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Optimisation of the Energy Consumption of a Small Passenger Ferry with Hybrid Propulsion

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ABSTRACT

The main goal in the design phase is to create a safe ship with a very efficient (and preferably zero-emission) propulsion system. To obtain such ships, new concepts are being developed for both propulsion systems and individual components. The choice of a propulsion system is not straightforward. To optimise the selection of the propulsion system, it is valuable to optimise the energy demand of this unit, which can be done by creating operational movement profiles that indicate the differences in energy demand needed to cover the same route within similar times. Optimisation can be performed based on many different criteria, especially for crowded waterways, and can not only reduce the amount of energy needed to power the propulsion system but also increase navigational safety. In this work, optimisation is carried out by searching the space of all possible solutions, which allows for an in-depth analysis according to various criteria.

Keywords: Optimisation, Green shipping, Hybrid, Energy management, Modern propulsion

INTRODUCTION

The main goal of every designer is to create an "ideal" ship whose components will operate with minimum energy consumption for the assumed operating parameters of the system. Current propulsion systems (of which combustion engines are the most popular) are often outdated, and generate large amounts of exhaust gases into the atmosphere. With the increasing awareness of environmental protection, classification societies are changing the regulations regarding the emission of toxic compounds. One of the current challenges in maritime transport is decarbonisation, which aims to reduce emissions of toxic compounds [1,2]. The search for new, emission-free solutions is inspiring scientists and engineers around the world, and great hopes have been pinned on the electric and hybrid propulsions in recent years due to the emergence of new solutions in this field. [3,4]. However, the use of these solutions will require problems to be overcome in terms of storing the energy needed to perform the transport tasks. The amount of electricity stored in batteries can be increased by adding additional batteries, but this significantly affects the space occupied on the ship and the total weight of the unit. Energy consumption analyses and assessments of environmental impact using advanced mathematical models can create new opportunities to improve ships and optimise the way in which they are operated.

ENERGY MANAGEMENT AS A CRITICAL ASPECT OF SAFE JOURNEYS

There is currently scant knowledge of the energy consumption of small inland vessels, as traditional resistance tests are carried out for vessels moving on long routes, where the energy used to perform manoeuvres is ignored as it has an insignificant impact on the total energy consumption in a given work cycle.

For small ships, the energy needed to perform manoeuvres has a significant impact on the final energy requirements of the unit, meaning that any analysis should take into account all stages of the cruise. This implies that traditional resistance tests for constant speeds, which do not take into account speed changes, are unreliable for this type of unit. Particularly on short routes, the acceleration and braking processes are very energy-consuming, and cannot be omitted from the energy balance.

Reducing energy consumption while still completing the transport task is crucial for all modes of transport. In the case of electric or hybrid propulsion, optimal use is of great importance, as electricity is stored in expensive batteries whose weight and dimensions affect the ship's transport capabilities. The higher the energy consumption, the larger the number of batteries and the greater the space that could be used for another purpose (e.g. for the transport of additional machines/people/products). For this reason, interest in electricity management systems for electric and hybrid ships has increased over the last few years [5-7].

METHOD AND CASE DETAILS

SHIP DESIGN

The ship considered here was developed in 2015–2016 as part of a research project involving a new ferry for the National Maritime Museum in Gdańsk [8,9]. The goal of this project was to replace the previous ship, which had existed since 1975. The main assumptions of the project were as follows:

- • The hull length was 12.0 m, and the width 5.0 m;
- • The number of passengers was 36;
- • The drive was supplied by electric, battery and photovoltaic panels.

This design task was solved using an innovative design method based on multi-criteria optimisation [10-12]. The developed design, referred to as Motława for the purposes of this study, is shown in Fig. 1.

