (the person supervising the simulation process). The second involves direct interaction of vessels simulated concurrently in several bridges as presented in the figure 3.

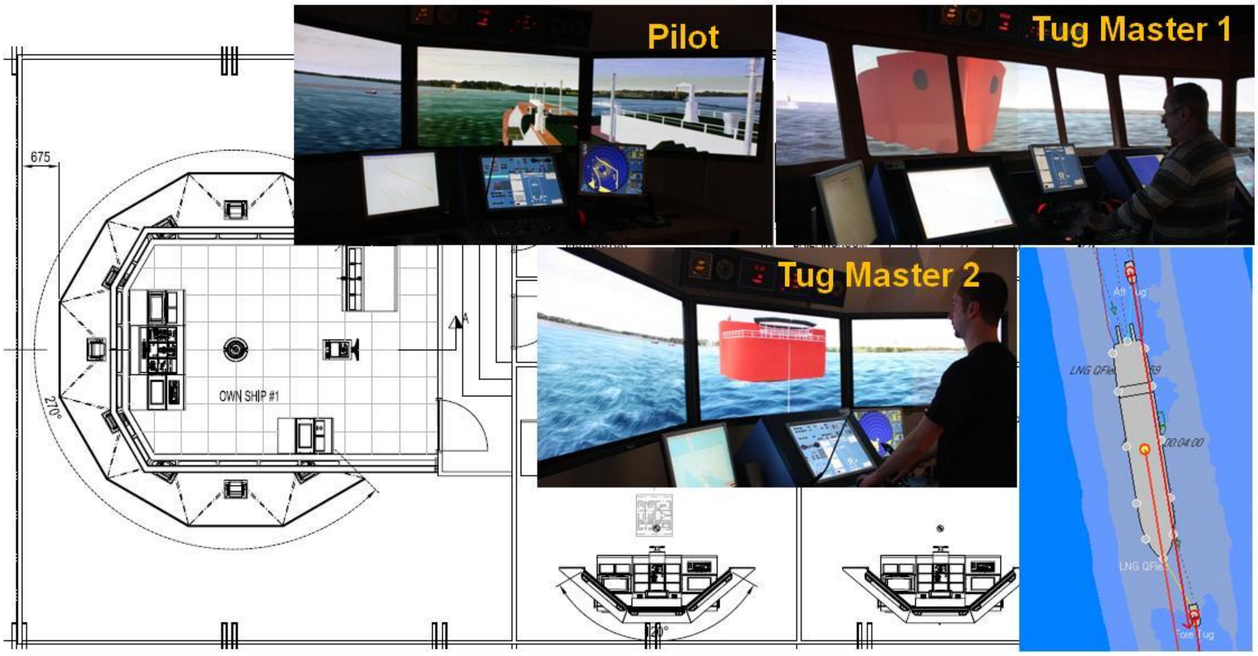

Fig. 3. Direct interaction of simulated ships in the multi-bridge simulator environment – own ship towing (own study)

The third option is a combination of both simulation techniques (e.g. two tugs simulated in bridges and two controlled by the instructor). In terms of physical realism and pilot – tug master cooperation, obvious advantages have second and third methods. They use actual hydrodynamic models of all assisting vessels or at least hydrodynamic models of pulling vessels in the combined variant. Performed FMBS were based on ship mathematical models of LNG QFlex type vessel (315m in length, 12.5m of draft) and 60tf bollard pull ASD-tugs (32m in length, 5.0m of draft) developed according to the low frequency floating body motion formulas [1], [12]:

$$\begin{cases} m(1+k_{11})\dfrac{dv_{xg}}{dt} = m(1+c_m k_{22})v_{yg}\omega_z + m(k_{11}-c_m k_{22})v_{cy}\omega_z + F_x \\ m(1+k_{22})\dfrac{dv_{yg}}{dt} = -m(1+c_m k_{11})v_{xg}\omega_z + m(k_{11}-k_{22})v_{cx}\omega_z + F_y \\ mL^2\left(\overline{r}_z^{\,2} + \overline{r}_{66}^{\,2}\right)\dfrac{d\omega_z}{dt} = -m(k_{22}-k_{11})(v_{xg}-v_{cx})(v_{yg}-v_{cy}) + M_z \end{cases} \tag{1}$$

