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DESIGN METHODOLOGY FOR SMALL PASSENGER SHIPS ON THE EXAMPLE OF THE FERRYBOAT MOTŁAWA 2 DRIVEN BY HYBRID PROPULSION SYSTEM

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ABSTRACT

Dynamic development in practically all fields of science and engineering has not passed over shipbuilding . In last years , engineers got to their use computer software which makes it possible to perform strength and hydrodynamic calculations as well as to visualize design projects in 3 D space [1-4]. At their disposal they have full spectrum of modern solutions associated with the use of advanced materials and technologies [5-7]. More and more attention is also paid to impact onto the natural environment [8,9]. Every new object must influence the environment as low as possible, beginning from building phase through its service life up to final utilization – such approach is called „green-shipping". However , not only practical reasons are important . Clients , i.e. ship owners and passengers of ships paid more and more attention to image of floating units. During decision taking on that from whom a transport service has to be ordered , the most modern ships of an attractive image matching with place and time, are often taken into consideration.
Such situation has become a basis for an idea of working out a concept of a new ferryboat for National Maritime Museum. As the ferry has to navigate in „the heart of the town", then , apart from strictly marine and engineering aspects , an important factor of its designing is its expected image - a set of significant meanings and emotions written in architecture language. The new ferryboat , like its historical predecessors , will never leave urban water routes.

Keywords: small passenger ships, urban ship, design methodology, hybrid propulsion system

INTRODUCTION

Urban ship, like autobus or tramway, is a permanent element of town space. For many inhabitants it is an object of adoration. On the one hand, it is also a symptom of multi-age tradition, attachment to maritime culture, on the other hand - a symptom of modernity of the town, an effective communication mean, and sometimes even a catalogue visit card. Such role is served by Venetian vaporettas, Parisian bateau mouche, rondvaartboten in Amsterdam, or „Hotaluna" i „Himiko" in Tokyo [Fig.1-1], which, apart from strictly utilitarian functions, are one of very important components of cultural identity of the town.

Fig. 1-1. The excursion ship „Hibiko" approaching the quay at Odaiba island, Tokio,photo by P.Gelesz

This is exemplified by a ferry which operate on Motława river between north cape of Granary Island (Wyspa Spichrzów), Ołowianka quay and Żuraw (Crane)- just in the heart of Gdańsk. Though the currently used ship „Motława" maintains its full serviceability, its 20-year service resulted in its technical and esthetic obsolescence. Its propulsion system and functionality are far from today standards, and its image – especially in the context of the marine located in the direct neighbourhood of National Maritime Museum, and yachts moored in it, as well as Maritime Culture Centre – may be taken rather not adequate.

Such situation has become a basis for an idea of working out a concept of a new ferryboat for National Maritime Museum. As the ferry has to navigate in „the heart of the town", then, apart from strictly marine and engineering aspects, an important factor of its designing is its expected image - a set of significant meanings and emotions written in architecture language. The new ferryboat, like its historical predecessors, will never leave urban water routes.

The design project has assumed that an entirely new concept of the ferry has to be worked out – possibly without copying the solutions used in the existing ferryboat „Motława" – under operation for a few dozen years. Because, as said Prof.A. Rylke, one of the fathers of post-war shipbuilding in Poland : „ *Contemporary ship, both in its structure and technical or economic functioning, is a very complex object . It must satisfy a large number of various requirements which are contradictory to each other, already due to their assumptions. To compromize the requirements and next to indicate a way toward their most proper realization constitutes the subject of one of the most crucial disciplines of shipbuilding taken in a modern way. Such discipline is theory of ship design... Its task is to create „ an ordered world" from chaos of issues and various requirements, whose rational, harmonious and mutual connection results in this what constitutes a ship of today." [10]*

The so formulated assumption of design methodology has made it necessary to assume a non-standard methods of the searching for and working out of ship hull parameters , based on the packet of initial parameters – external limitations, hard design assumptions (rules and regulations) and soft design postulates (whishes and visions of designers and to-be-operator).

