Main Particulars Optimisation of a Sea-Going Ferry for a Given Shipping Route

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The paper presents a two-stage optimisation approach of sea-going ferry main particulars intended for a particular route. The method is especially suited for determining owner's specific design requirements. The goal of the first stage is a maximisation of cargo capacity, mostly in terms of the total lane length. Empirical method based on the fleet statistics of existing ferries is used throughout the stage one. The objective function of the second stage are the capital and service costs of a ferry, which are to be minimised. The solution of the latter optimisation will essentially involve a ship manoeuvring motions simulation.

Keywords: ferry, ro-pax, design, optimisation, ship manoeuvring, simulation.

1. INTRODUCTION

Special methods of marine traffic engineering are used while preparing owner's-specific optimal design requirements of a new ferry intended for a particular route, terminals thereof, and operating conditions. This is a task involving lots of engineering efforts.

In the owner's-specific design of a ferry the following are determined:

- length,
- breadth,
- draught,
- lateral windage area,
- number of propellers,
- delivered horse power,
- the power of bow and stern thrusters,
- number and type of stern rudders,
- lane length and number of.

The owner usually makes the following assumptions:

- maximum cargo capacity (mostly taken according to the terminal dimensions);
- maximum allowable hydro-meteorological conditions in given terminals;
- maximum price;
- service (economical) speed.

Such formulation of the problem has led to a development of two-stage design optimisation procedure of a sea-going ferry as assigned to particular route. These stages can be briefly summarised as follows:

- optimisation using empirical/analytical methods of marine traffic engineering (stage 1);
- optimisation using manoeuvring simulation methods of marine traffic engineering (stage 2).

2. FERRY MAIN PARTICULARS OPTIMISATION IN MARINE TRAFFIC ENGINEERING USING EMPIRICAL METHODS (STAGE 1)

The goal function here is maximising a ferry's cargo capacity (mostly in terms of total lane length) [Gucma et al., 2012]:

$$Q = f\left(L_{OA}, L_{BP}, B, T, F_L\right) \rightarrow \max \qquad (1)$$

with the following constraints:

1. $T \le h_{\min} - \Delta$
2. $L_{OA} \le l$
3. $B \le b$

4. $\frac{L_{BP}}{B} \approx K$

where:

Q	ferry's cargo capacity;
L_{OA}	length over all;
L_{BP}	length between perpendiculars;
B	breadth;
F_L	lateral windage area;
T	draught;
$h_{\min}$	minimum depth at ferry terminal;
Δ	under-keel-clearance;
l	length of safe nautical area directly available at terminal or turning basin;
b	breadth of safe nautical area directly available at terminal or turning basin;
K	ratio ensuring a certain propulsive performance of hull.

The magnitudes l and b are functions of the maximum allowable wind velocity for the operation of a ferry and parameters of the nautical area of the smallest terminal berth allocated (if multiple):

$$l = f_1\left(V_{w\max}; \mathbf{A}\right) \tag{2}$$

$$b = f_2\left(V_{w\max}; \mathbf{A}\right) \tag{3}$$

where;

$V_{w\max}$ – maximum allowable wind velocity for the planned ferry's operation;

$\mathbf{A}$ – nautical area parameters at the terminal.

Based on length and breadth (l, b) of the safe nautical area close to the terminal, the maximum length L_{max} and breadth B_{max} of a ferry is established using empirical methods of marine traffic engineering science [Gucma, 2001].

Proper realisation of stage 1 requires the owner to provide the following quantities:

L – a set of expected ferry's lengths (over all) as arising from discrete values of feasible lane lengths that normally allow for a multiplicity of length of trucks/trailers or rail cars;

B – a set of expected ferry's breadths as coming from a number of parallel lane lengths.

Thus we have:

$$\mathbf{L} = \left\{L_{\min} + l_s; L_{\min} + 2l_s; \ldots; L_{\min} + nl_s\right\}$$
$$\mathbf{B} = \left\{B_{\min} + b_s; B_{\min} + 2b_s; \ldots; B_{\min} + nb_s\right\}$$

where:

$L_{\min}$, $B_{\min}$	minimum length and breadth of a ferry;
l_s, b_s	length and width of a cargo unit (i.e. truck/trailer or rail car) with adequate stowage margin.