$$\begin{bmatrix} v_{cx} \\ v_{cy} \end{bmatrix} = \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix}^T \cdot \begin{bmatrix} |\vec{v}_c|\cos\gamma_c \\ |\vec{v}_c|\sin\gamma_c \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} v_{NS} \\ v_{EW} \end{bmatrix} = \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix} \cdot \begin{bmatrix} v_{xg} \\ v_{yg} \end{bmatrix} \tag{3}$$

$$\frac{dx_0}{dt} = v_{NS}, \ \frac{dy_0}{dt} = v_{EW}, \ \frac{d\psi}{dt} = \omega_z \tag{4}$$

where:

v_{xg}, v_{yg}, ω_z – longitudinal velocity (in direction of a ship bisector line x_b in Cartesian ship fixed coordinate system) [m/s], transverse or lateral velocity (in direction of y_b) [m/s], angular velocity (around z_b) over the ground [rad/s],

$\left|\vec{v_c}\right|, \gamma_c$ – current speed [m/s] and direction [°] in local (area) Cartesian coordinate system,

x_0, y_0, ψ – coordinates of position [m] and ship's heading [°] in local (area fixed) Cartesian coordinate system,

m, L – ship's mass (displacement) [kg] and ship's length at waterline [m] (L is equalled to length between perpendiculars for construction draft),

$\overline{r_z}$ – dimensionless radius of inertia [–],

$k_{11}, k_{22}, \overline{r_{66}}$ – dimensionless coefficients of added masses [–],

c_m – dimensionless reduction coefficient [–] (due to the effects of viscosity),

F_x, F_y, M_z – external forces (resultant longitudinal force in direction x_b [N], resultant lateral force in direction y_b [N], and moment of force around z_b [Nm]).

All of the above external forces (passive and active excitations on the hull coming from the water resistance, wind, thrusters, steering devices, shallow water effects, bank effects, ship-to-ship effects and finally tugs) are functions of component speeds of the vessel relative to the water (v_x, v_y, ω_z) or functions of resultant speeds through the water and ship's drift angle (v, ω_z, β) (angle between ship's heading and course through the water):

$$\begin{cases} F_x = F_x\left(v_x, v_y, \omega_z\right) \\ F_y = F_y\left(v_x, v_y, \omega_z\right) \\ M_z = M_z\left(v_x, v_y, \omega_z\right) \end{cases} \tag{5}$$

$$v_x = v_{xg} - v_{cx}, v_y = v_{yg} - v_{cy}$$

The parameters (constant and variable as functions of component speeds) used in (1) and (5) formulas have been tuned according to real ships sea trials to achieve high fidelity (less than 5% variance). The details of procedure of hydrodynamic model parameters estimation used in the research can be found in [2].

In order to simulate ship's pulling by a towline the ship hydrodynamic model must take into account the external force applied to certain points of the hull (bollards, bits, towing winches, towing hooks). These connections may be either fast or with controlled tension and length of the rope through the towing winch of the tug. The parameters of the modelled connection are the maximum length, breaking force, elasticity and density of the towline, and power, maximum winch speed and winch speed as a function of load – rope's tension. During the process of towing the movement of towed vessel will depend on:

- the forces due to hydrodynamic and aerodynamic resistance dependent on the speed and drift angle, the forces of propellers, rudders, tug's pull;
- the tug's attitude in relation to towing rope and the towed vessel attitude in relation to towing rope,
- positions of the rope attachment points on both vessels.

4. PULLING STERN-TO-BOW AND BOW-TO-BOW IN FMBS

In many harbours and waterways of the world ASD-tugs are more and more commonly used due to their extensive shiphandling capabilities. Quite large part of the ASD-tugs is built for push-pull operation from their bow only but the rest is designed in a way that the tugs can effectively operate either as conventional tugs by using the stern winch or as tractor tugs by using the bow winch.

The equilibrium (static balance) conditions for a tug between the hull (h), thruster/propeller (p), and towing (t) forces in tug's fixed coordinates take the form:

$$\begin{cases} F_{hb} + F_{pb} + F_{tb} = 0 \\ F_{hl} + F_{pl} + F_{tl} = 0 \\ M_h + M_p + M_t = 0 \end{cases} \tag{6}$$

where:

F_b, F_l – longitudinal (along tug bisector line) and lateral components of each force [N],

M – moment developed by particular force component [Nm].