Within the group of external limitations, the dominating requirements resulted from the character of sailing waters area and a mode of the ferryboat operation. Size of mooring places and a way of positioning the ship against water lane axis during mooring operation, forced to limit ship's hull length and breadth to L=12,00 m and B=5,00 m, respectively. Similarly, data on water depth distribution over the assumed service route of the ferry made it possible, in this design stage, to assume its full draught T_{max}=1,30m.

The precision improving of expected ferryboat's parameters made it possible to start working on the underwater hull form design. It was necessary to find compromise between contradictory parameters.

The ship should have a required displacement at fulfilled requirements for transverse and longitudinal stability, unsinkability, and, in view of its propulsion – it should have as far fine form of underwater hull as to show possibly low resistance to motion. For searching for the best solution fulfilling the given criteria, some number of hull underwater form models was preliminarily selected and multi-criteria poly-optimization was performed to find a solution close to the nearest optimum.

ISSUES OF MULTI-CRITERIA OPTIMIZATION

Optimization models make it possible to organize complex systems of mathematical equations and inequalities which represent target functions and constraints, in order to make an optimum decision selected out of a large number of possible ones. Optimum decision is that which satisfies the target given by decision maker, however within the field of various limiting conditions.

Optimization may be divided into:

- one-criterion (one-dimensional) optimization, when choice is made on the basis of one representative assessment criterion,
- multi-criteria optimization (multi-dimensional, poly-optimization), when choice is made on the basis of more than one assessment criterion.

One-criterion issue is characteristic of a strict structure, i.e. it is solved by using a model in which both target function and constraints are determined. The issue is solved by means of optimization tools, and the itself process of searching for an optimum solution consists in solving the set of appropriate equations.

Multi-criteria issue may have, but not necessarily, a strict structure. In the case of a multi-criteria programming model, the multi-dimensional issue has strict structure, however in case of specific ones (choice, classification, ranking) there is a lack of a strict structure. In case of strict structure this is multi-criteria optimization, otherwise – the issue of decision aiding.

In case of application of a large number of assessment criteria for the best solution, contradiction between the criteria often takes place. It means that the searched solution does not extremize all the criteria considered separately, but constitutes a kind of compromise between them. The multi-criteria optimization issue first of all consists in defining the compromise. In many cases it is possible to formulate, based on heuristic knowledge on the process under optimization, another, substitute criterion in respect of which a compromise solution is searched for.

The multi-criteria optimization issue may be formulated as follows [11].

Let :

$\boldsymbol{X} = \{x_l\}$, $l = \mathbf{1}, \mathbf{2}, \ldots, N$ be a vector of decision variables taken as independent ones,

$\boldsymbol{F} = \{f_i\}$, $i = \mathbf{1}, \mathbf{2}, \ldots, M$ be a set of criteria (functions) in respect of which solutions are assessed during searching for a compromise.

Moreover, let be given the constraints put upon solution values:

- inequalities:

$$\boldsymbol{G} = \{\boldsymbol{g}_k\}, \boldsymbol{k} = 1, 2, \ldots, \boldsymbol{K}, \text{where: } \boldsymbol{g}_k(\boldsymbol{X}) \leq \mathbf{0} \quad (1)$$

- equations:

$$\boldsymbol{E} = \{e_j\}, j = 1, 2, \ldots, J, \text{where: } e_j(\boldsymbol{X}) = 0 \quad (2)$$

Multi-criteria optimization is aimed at finding the solution for which the following condition will be satisfied :

$$min\boldsymbol{F}(\boldsymbol{X}) = \{f_1(\boldsymbol{X}), f_2(\boldsymbol{X}), f_3(\boldsymbol{X})\} \quad (3)$$

If maximization of a certain function f* is required then an auxiliary criterion may be introduced according to the relation :

$$minf_l(\boldsymbol{X}) = -maxf_l^*(\boldsymbol{X}) \quad (4)$$

Historically, attempts to find an optimum solution were made by Leibniz and Euler; solutions belonging to I. Newton, J. Bernoulli and D. Bernoulli should be also mentioned. Mathematical background for optimization was formulated by Lagrange and Hamilton, and finally, Pareto, economist of Italian –French origin, formulated the principle of multi-criteria optimization for economic issues, which was later called the optimization in the sense of Pareto, if to find a better solution against at least one criterion is not possible without its worsening in respect of the remaining ones. The principle is graphically presented in Fig. 2-1.