Then we produce for the optimisation procedure a special set of discrete lengths and breadths of a ferry (L_i, B_i) meeting the following conditions:

$$L_{\max} \geq L_i \subset \mathbf{L}$$
$$B_{\max} \geq B_i \subset \mathbf{B}$$

The lateral (maximum) windage area F_L is a function of the so-called power index M_w that takes into account the total power of lateral thrusters and a part of main propulsion power [Gucma et al., 2012], [Kowalski, 2011].

$$F_L = f_3\left(M_w\right) \tag{4}$$

The required power index for safe operation can be estimated on the basis of the aforementioned wind velocity limit $V_{w\ \max}$ and the ferry's length L_{OA}:

$$M_w = f_4\left(V_{w\max}; L_{OA}\right) \tag{5}$$

As result of the first stage of optimisation, refer to Equation (1), the following main particulars are determined, which are further input to the second stage of optimisation (see next chapter):

L_{OA} – length overall;
L_{BP} – length between perpendiculars;
B – breadth;
T – draught;
F_L – lateral windage area.

3. FERRY MAIN PARTICULARS OPTIMISATION IN MARINE TRAFFIC ENGINEERING USING MANOEUVRING SIMULATION METHODS (STAGE 2)

During the stage 2 the capital and service costs of a ferry, with the main geometric particulars (L_{OA}, B, T, F_L) as originated from stage 1, are being minimised. The goal function of stage 2 can be written in the form:

$$Z = f(m_P, DHP, m_{LTU}, N_{LTU}, m_R, A_R) \rightarrow \min \quad (6)$$

under the restraints:

1. $\mathbf{d}_i (1-\alpha) \subset \mathbf{D}$ $(i = 1 \ldots n)$
2. $E_{il} (1-\alpha) \leq E_{max\,l}$ $(i = 1 \ldots n;\ l = 1 \ldots m)$
3. $V_{B\,ik} \leq V_{Bmax\,k}$ $(i = 1 \ldots n;\ k = 1 \ldots p)$

where:

Z	generalised capital and service costs;
m_P	number and type of propellers;
DHP	delivered horse power;
m_{LTU}	number of lateral thruster units;
N_{LTU}	power of a single lateral thruster unit;
m_R	number and type of stern rudders;
A_R	rudder area (single);
$\boldsymbol{d}_i(1-\alpha)$	safe (demanded) manoeuvring area at confidence level $(1-\alpha)$ for i-th ferry's version;
$\boldsymbol{D}$	navigable area;
$E_{il}(1-\alpha)$	berthing impact energy of i-th ferry's version for l-th berth point at confidence level $(1-\alpha)$;
$E_{\max l}$	maximum allowable berthing impact energy for l-th berth point, given consideration to strength of berth, fender, and ship's hull;
$V_{B\,ik}$	propeller race velocity of i-th ferry's version for k-th seabed point at confidence level $(1-\alpha)$;
$V_{B\max k}$	maximum allowable propeller race velocity for k-th seabed point.

The second stage essentially involves building a ferry's manoeuvring mathematical model and performing various simulation scenarios in a ship handling simulator, of course allowing for control input from actual captains or pilots.

The capital costs analysed in stage 2 essentially involve the investment costs of particular appendages, including the lateral thruster units.

The service costs consist of potential maintenance and repair costs as well as manoeuvring time and fuel savings over the assumed service life of a ferry.

Generally, the number and type of propellers is usually fixed, e.g. 2 propellers of controllable pitch type are the common option as providing effective manoeuvring, particularly during transverse (crabbing) and/or astern movement [Gucma et al., 2012]. Additionally, the number of stern rudders is also two, but the type (e.g. standard, Becker or Schilling) and area of a rudder is very often not yet decided on and shall be determined through manoeuvring simulation.

DHP is the maximum power transferred to main propellers. However, this value may not be lower than that needed for preserving the service/contractual speed for given ferry's hull and superstructure in deep-water conditions. The latter is an output of standard power analysis and frequently supported by resistance and propulsion tests in towing tanks. Ship manoeuvring in restricted area, especially under unfavourable hydro-meteorological and nautical conditions, sometimes requires additional power and/or torque on the running propellers. In addition, a number of lateral thruster units have to be always installed, some of them even as stern thrusters. The initial guess (as minimum requirement) on lateral thrusters comes from transforming the formula for the power index M_W. The latter has been estimated by Equation (5).

The simulation experimental design, consisting of the tested values for particular parameters and characteristic simulation scenarios (including nautical area arrangement and the most severe weather conditions), is empirically/pragmatically established. Normally, 5 to 7 series of simulation runs are sufficient. These series correspond to a different ferry's manoeuvring model as prepared for each design option. The series itself consists of a certain number of manoeuvres to be performed, encompassing berthing, unberthing, and turning in most adverse weather conditions. Due to necessity of balancing not only physical forces (where rather simple static analysis can be applied), but also inertia forces (arising in transient phases of manoeuvring, e.g. in acceleration and deceleration, including curvilinear motion) such dynamic analysis is absolutely the only choice. Partly, due to the fact that human factor can easily be integrated therein.