The detailed analytical solution to (6) was presented in [2]. But to simplify considerations one can assume that the tug has common point of the hydrodynamic and aerodynamic resistance to which the resultant force F_h is applied. This can be interpreted as situation where M_h=0 (in reality a part of the thrust force is used to maintain this equilibrium). In such case, which can be presented more clearly in a figure (see figures 4 and 5), the tug master in order to keep the towline at the correct angle β_T and appropriate pull force F_p set by the captain or pilot of the towed vessel, without changing the position of the tug relative to the vessel, has to maintain continuous balance or implement empirically the complex optimization function:

$$g = n_1 \left(\frac{F_t \sin(\beta_T - \beta_{T\psi} + \alpha_t) - F_h \sin \beta_T}{\sin(\beta_T - \beta_{T\psi}) \cos(\beta_T - \beta_{T\psi})} \right)^2 + \\ + n_2 \left(F_p r_p \sin(\beta_T - \beta_{T\psi}) - F_t r_t \sin \alpha_t \right)^2 \to \min \tag{7}$$

where:

$\beta_{T\psi}$ – tug's drift angle [°], $\beta_{T\psi} = 180^\circ - \alpha_h$,

β_T – angle of pulling force set by the captain of the towed vessel [°],

α_t – angle of thruster force in relation to tug's bisector line [°],

r_p, r_t – distances between rotation centre and points of pulling and thrust force application [m],

n_1 – scaling factor for component forces balance [1/N^2] or [1/tf^2],

n_2 – scaling factor for moments balance [(Nm)$^{-2}$] or [(tfm)$^{-2}$],

F – absolute value of appropriate forces [N].

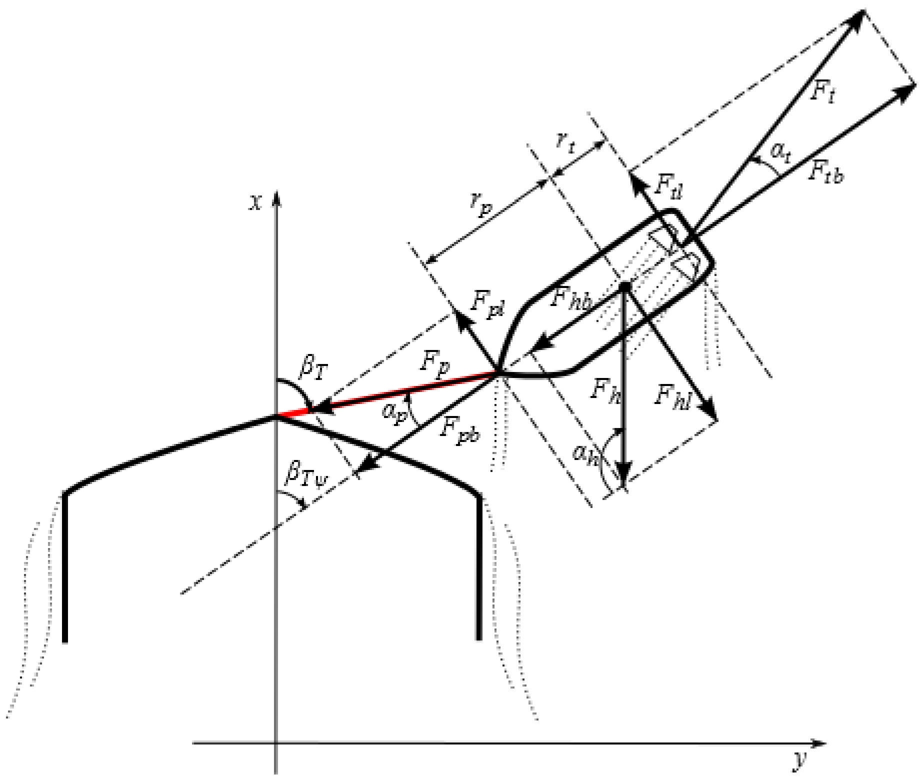

Fig. 4. Forces equilibrium while pulling bow-to-bow (own study)