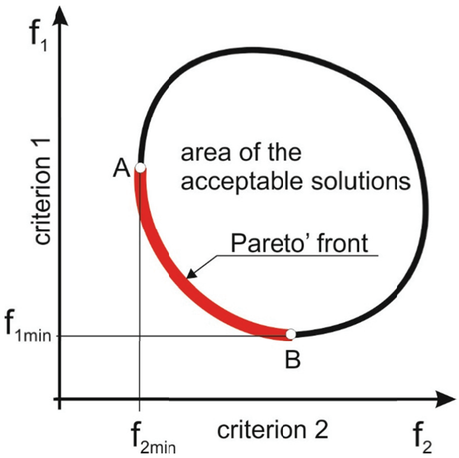

Fig. 2-1. Definition of optimum in the sense of Pareto

The solutions situated within the area indicated with red line, belong to optimum solutions in the sense of Pareto. Each of them is characteristic of that any attempt to bettering one of the criteria results in worsening the other.

Among multi-criteria optimization methods can be numbered a. o. the weighing criteria method, hierarchy optimization method, and also method of evolutionary algorithms [12-15].

The method of weighing criteria consists in the reducing of multi-criteria optimization to single-criterion one by introducing a substitute criterion based on a weighing sum of criteria:

$$Z = \sum \left(w_q \cdot f_q(\boldsymbol{X})\right) \quad (5)$$

where:

$$0 \leq w_q \leq 1 \quad \text{and} \quad \sum_{q=1}^{M} \boldsymbol{w}_q = 1$$

Its solution can be graphically presented as a point of intersection of area of acceptable solutions and the hyper straight line *P* dependent on value of the criteria significance coefficient w_q (Fig. 2-2).

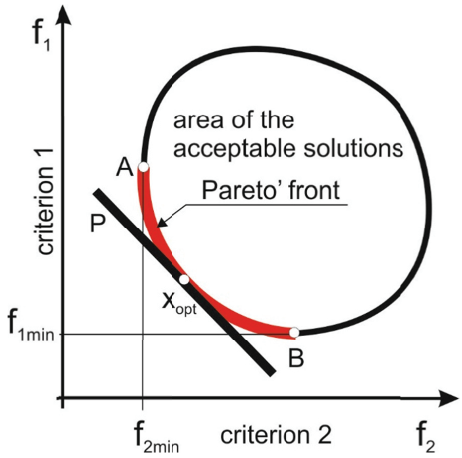

Fig. 2-2. Graphical presentation of optimum according to the method of weighing criteria

In order to balance impact of particular criteria, their normalization may be introduced. A problem in the method is *a-priori* choice of values of weights of criteria, that may obviously lead to different solutions.

In the analyzed issue the set of criteria (functions) $F = \{f_i\}$, $i = 1, 2, \ldots, M$ against which a compromise was searched for between a few contradictory parameters, resulted from the requirements for transverse and longitudinal stability, unsinkability and simultaneous need to minimize resistance criterion.

DESIGN PROCESS

When preliminary design assumptions are made, a CAD software which allows to make spatial visualizations and parametric form of the design, was used. The applied software made it possible to carry out graphical programming without any need of knowledge of programming languages, due to having projects in a parametric form, and to obtain new free shapes by building connections between various geometrical objects, their transformations and functions.

During initial phase of the design process 8 different hull geometry forms were generated (Fig. 3-1). All of them were longitudinally and transversely symmetrical and free of any appendages at this design stage. They were based on traditional hull forms including : flat-bottomed, spheroidal, keel - fitted, and cruiser –stern- ended. During searching