Due to a limited number of simulation series used, in view of the cost-effectiveness of research, the final values of parameters are interpolated or extrapolated.

The complexity of ferry (or ro-pax) manoeuvring mathematical model is really huge. In parallel, there are strong demands on simulation of this specific/self-contained (without tug assistance) operation, being used in nautical safety and effectiveness studies of various ship and harbour development projects. Over the last years there are being seen lots of scientific efforts and a significant progress in the field of ship manoeuvring hydrodynamics, e.g. [Zhao, 1994], [Martinussen, 1996], [Quadvlieg, Toxopeus, 1998], [Ishibashi, Kobayashi, 2000], [Lee, Fujino, 2003], [Yoo et al., 2006], [Misiag et al., 2007], [Lee et al., 2011], [Khanfir et al., 2012], and many others.

For this reason, the mathematical models used in visual full-mission and PC-based (bird's eye view) simulators of the Maritime University of Szczecin incorporate as a rule lookup-tables for storing various hydrodynamic coefficients [Artyszuk, 2013]. The latter are functions of ship motions and certain control parameters (e.g. helm angle). This way, we are always open to new results of model tests and CFD computations. Additionally, special identification or calibration procedures have been developed to assess the hydrodynamic effects based on full-scale ship performance of similar ships [Artyszuk, 2013]. For this purpose, the close long-term cooperation with national ferry line owners/operators has also enabled our institution to collect a tremendous database of detailed manoeuvring records for berthing and unberthing operations of different twin-screw ferries in particular terminals.

Since the rough estimates of the hydrodynamic coefficients arising in the ship manoeuvring differential equations, either by published model tests of similar ships or some regression formulas, surprisingly do not provide the real-world ship motion response. Hence there is a necessity to calibrate/optimise the model according to the available sea trials, especially those parts of the model dealing with the hull forces. The latter can be described in the most general form (either directly or be transformed to) by:

$$\begin{bmatrix} F_{xH} \\ F_{yH} \\ M_{zH} \end{bmatrix} = 0.5\rho LT\left(v_{xy}^2 + \omega_z^2 L^2\right)\begin{bmatrix} c_{spd}\left(v_{xy}\right)\cdot c_{fxhm}\left(\beta,\Omega_m\right) \\ c_{fyhm}\left(\beta,\Omega_m\right) \\ Lc_{mzhm}\left(\beta,\Omega_m\right) \end{bmatrix} \quad (7)$$

$$v_{xy} = \sqrt{v_x^2 + v_y^2}\,,\ \mathrm{arctg}\beta = \frac{-v_y}{v_x}\,,\ \beta \in \left(-180°,+180°\right\rangle \quad (8)$$

$$\Omega_m = \frac{\omega_z L}{\sqrt{v_{xy}^2 + \omega_z^2 L^2}}\,, \Omega_m \in \left\langle -1,+1 \right\rangle \quad (9)$$

where:

F_{xH}, F_{yH}, M_{zH}	- hull surge and sway force, an yaw moment;
ρ	- water density;
L, T,	- ferry's length (between perpendiculars) and draft;
v_{xy}, β, Ω_m	- total linear velocity, drift angle, modified dimensionless yaw velocity;
c_{spd}	- corrective factor accounting for the hull resistance change with forward velocity (especially in the lower and upper region of velocities);
c_{fxhm}, c_{fyhm}, c_{mzhm}	- lookup table-stored hull hydrodynamic (the so-called modified) coefficients.

The identification scheme presented in Figure 1 has a lot of practical advantages. The concept is based on selecting somehow arbitrary but reasonable initial estimates of the hull and rudder mathematical models. Then, taking into account the time series of surge v_x, sway v_y, and yaw velocity ω_z, as experienced in full scale, the hull sway force and yaw moment coefficients, c_{fyhm} and c_{mzhm}, are calibrated along the β-Ω_m combinations characteristic for the manoeuvre in concern. For many manoeuvres, especially relating to twin-screw ferries, the adjustments made to the hull force are quite independent of the underlying rudder force model, of course in its reasonable limits. The best for the mathematical model identification seem to be the turning tests at maximum helm. A proper reproduction of turning test transients often makes even the z-tests and spiral tests useless in view of additional new information for the identification of hull force. However, it should be emphasised that the prediction of the latter two types of manoeuvre are more liable to the rudder model than the prediction of the turning transient. which is the often forgotten factor in nautical studies, where most of the concerns are still safety-related.