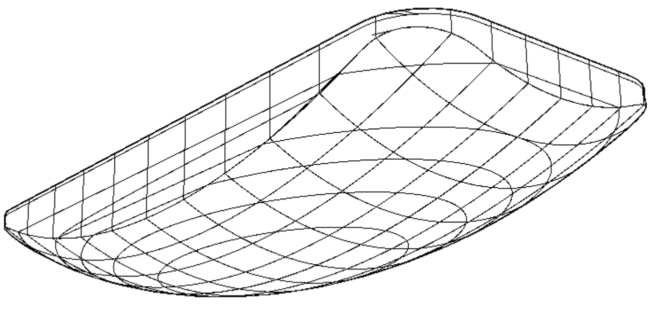

Fig. 1. Hull of Motława [5]

This paper presents an analysis of the optimisation of energy demand for the propulsion system. The energy needed to power other systems, such as lighting or heating, is not taken into account here.

PROPULSION SYSTEM

The proposed solution involves a serial hybrid drive system based on two azimuth thrusters, powered by electric motors with permanent magnets and equipped with its own battery pack (Fig. 2). This allows the ship to achieve the expected high level of manoeuvrability.

Due to safety requirements and expected unsinkability, the ship is divided into watertight compartments. The main switchboard of the power supply system is located in the central part of the ship, which is easily accessible from the crew room.

Lithium batteries grouped into water resistant modules of 86 V rated voltage and 5 kWh capacity are selected as the power supply. Each module consists of 78 $LiFePO_4$ cells connected in a series-parallel circuit (configuration 26S3P). The number of modules depends on the selected operational profile. For safety reasons, these lithium batteries are placed in sealed containers with mechanical ventilation, with varying efficiency depending on the temperature of the cells.

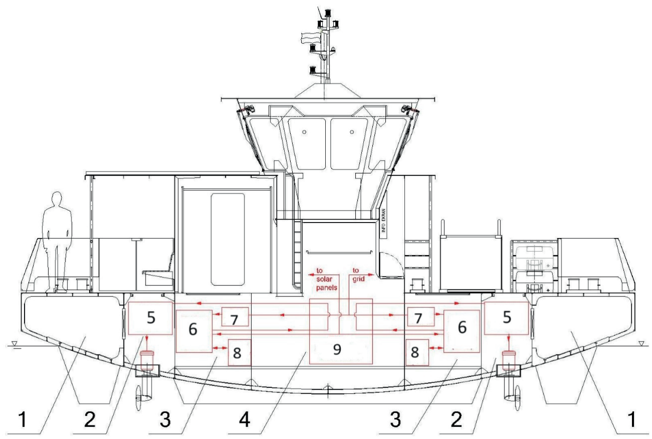

Fig. 2. Propulsion and power supply system schematic of the Motława ferry: 1 – collision bulkhead; 2 – propulsion compartment, 3 – battery compartment, 4 – crew room with main switchboard, 5 – DC/AC power converter, 6 – BMS (battery management system), 7 – grid charger, 8 – main battery unit, 9 – central connectors and control unit

The criterion for optimising the energy consumption was the minimum energy consumption for a specific period of movement of the vessel. This choice was made due to the specificity of the water area in which the vessel moves and the planned transport effect. The ferry cruises between two banks of the river, and its route crosses the main shipping route running along the river.

Photovoltaic panels installed on the unit are intended to function as additional power supply, and are used to power small systems inside the ship (e.g. lighting).

TESTS

MODEL TESTS

We began by carrying out traditional model tests for constant speeds, in accordance with the ITTC procedure [13], although these tests provide only a partial knowledge of the energy requirements of the propulsion system. In the next step, tests were carried out of the other stages of the unit's movement, such as acceleration, gliding (moving only by the force of inertia and braking.

A model at 1:10 scale was used in this experimental research. The method used to model the vessel's hull has been described in other articles [8,9]. Table 1 shows the parameters of the actual unit and the scale model.

Tab. 1. Main parameters of the model and the full-scale ship

	Full-scale model	Model at 1:10 scale
L – ship length [m]	12	1.2
B – ship breadth [m]	5	0.5
L_{WL} – ship waterline length [m]	10.47	1.047
T – ship draught [m]	0.93	0.093
V – displacement volume [m^3]	23.12	0.0231
Aw – wetted area [m^2]	50.53	0.5053

FULL-SCALE TESTS

The measured total resistance of the model was recalculated to the scale of the real ship based on Newton's second law of motion and the Froude method. The energy values for the real unit were scaled based on the acceleration stage. The obtained model functions were the same for both the model and the real unit. Different coefficient values were selected for the model functions of the model and real units. Fig. 3 shows the correlation between the model functions and the measured data.