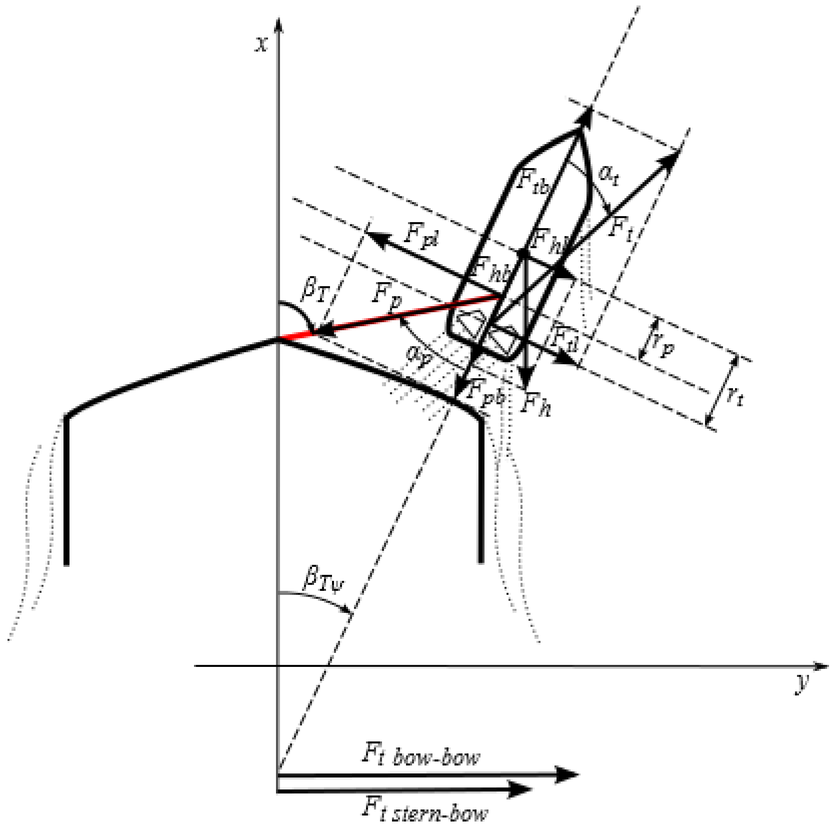

Fig. 5. Forces equilibrium while pulling stern-to-bow (own study)

Figures 4 and 5 present a tug in the kinematic equilibrium condition with identical pulling forces in two considered modes of operation: bow-to-bow (the towline fastened to the tug's bow and to assisted ship's bow) and stern-to-bow (the towline fastened to the tug's stern winch, in front of its thrusters, and to assisted ship's bow). Comparison of the two figures gives an indication of the difference in thrust forces required to obtain the same pulling force in these two operational modes. As it can be noticed the thrust force in bow-to-bow operation must be higher than the thrust force in stern-to-bow operation for the same resultant pulling force. Consequently the maximum pulling forces that can be applied by an ASD-tug when operating bow-to-bow are smaller comparing to the same ASD-tug with the same speed when operating stern-to-bow. This important phenomenon has to be taken into account during FSA based on FMBS studies with ASD-tugs assistance.

In order to assess parameters of ASD-tugs assistance necessary for LNG QFlex type vessels scheduled for Świnoujście LNG terminal the research was performed with four tug masters working in both bow pulling modes. The main goal was to ascertain which pulling mode should be preferred and what fairway speed limits should be fixed. The efficiency of 60tf bollard pull ASD-tug when operating bow-to-bow and stern-to-bow with 100m towline was compared in simulation trials for ship speeds of 4 and 6 knots (approx. 2 and 3 m/s). The averaged data of pulling force gathered from four simulation trials in the so called "zero conditions" (no wind, current, bank and canal effects) is presented as function of pulling force angle in the figure 6.

