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DESIGN PARAMETERS OPTIMISATION OF ROPAX FERRY USING SEAKEEPING CHARACTERISTICS AND ADDITIONAL WAVE RESISTANCE

Key words

Sea-keeping, ROPAX ferry, rolling, motion sickness index, additional wave resistance, design parameters, artificial neuron networks, optimisation, Pareto method, fuzzy logic.

Summary

This paper presents the multi-criteria design parameters of the optimisation of the ROPAX ferry using sea-keeping characteristics and additional wave resistance. The design criteria were formed using the method based on deterministic scenario and the partial objective functions were determined as artificial neuron networks. The design parameters' optimisation was carried out with the Pareto method. The best design variants were chosen using the elements of fuzzy logic that allowed, among other things, to present design quality with linguistic variables. This approach allowed choosing the best variant concerning all criteria at the same time.

Introduction

In the process of ship design, new solutions are searched in which both fulfil economic criteria and correspond to technical limitations. Economic criteria are the many requirements of a shipowner, such as operational velocity, which significantly influences the cost-effectiveness of ship operation on a given cruise line. Because the ship is often operated in a storm, achieving assumed service velocity depends, among other things, on additional wave resistance of the ship. For some types of ships, i.e. passenger and car ferries, more and more often the essential technical limitation is insensitivity to weather conditions, which means the good sea-keeping characteristics of the ship. The additional wave resistance and good sea-keeping characteristics of the ship are significantly influenced by the shape and size of a ship's hull. Therefore, these characteristics of the ship must be modelled no later than at the stage of the ship's parametric design. A wrong size of the ship's hull irreversibly worsens the quality of the design and changing any parameters in an already built ship is economically unprofitable.

The purpose of the research presented in this paper was to determine the optimal values of the design parameters of the passenger and car ferry according to the assumed economic criteria and technical limitations. The method used for optimisation was the method presented in [1] based, among other things, on the Pareto optimisation principle. This method, however, does not give instructions on how to choose the final solution. Therefore, the purpose of the research presented in this paper was to work out a method of choosing the optimal solution among P-optimal ones. In order to solve this problem, elements of fuzzy logic were used.

1. Design task

In the research, the same design task was formed as in [1], i.e. to find the vector of independent variables $X = X(X_1, X_2, \dots X_n)$ which minimises the function of partial objectives under specified constraints for the passenger and car ferry in storm weather conditions.

The assumptions in the research (according to [1]) were as follows:

- independent variables – design ship parameters: L/B, B/d, CB, CWL, where: L, B, d–length, width and draught of ship, CB–block coefficient, CWL–waterline coefficient;
- constraints:
  - theoretical volume of underwater hull $V = 17500$ m^3,
  - L/B within the range from 5,17 to 7,64,
  - B/d within the range from 3,22 to 4,46,
  - CB within the range from 0,6 to 0,64,
  - CWL within the range from 0,8 to 0,85, and
  - initial transverse metacentric height GM = 1m.

A method based on deterministic scenarios and presented in [2] was used in order to form the design criteria. Therefore, the following scenario was assumed:

- the velocity of designed passenger and car ferry in statistical storm weather conditions is v = 5 kn,
- the significant wave height is 3 m,

- the characteristic wave period falls within the range from 3 to 18 s,
- the wave approaches ship from various directions.

It was assumed that for such conditions, the design of the ship must have the following values:

- the least possible motion sickness index MSI (under ISO 2631/3), according to [3] for a wave approaching with angle $\beta=120^{o}$ (in configuration: 180^{o} – opposite wave, 0^{o} – stern wave),
- the least possible additional wave resistance R for $\beta = 180^{o,}$
- the least possible rolling ϕ for $\beta = 30^{o}$,
- the least possible lateral acceleration on car deck a_t according to [2] for $\beta=30^{o}$.

In order to solve the problem of optimisation, at the first stage of the research, the functions of the above partial objectives were determined in accordance with independent values.