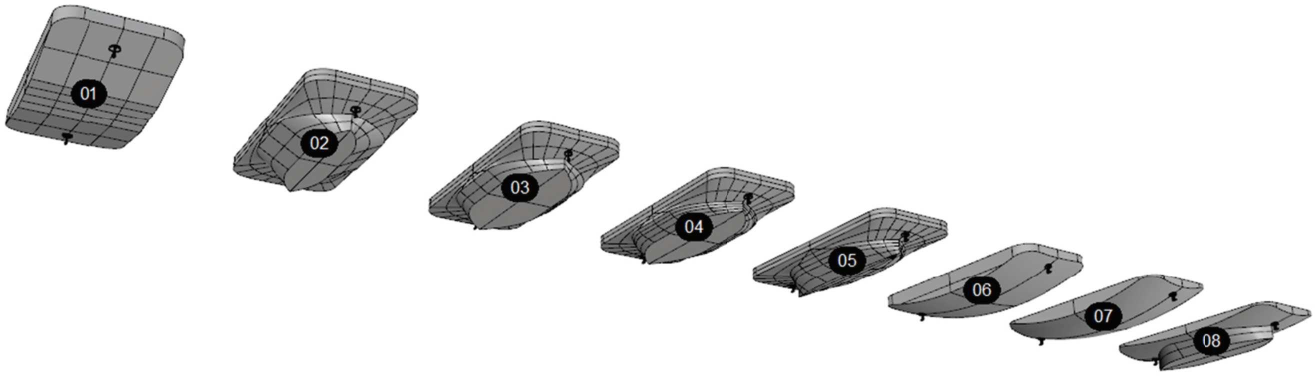

Fig. 3-1. Considered variants of underwater part of designed ferryboat

for an optimum solution, stability criteria were tested by means of CAD software. Resistance qualities calculated by using the parametric method, were analyzed with the use of a spreadsheet program.

Results obtained in this stage made it possible to select the hull form somewhere between cubical and spheroidal one, intended for further optimization. In the final phase of the design process a genetic algorithm contained in a software for searching for optimum in the sense of Pareto, was used [16].

The hull No. 07 which showed optimum features for the assumed criteria, was selected for further actions. Since the moment, the design work was running along many paths:

- design of hull,
- design of propulsion system,
- design of ship body, deck arrangement, wheelhouse position and system.

PROPULSION AND SUPPLY OF THE FERRYBOAT

Progress in electric drive technology and supply systems more and more influences solutions used in shipbuilding. Dynamically developing hydraulic drive is also widely applied, though less often, to main propulsion systems [17-19].

The hybrid parallel drive based on two motors – high-pressure engine and electric motor –as well as the hybrid serial drive based on one electric motor, are more and more often installed on inland floating units . Main reasons for growing popularity of such solution are : propulsion flexibility, easiness and speed of performing manoeuvres and negative environmental impact reduced to a minimum [20-22]. It results from the fact that fully electrical propulsion does not emit exhaust gases and is practically noiseless. The largest pollution burden takes place during production and utilization of motor, especially electric batteries containing lithium.

In view of specificity of water area on which the ferryboat is intended to operate,especially its small size and high traffic rate, it was decided that the ferry should be of high maneouvrability qualities. The more so, because the ferry which operates in a shuttle mode, does not navigate straight ahead between quays but every time it makes slight turn by 900. To satisfy owner's expectations it was decided that the ferry in question will be fitted with electric propulsion based on pod propellers installed at bow and stern. The selected