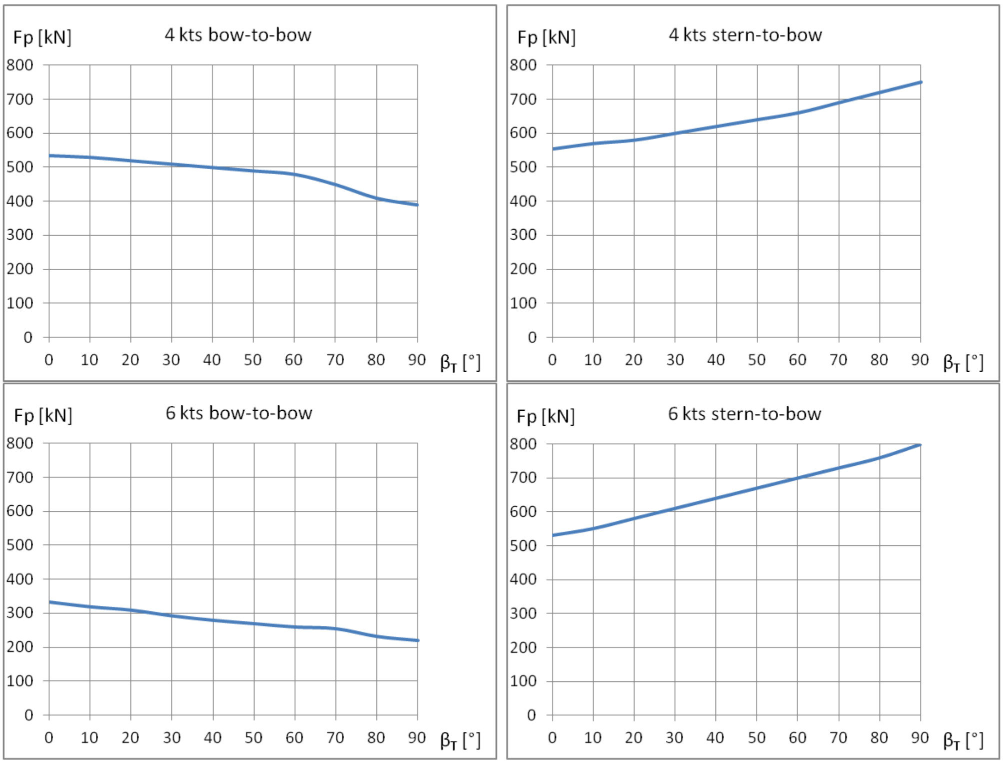

Fig. 6. Performance diagrams of 60tf (600kN), 32m long ASD-tugs during FMBS (own study)

As can be seen in the figure 6 the difference in both pulling modes are quite significant even at 4 knots (additionally there is approx. 5% lower bollard pull while moving astern when towing bow-to-bow). The crosswise (steering) forces that can be applied are almost twice as high when the ASD-tug is towing stern-to-bow, as a conventional tug, compared to when towing bow-to-bow. This difference becomes higher with the rise of speed (up to 3.6 times for 6 knots). The reason is mainly more "indirect" type towing [4] that can be applied while towing stern-to-bow with higher speed. This could lead to the conclusion that stern-to-bow mode is much more efficient (especially because the path width is also narrower), but such generalization is overreached as no consideration to safety factors was given. What was evident during simulation studies and emphasized by tugs masters is:

- a tug operating bow-to-bow has also full pushing force available, e.g. during berthing manoeuvres;
- in narrow spaces where tugs are operating on a short towline, thrusters of a tug operating stern-to-bow are close to the ship's hull, which results in a reduction of effective pulling force;
- largest tug forces are mostly needed when ship's speed is close to zero and then the difference in maximum pulling force between the two mode becomes minimal;
- changing working mode while assisting is risky and time consuming operation.

Figure 7 presents data recorded during FMBS studies performed.