2. Functions of partial objectives

The functions of partial objectives, which are necessary to solve the design task, must be in the form of analytic functions approximating the assumed independent values. Functions used in the research were described in [1] as follows:

$$MSI = \frac{\left(\dfrac{1}{1+e^{-([\mathrm{CB,CWL,CB/CWL,L/B,B/d}]\times S+P)\times A-B)}}\times C-\alpha_0\right)-\alpha_1}{\alpha_2} \qquad (1)$$

$$R = \frac{\left(\dfrac{1}{1+e^{-([\mathrm{CWL,CB/CWL,L/B,B/d}]\times S+P)\times A-B)}}\times C-\alpha_0\right)-\alpha_1}{\alpha_2} \qquad (2)$$

$$a_t = \frac{\left(\dfrac{1}{1+e^{-([\mathrm{CB,CWL,CB/CWL,}L\mathrm{/B,B/d}]\times S+P)\times A-B)}}\times C-\alpha_0\right)-\alpha_1}{\alpha_2} \qquad (3)$$

$$\phi = \frac{([\mathrm{CB,CWL,CB/CWL,B/d}]\times S+P)\times A+6{,}96)+1{,}049}{0{,}189} \qquad (4)$$

where:

MSI – motion sickness index [%],

R – additional wave resistance [kN],

a_t – maximal lateral acceleration on car deck [m/s^2],

ϕ – significant amplitude of roll [^{o}],

L – length of ship,

B – width of ship,
d – draught of ship,
CB – block coefficient
CWL – waterline coefficient.

A, B, C, S, P, α_0, α_1, α_2 – matrix, vectors and weight factors of some neuron networks are presented in [1].

3. Choosing optimal hull design parameters with the Pareto method

In this part of the experiment, the hull's shape parameters of the passenger and car ferry were searched according to the assumed criteria. In order to do that, the method and the results of the research presented in [1] were used. The method used here is based on the optimisation condition according to Pareto, which may be presented in the following way [4]:

$$(\forall i)(x_i \le y_i) \wedge (\exists i)(x_i \le y_i) \tag{5}$$

where:

x, y – vectors.

It is also said that the y vector is dominated by the x vector. If a given vector is not dominated by any other vector, it is called an undominated vector.

Fig. 1 presents the set of dependent variables for all optimal solutions, according to Pareto (i.e. undominated solutions) in the considered design task. The set was described in [1]. It was presented in relation to the value of a motion sickness index.

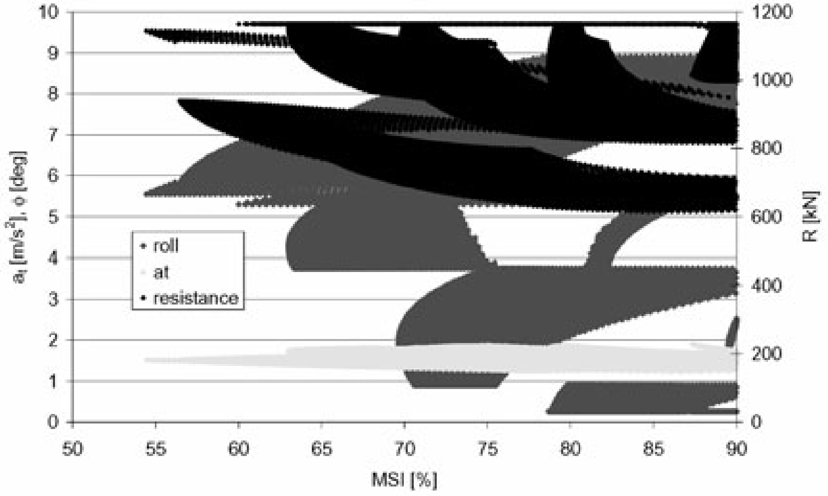

Fig. 1. The set of all optimal design solutions according to Pareto: MS = 55÷90%, R = 614÷1164 kN, $\phi = 0{,}26 \div 8{,}91^{\circ}$, $a_t = 1{,}22 \div 1{,}91$ m/s^2 [1]

Next, fuzzy logic was applied to choose the optimal solution among all solutions presented in Fig. 1.

4. Applying fuzzy logic in the choice of the design solution

Fuzzy logic is applied in every case in which formal logic causes problems with representing the process in mathematical language or when the calculation or the selection of variables to solve the problem is impossible. In the analysed design problem, fuzzy logic was applied as an element supporting the assessment of design quality (low, average, high quality) and the choice of the best design (the best quality for all values).