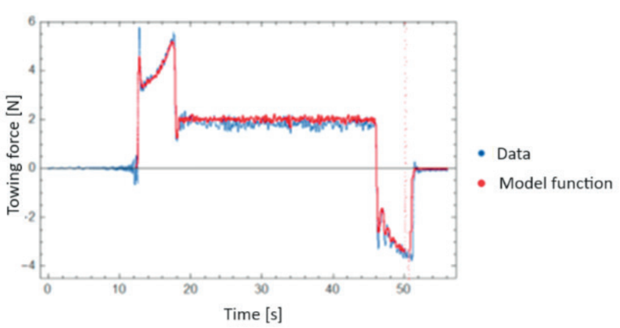

Fig. 3. Model functions for the acceleration, constant speed and deceleration stages, while accelerating to the desired model speed (8 km/h for a real unit)

The method used to recalculate the values for each stage was described in detail by Wrzask [14]. The model functions of the towing forces for all stages were consistent for all of the velocities and accelerations tested.

For the installed propulsion system, the efficiency values at individual stages are presented in Table 2. The efficiency for each individual element was estimated based on the manufacturer's recommendations (e.g. for the gear and clutch) or on the basis of tests of a similar unit (e.g. for the ship's propeller and electric motor).

Tab. 2. Efficiency at each stage of movement

	Stage			
Efficiency	Acceleration	Constant	Gliding	Braking
η total	0.29	0.41	-	0.29
η mot	0.9	0.9	-	0.9
η prop	0.35	0.5	-	0.35
η shaft	0.97	0.97	-	0.97
η clutch	0.97	0.97	-	0.97
η gear	0.97	0.97	-	0.97

OPTIMISATION OF ENERGY CONSUMPTION WITH THE CHOSEN STRATEGY

After rescaling the model values to a real unit and calculating the actual energy demand, taking into account the efficiency, three movement strategies were developed: ACB (acceleration, constant, braking), AGB (acceleration, gliding, braking), ACGB (acceleration, constant, gliding, braking).

Multi-criteria optimisation was selected for analysis, as this allowed us to determine the optimal operational profile depending on the current route conditions. Optimisation was performed for each strategy by searching the space of possible solutions to explore different optimisation criteria. The main optimisation criterion was to obtain the lowest energy demand for a short time needed to reach the planned route. The assumed operating route for the ferry was 100 m, between two banks of the river. The energy demand values given below refer to one full day of operation, based on the assumption that the installed batteries will be charged at night.

Each of the stages considered here had its own limitations, but the main overall limitation on the optimal solution was a time of below 100 s (a limitation resulting from the water area in which the unit is intended to move). As a result, 250 acceptable solutions were developed that could be used depending on the criterion selected, which can be chosen freely. During the optimisation process, the model functions for the values of forces and resistance were determined based on model tests. After scaling these values to the real object, the values of the work performed by the unit during a single course were determined. The force values were determined from Newton's second law of dynamics. The problem of optimising energy demand for the movement speed profile of the ACB and ACGB unit was defined as a function of the minimum energy demand, which depended on the number of stages and the time needed to perform a given manoeuvre. The distance covered in each stage was one of the limitations.

The optimal solution is shown in Fig. 4.