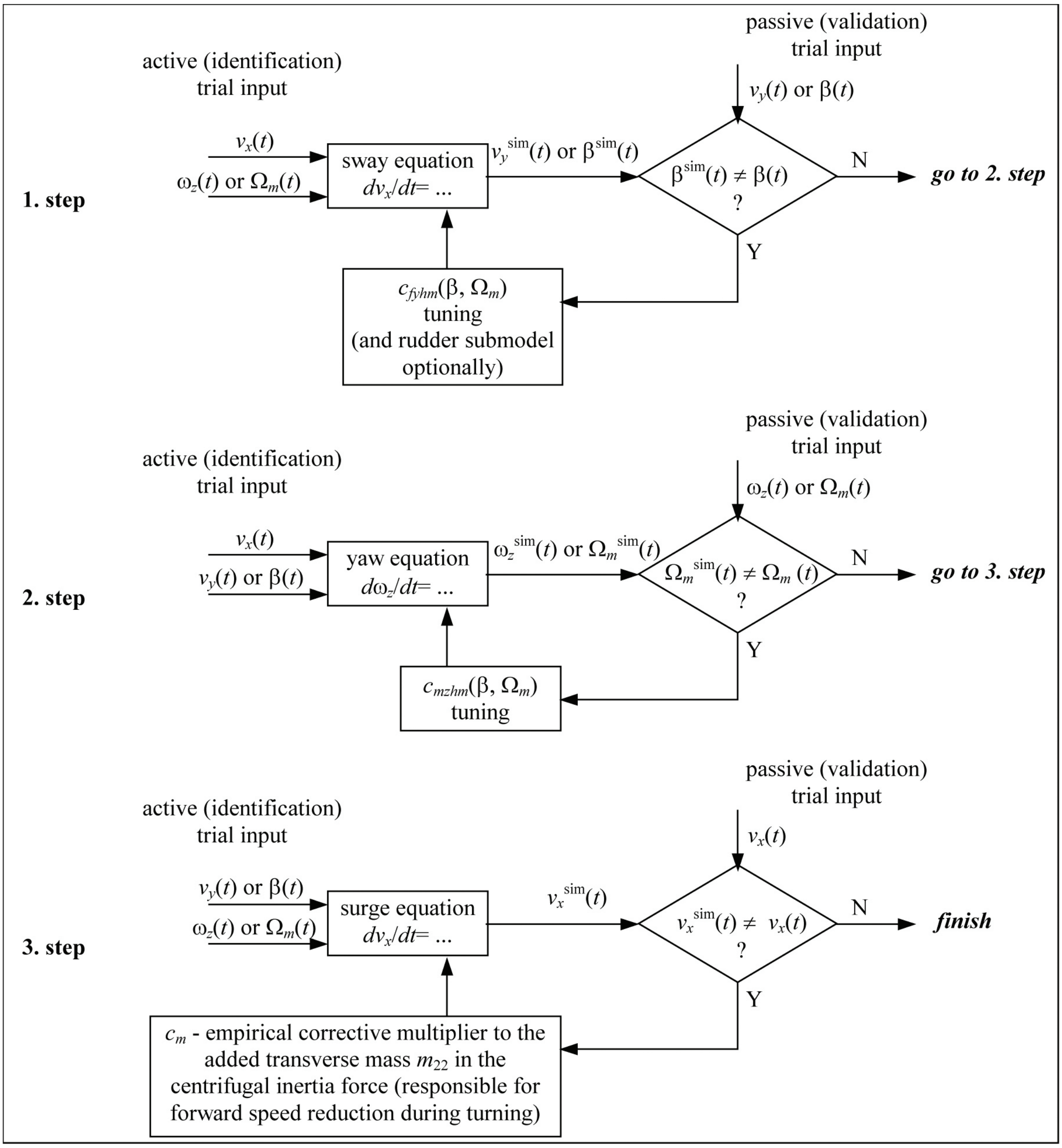

Fig. 1. Optimization scheme of manoeuvring mathematical model.

4. CONCLUSIONS

The rough formulations of the second-stage goal (cost) function Z in our past practical but successful applications of the presented optimisation method calls for further improvement, especially in the aspects of statistical significance of the results. Also, a big challenge presently is the conversion of time, ease, and ship's main engine harmful emissions during harbour manoeuvring into the money. These three things represent to much extent the effectiveness of manoeuvring,

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