In the first phase of the research, the set of optimal solutions, according to Pareto, was fuzzied, using a membership function represented by equation:

$$\mu(x_i) = \begin{cases} 1 & dla \quad x_i \geq \alpha_{2(i)} \\ 0 & dla \quad x_i \leq \alpha_{1(i)} \\ \dfrac{x_i - \alpha_{1(i)}}{\alpha_{2(i)} - \alpha_{1(i)}} & dla \quad \alpha_{1(i)} < x_i < \alpha_{2(i)} \end{cases} \tag{6}$$

where:

$\mu(x_i)$ – the value of membership function for dependent i-variable (i = MSI, ϕ, R, a_t),

x_i – the value of dependent i-value (determined by equation (1), (2), (3) or (4)),

$\alpha_{1(i)}$, $\alpha_{2(i)}$ – threshold values according to Table 1.

The graphic representation of the function (6) and its linguistic interpretation are presented in Fig. 2. The values of coefficients $\alpha_{1(i)}$, $\alpha_{2(i)}$ are in Table 1.

In the second phase of the research, fuzzied design solutions were assessed with equation (6). For the assessment of design quality, minimum operator MIN was used according to equation:

$$MIN = MIN(\mu(MSI), \mu(R), \mu(\phi), \mu(a_t)) \tag{7}$$

where:

MIN – minimum operator,

$\mu(MSI)$, $\mu(R)$, $\mu(\phi)$, $\mu(a_t)$ – membership functions of variables.

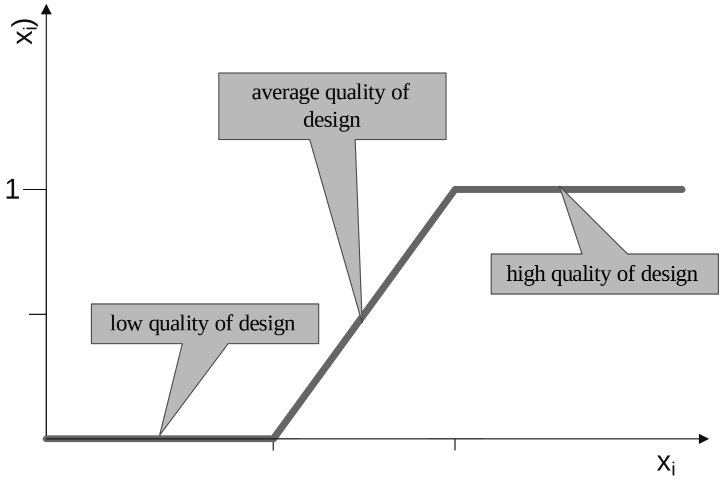

Fig. 2. Membership function represented by the equation (6)

Table 1. Values of coefficients $\alpha_{1(i)}$ and $\alpha_{2(i)}$ for dependent variables

	Dependent variable *i*			
	MSI [%]	R [kN]	ϕ [^{o}]	a_t [m/s^2]
$\alpha_{1(i)}$	64,71	734,09	5,17	1,32
$\alpha_{2(i)}$	69,86	796,02	5,72	1,44

The research proved that the best design solutions were achieved for the following values of design parameters: CB=0,62, CWL=0,8, L/B=5,97÷6,04, B/d=4,11÷4,16. Values of t norm MIN for the above solutions are presented in Fig. 3. Among the presented solutions, the best one is option: L/B=4,15 and L/B=5,99.

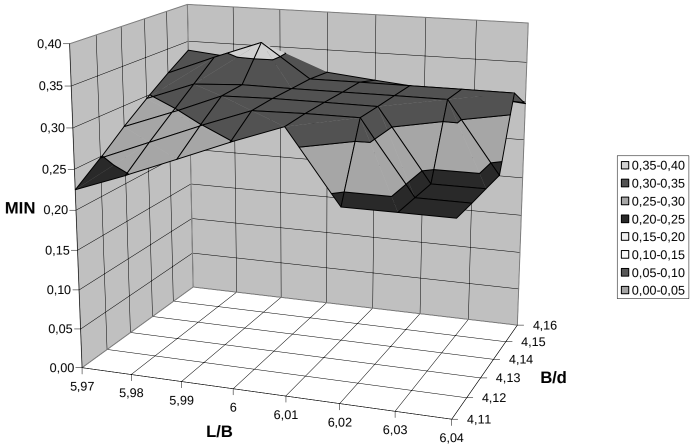

Fig. 3. Values of t norm MIN for the best design solutions, CB=0,62, CWL=0,8, L/B=5,97÷6,04, B/d=4,11÷4,16

The design solutions in Fig. 3 have the various characteristics of partial criteria. Figures 4÷7 present the values of membership functions in alternative designs. It allows thoroughly accessing the qualities of alternative designs regarding partial criteria and choosing the best option that meets the requirements of the ship owner.