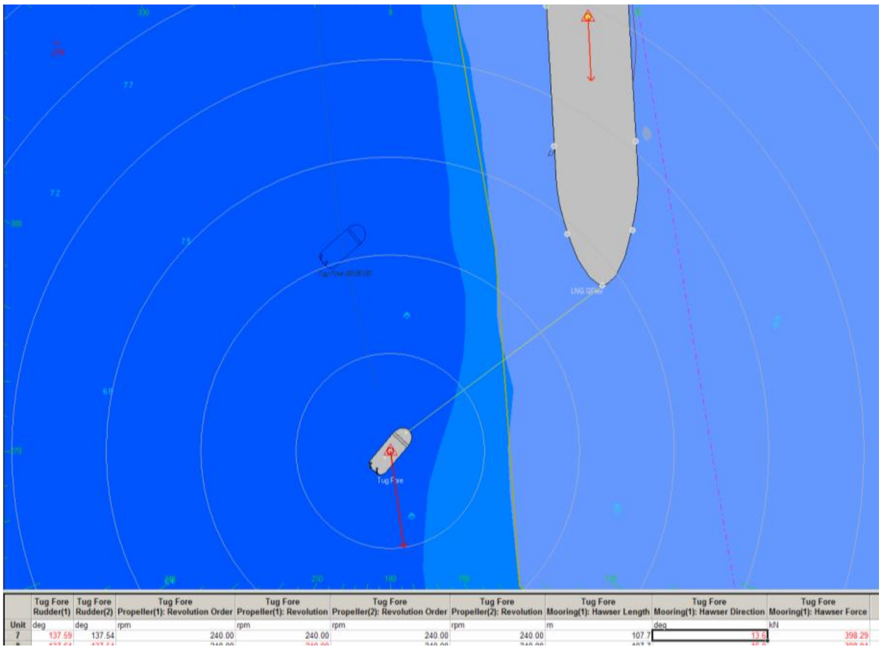

Fig. 7. Data recorded during FMBS of Q-Flex type vessel with bow-to-bow tug assistance (own study)

Additionally, to evaluate the number of tugs necessary for Q-Flex vessel while approaching and leaving the Świnoujście harbour, extra simulation of emergency situations (Q-Flex engines or rudders fault) in vA=12.5m/s wind condition (set as safety limit) was performed. Using standard formula for wind resultant force acting on ship's hull [1]:

$$F_{yA} = 0.5 \cdot \rho_A \cdot A_L \cdot v_A^2 \cdot c_{fyA90} \tag{8}$$

where:

ρ_A = 1.23 kg/m^3 – air density,

A_L = 7400 m^2 (loaded) or 8400 m^2 (ballast) – ship's lateral windage area,

c_{fyA90} = 1.1 – dimensionless coefficient of lateral aerodynamic force for relative wind angle of 90° (transverse wind),

it was evaluated as 78tf for loaded Q-Flex condition and 90tf for ballast Q-Flex condition. So at least two 60tf tugs were selected as active assistance while navigating the fairway (at least 30tf bollard pull was left as reserve for ship's rotation moment compensation). Usage of two 60tf pulling tugs (bow and aft tugs) confirmed data received from previous simulations (presented in figures 6 and 7). Execution of simulation scenarios with aft tug acting more indirectly, similarly to bow tug stern-to-bow, and bow tug acting in bow-to-bow configuration, that was easier to handle and sufficiently effective after reduction of speed below 5 knots, confirmed that the tugs assistance parameters were set correctly.

5. CONCLUSIONS

Full Mission Bridge Simulation Studies performed in Kongsberg Polaris type ship simulator of Maritime University of Szczecin revealed their usefulness for identification and minimization of the risks existing during manoeuvres of ships with tugs' assistance in newly designed or modernised water areas. As for tugs' effectiveness, at speeds higher than approx. 4 knots in calm water (up to 10 m/s wind), when operating bow-to-bow the 60tf tug's capability in generating steering forces decreased fast with ship's speed, but when operating stern-to-bow steering forces were higher and even increased with speed due to more indirect type towing. Practical speed limit for rendering assistance when fastened bow-to-bow lied in the range of 5 – 6 knots, while for stern-to-bow operation a speed of approx. 7 knots was regarded as safe maximum. Risks were much smaller during the procedure of making fast bow-to-bow compared to making fast stern-to-bow. With the approach from a position ahead of the bow there was hardly any risk of hitting the ship's hull with the tug or fouling the tug thrusters with a towline slipped into the water. A risk of capsizing when fastened bow-to-bow was also minimal, contrary to stern-to-bow operation, where lists of up to 40° were recorded during FMBS studies. In case of operating bow-to-bow, path width and total length of ship and tug was several metres larger than when the tug was operating stern-to bow, assuming the same tug size and towline length. Anyway, operations by separate azimuth control handles were considered more natural and logical by tug masters when ASD-tug was operating bow-to-bow (stern first). That is why the final recommendation of working mode was left to the decision and experience of specific tug masters who generally preferred configuration of pulling tugs as bow-to-bow forward and bow-to-stern aft.

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