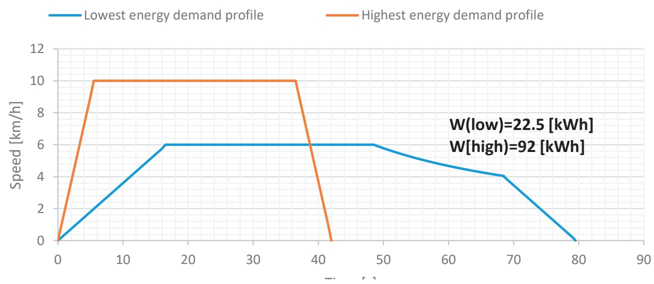

Fig. 4. Comparison of the best and worst energy demand profiles

In view of the diversity of the solutions obtained here, Figs. 5 and 6 present exemplary profiles for ACB and ACGB strategy solutions, along with their energy demand.

A comparison of these two strategies, depending on the acceleration and speed, indicates that the ACGB strategy allowed a lower energy demand to be achieved. However, using this strategy means that a longer time is required to cover the entire route. In addition, during gliding (where the movement is provided by inertial forces), the manoeuvring abilities of the unit deteriorate, as the assumption at this stage is that the ship moves in a straight line, without the possibility of changing direction.

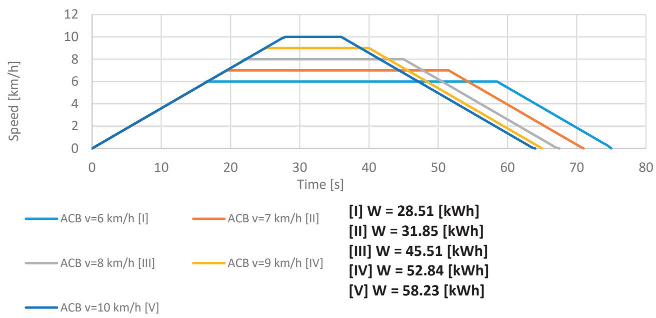

Fig. 5. Differences in energy consumption for the ACB movement strategy, depending on velocity, for the same acceleration.

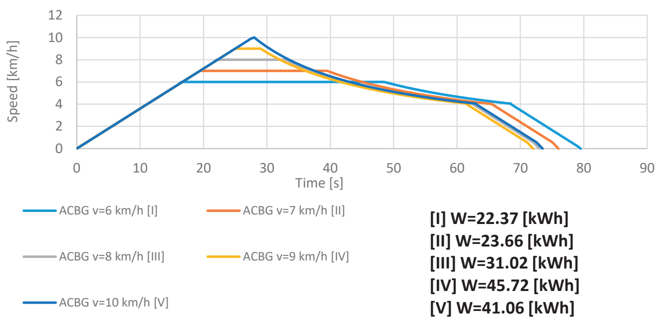

Fig. 6. Differences in energy consumption for the AGCB movement strategy, depending on velocity, for the same acceleration.

RESULTS AND DISCUSSION

Depending on the speed and acceleration, the results for the energy demand differ and the speed profiles have different waveforms. The pie chart in Fig. 7 shows the proportions of the results obtained in relation to the entire space of possible solutions.

It can be seen that most solutions require energy in the range of 20–60 kWh per working day. This is over 75% of all possible solutions.

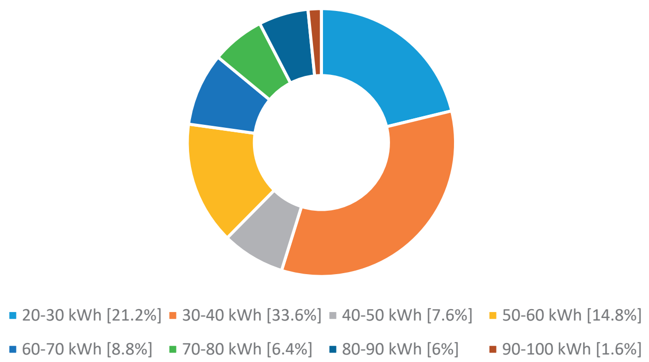

Fig. 7. Summary of percentage ranges for all solutions

The obtained results make it possible to calculate the energy demand depending on the desired acceleration or velocity. The time needed to complete the one-way route was also included in the calculations. A comparison of the two extreme movement profiles is given in Fig. 4, but it is also possible to find intermediate solutions between them. Depending on the selected speed profile, there is a visible difference in the time needed to complete the planned route. Hence, the optimisation process carried out here is universal, and allows for a practical approach to meeting the demand for a given route and the possible obstacles that may occur.