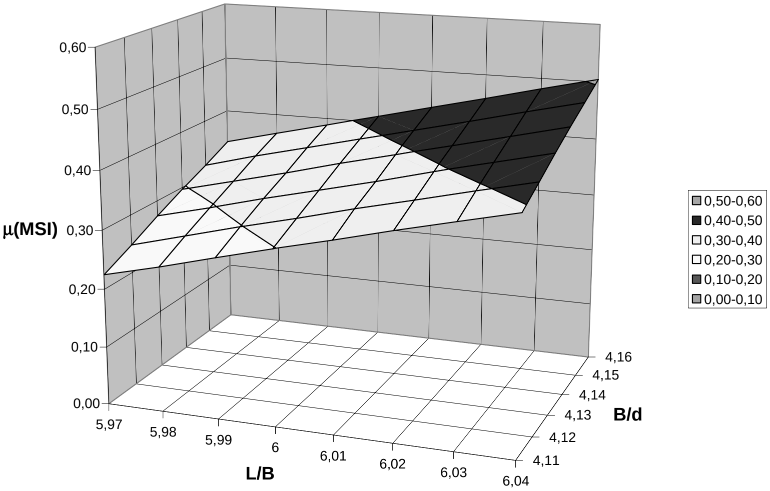

Fig. 4. Values of membership function μ(MSI) for design solutions of CB=0,62, CWL=0,8, L/B=5,97÷6.04, B/d=4,11÷4,16

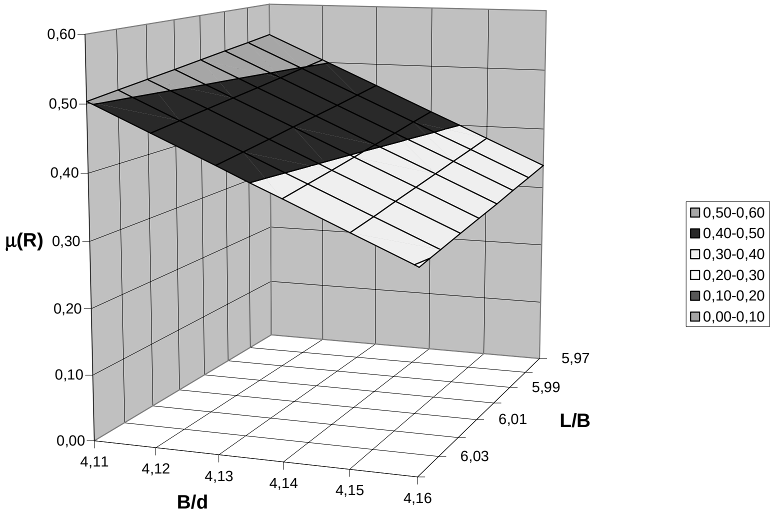

Fig. 5. Values of membership function μ(R) for design solutions of CB=0,62, CWL=0,8, L/B=5,97÷6,04, B/d=4,11÷4,16

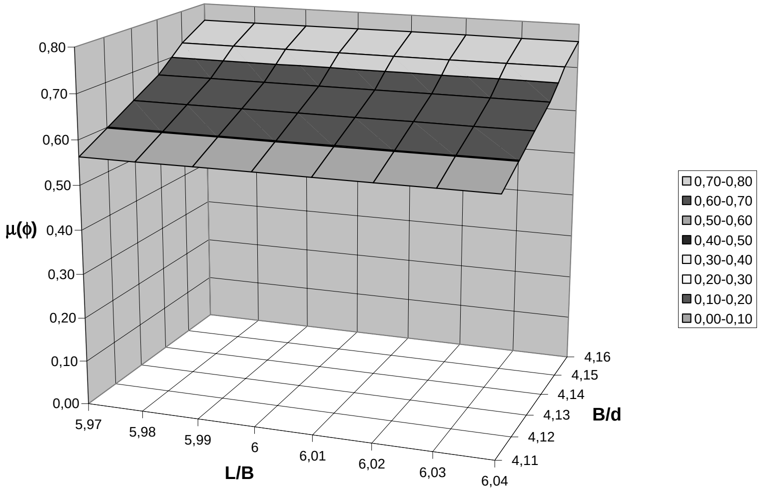

Fig. 6. Values of membership function μ(ϕ) for design solutions of CB=0,62, CWL=0,8, L/B=5,97÷6,04, B/d=4,11÷4,16