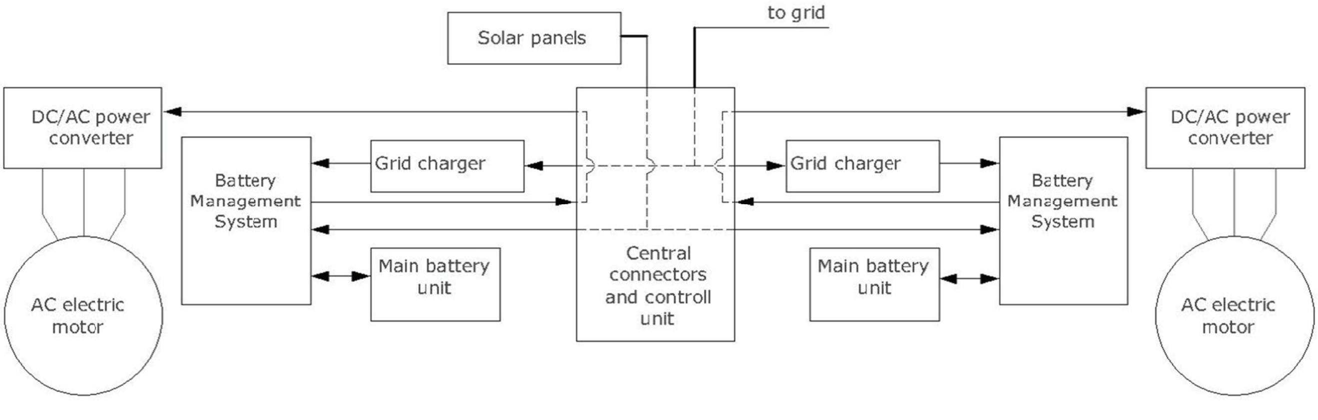

Fig. 4-1. Schematic diagram of the propulsion and supply system of the ferryboat Motława 2

Fig. 5-1. Visualization of the designed ferryboat

propellers were azimuthal ones driven by electric vertical-shaft motors which drive in turn, through reduction gear, the dedicated propellers. Rotation of the propellers around their axis is executed electrically. Paying attention to possible simplification of construction, in preliminary design stage one selected the propellers with the air-cooled engine of 15kW output. As the supply system was based on lithium batteries charged from electric network (grid), and an independent block of photovoltaic panels, the propulsion system was qualified to be hybrid serial one. Based on experience gained from other designs it was stated that especially good maneouvrability qualities are provided by towing propulsion. Therefore, in the preliminary design stage it was concluded that in an ideal case, during bringing up to speed, only one of the propellers – always that towing – will operate. The other will be used during stopping braking just before mooring the ferry. During move in opposite direction the roles of propellers are reversed. In case when a situation forces helmsman to make sudden manoeuvres, the two propellers are always instantly ready to work in order to execute various maneouvres, e.g. side drifting, which is non-available for ships propelled conventionally.

Having in mind that a high degree of navigation safety is expected from the side of passenger ship, one decided to split the supply system into two autonomous circuits. Schematic diagram of the propulsion and supply system is presented below (Fig 4-1).

A problem unsolved in preliminary design stage was the preparation of a reliable energy balance. As results from measurements taken on the currently used floating unit, it usually moves with the speed below 5 km/h and the whole trip lasts only about 2 minutes.

In order to verify experimentally value of power demand, a hull model was built in 1:10 scale to perform tests aimed at power demand identification and maneouvrability verification of the ferryboat.

The executed model tests made it possible to confirm the suppositions that two azimuthal propellers of 15 kW output each can be used to propel the ferryboat in question. The lithium batteries installed on the ferryboat are of sufficient capacity to supply the ship's propulsion system during twenty-four-hour intensive operation. Owing to that, the necessary charging process can be carried out only once a day – in the night. This is of a decisive impact on the batteries life, which is an important issue for ship owner as it influences profitability of the proposed solution.

It may be added that in view of the specific area of navigation over Motława and Dead Vistula (Martwa Wisła) river, and operation not farther than 100 m from river side, the classification society did not required to install a reserve electric generating set. In case of the necessity to make a longer trip, e.g. for repair, such emergency electric generating set may be temporarily placed on the deck. One decided to install battery charger under the deck. It was possible to do because, in order to obtain possibly long life of the batteries, only a slow (10 h - lasting) small - current charging process was assumed. Therefore, the chargers have small dimensions and their connection to a power network is made through typical three-phase contactors. Moreover, one more practical advantage results from such solution, namely, the low power absorption from the network does not lead to the necessity of building a high -power terminal.

The ship owner was proposed to cover the roof slope of one of the Museum's building by photovoltaic panels with total output of over 20 kW. It could reduce cost of power supply to the ship.

CONCLUSIONS

- Design process of small, untypical, non-serial floating unit requires to apply a modern approach based on optimization algorithms.
- Parametric design of small ship hull with application of optimization algorithms seems to be a promising approach.
- Advantages resulting from possibility of project's modification in real time make it possible to carry out multi-path work by a few design teams simultaneously.

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BIBLIOGRAPHY

1. Sabik A., Kreja I.: *Large thermo-elastic displacement and stability FEM analysis of multilayered plates and shells.* Thin-Walled Structures. Vol. 71, (2013), pp.119-133.