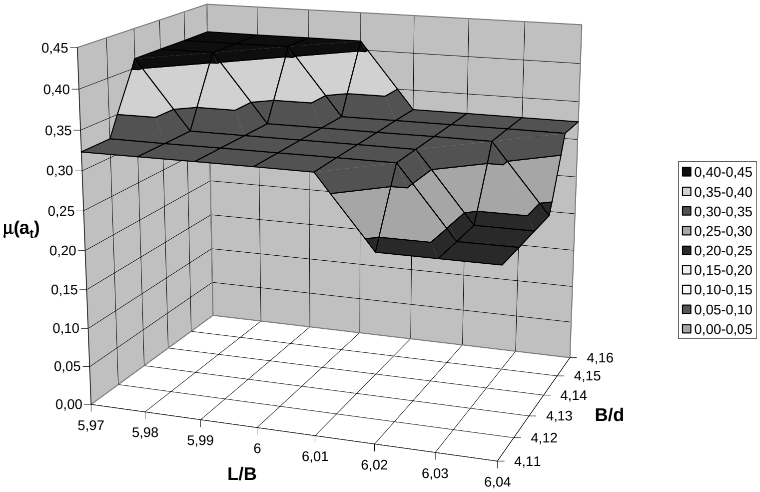

Fig. 7. Values of membership function $\mu(a_t)$ for design solutions of CB=0,62, CWL=0,8, L/B=5,97÷6,04, B/d=4,11÷4,16

Conclusions

This paper presents the parametric modelling of a ship's dimensions on the basis of the following properties of a passenger and car ferry:

- sea-keeping characteristics during a storm, i.e. motion sickness index, rolling, crosswise acceleration on a car deck,
- additional wave resistance.

The optimal design solutions were chosen using the Pareto method. The best design solutions were chosen using the elements of fuzzy logic. It allowed presenting the quality of the design with linguistic variables: low, average, and high quality of the design.

As a result, the design parameters of passenger and car ferry were determined that the design achieved the best quality regarding all partial criteria (Fig. 3). Within the given range of design parameters, it was possible to choose design solutions meeting selected partial criteria (Fig. 4–7). The proposed approach enables a decision-maker (ship owner, naval architect) to choose the most advantageous design option.

The presented approximations may be used in design analysis (e.g. according to [5]) or as objective functions in other optimisation methods of ship design parameters. This approach, thanks to the application of fuzzy logic in assessing the quality of design option, allows reducing a multi-criteria design problem to a single-criterion. In this case, many partial criteria may be presented with one criterion, e.g. minimum operator of t norm, and solutions may be searched for which this operator achieves its maximum value. Such an approach may be applied, among other things, in optimisation methods based on genetic algorithms. It should be mentioned that the presented method is an attempt of a problem solution for taking into account sea-keeping characteristics in the design process of a ship. The method should not be treated as a formal approach.

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Reviewer:
Lech KOBYLIŃSKI

Optymalizacja parametrów projektowych promu pasażersko-samochodowego pod kątem wybranych właściwości morskich i dodatkowego oporu na fali

Słowa kluczowe

Właściwości morskie, prom roro, kołysania boczne, przyspieszenia poprzeczne, dodatkowy opór na fali, parametry projektowe statku, sztuczne sieci neuronowe, optymalizacja wielokryterialna, metoda Pareto, logika rozmyta.

Streszczenie

W artykule przeprowadzono wielokryterialną optymalizację parametrów projektowych promu pasażersko-samochodowego pod kątem wybranych właściwości morskich i dodatkowego oporu statku na fali. Kryteria projektowe sformułowano posługując się metodą opartą na scenariuszach deterministycznych, natomiast funkcje celów cząstkowych wyznaczono w postaci sztucznych sieci neuronowych. Optymalizację parametrów projektowych przeprowadzono metodą Pareto. Do wyboru najlepszych wariantów projektowych wykorzystano elementy logiki rozmytej, co pozwoliło m.in. na przedstawienie walorów projektu za pomocą zmiennych lingwistycznych. Takie podejście umożliwiło wybór wariantu najlepszego pod kątem wszystkich kryteriów jednocześnie.