2. Iwicki P., Tejchman A., Chróścielewski J.: *Dynamic FE simulations of buckling process in thin-walled cylindrical metal silos*. Thin-Walled Structures, Vol. 84 (2014), pp. 344-359.

3. Kozak J., Tarełko W.: *Case study of masts damage of the sail training vessel POGORIA*. Engineering Failure Analysis, Vol. 18, No. 3 (2011),pp. 819-827

4. Kaliński K.: *The finite element method application to linear closed loop steady system vibration analysis.* International Journal of Mechanical Sciences 39, 3 (1997), pp. 315–330.

5. M. Siemiątkowski, W. Przybylski: *Simulation studies of process flow with in-line part inspection in machining cells.* Journal of Materials Processing Technology Vol.171, No. 1, (2006), pp. 27-34.

6. A. Zieliński, H. Smoleńska, W. Serbiński, W. Kończewicz, A. Klimpel: *Characterization of the Co-base layers obtained by laser cladding technique.* Journal of Materials Processing Technology,Vol. 164–165, (2005), pp. 958–963.

7. M. Deja, M. S. Siemiątkowski: *Feature-based generation of machining process plans for optimised parts manufacture.* Journal of Intelligent Manufacturing Vol. 24, (2013),No. 4, pp. 831–846.

8. Kropiwnicki J., Kneba Z.: *Carbon dioxide potential reduction using Start-Stop system in a car.* Key Engineering Materials, Vol. 597 (2014), pp. 185-192.

9. Kropiwnicki J., Kneba Z., Ziółkowski M.: *Test for assessing the energy efficiency of vehicles with internal combustion engines.* International Journal of Automotive Technology, Vol. 14, (2013), No. 3, pp. 479-487.

10. Rylke A.: *Theory of ship design* (in Polish), L.M.Nogid ? . Wyd. Morskie Gdynia 1962.

11. Eschenauer H., Koski J., Osyczka A.: *Multicriteria Design Optimization*. Springer-Verlag, Berlin 1990.

12. Osiński Z., Wróbel J.: *Theory of structures* (in Polish). PWN, Warsaw 1995.

13. Peschel M., Riedel C.: *Poly-optimization: methods of compromise decision making in engineering problems* (in Polish). WNT, Warsaw, 1979.

14. Seidler J., Badach A., Molisz W.: *Methods for solving optimization tasks* (in Polish) . WNT, Warsaw 1980.

15. Stadnicki J.: *Theory and practice of solving optimization tasks with examples of technical applications* (in Polish). WNT, Warszawa 2006.

16. Karczewski A., Piątek Ł.: *Reducing the Environmental Impact of the Public Water Transportation Systems by Parametric Design and Optimization of Vessels' Hulls. Study of the Gdańsk's Electric Passenger Ferry* (2015-2016), Architecture for the Society of Knowledge, Vol. 1, Faculty of Architecture, Warsaw University of Technology, Warsaw 2016, pp. 314-321.

17. Śliwinski P. : *Flow of liquid in flat gaps of the satellite motor working mechanism*. Polish Maritime Research, Vol. 21, No. 2 (82) (2014), pp. 50-57.

18. Śliwinski P.: *The basics of design and experimental tests of the commutation unit of a hydraulic satellite motor.* Archives of Civil and Mechanical Engineering, vol. 16, (2016), No. 4, pp. 634-644.

19. Mikielewicz J., Mikielewicz D. : *A simple model of circular hydraulic pump.* International Journal of Heat and Mass Transfer, Vol. 52(1), (2008) pp.17-21,

20. B. Zahedi, L.E. Norum, K.B. Ludvigsen: *Optimized efficiency of all-electric ships by dc hybrid power systems.* J. Power Sources. 255 (2014) pp. 341–354.

21. V. Lady, N.- German, L.N. Gas, V. Lady, ? *Fuel cells Norwegian hybrid ship aims to cut* CO_2*-emissions by 50 percent* . 02/13/2011, (2011) pp. 2–4.

22. M. Lapuerta, O. Armas, J. Rodríguez-Fernández: *Effect of biodiesel fuels on diesel engine emissions*. Prog. Energy Combust. Sci. 34 (2008) pp. 198–223. doi:10.1016/j.pecs.2007.07.001

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