For a route of the same length and a given permissible duration of one trip, the work can be performed with energy consumption ranging from approx. 22.5 kWh to approx. 90 kWh. To better illustrate the difference, we can assume very unfavourable weather conditions (strong wind, large waves) and a helmsman who is insufficiently trained in how to operate a unit with an electric drive; to ensure safety under these conditions (preventing faster consumption of the energy stored in the batteries as a result of incorrect operation), we can add an allowance energy of 50% to the abovementioned extreme variants, which gives values of 33.5 and 135 kWh. If we calculate the energy demand in the case presented here for an entire year of operation, we obtain values of 12,227.5 kWh (37.5 × 365 days) and 49,275 kWh (135 × 365 days). From a comparison with the obtained results, we see that the energy needed for the speed profile with the highest demand could be used to power four units similar to the proposed ferry, using an optimal speed profile.

The choice of propulsion system has a significant impact on the results. Since the ship's propeller is the most highly loaded element of the system, it generates the greatest losses. From Table 2 above, which shows the efficiency of individual elements of the drive system, it can be seen that the greatest losses occur in the acceleration and braking stages when the propeller operates under the most unfavourable conditions (due to the type of flow around the ship and oversteering).

CONCLUSION

In this paper, we have considered the problem of managing electrical energy in units with electric and hybrid propulsion systems (where the drive system is powered by batteries). Due to the specific nature of this propulsion system, it is not possible to recharge the batteries during short stops, so the amount of energy provided for a given period of work must be sufficient to perform it. This issue is particularly important, as there is a need to avoid a situation where the unit cannot continue to operate due to a lack of energy needed to power it, as this is dangerous to passengers who may become trapped on the water.

Currently, there are many solutions available for ship propulsion systems, and the choice of the right one is the designer's responsibility. When deciding on a specific solution, many factors should be analysed. The growing interest in environmentally friendly shipping favours a choice between electric or hybrid propulsion systems. We have also described the advantages of choosing an electric propulsion system and have shown that choosing the appropriate operating profile for the unit permits the number of batteries installed to be reduced, which allows for a larger cargo space.

The design of an electric propulsion system for small vessels poses many problems. The regulations of classification societies for such units are often still being created, and are constantly evolving. In general, they mainly describe drive systems for large ships, and meeting these requirements is very difficult for small units, due to the small cargo space on the unit. It is therefore necessary to look for solutions that will limit the number of batteries installed, as these are the main source of electricity stored on the ship. A helmsman who is to operate a battery-powered ship should be properly trained to prevent situations such as a lack of energy. Choosing the appropriate operational profile therefore allows the safety of navigation to be increased.

Despite the technological developments that have occurred in electronics over recent years, specialised devices such as power generators and the various types of controllers, converters, and batteries available on the market are very expensive, and the lead times for orders for specialised elements may be very long. Such devices are also complicated, and often fail. For example, when we consider the life cycle of a battery, it can be seen that this is a device that may fail prematurely, even with proper operation, which in the case of electric drive systems may prove disastrous. The operator should therefore strive for optimal use of the electricity stored in the batteries, and should ensure that the appropriate operating regimes recommended by the manufacturer are maintained, such as temperatures, voltage ranges, or charging and discharging currents. The proposed method of saving energy described in this work is based on rational movement, with the lowest possible energy consumption, using the optimal profile of the ship's cruising speed. The chosen criterion can be supplemented with parameters such as distance and time, which are determined by the body of water in which the designed unit moves. The speed profile of the vessel can be freely selected, and represents a set of manoeuvres and speeds with which a unit covers a given route. Additional criteria, such as time, are very important here, as shortening the period of movement can often be achieved by setting higher speeds and accelerations. However, this is associated with a significant increase in the energy demand of the unit's drive system.

The research carried out here is very important in the context of the growing interest in artificial intelligence, which in time will allow large ships to be made fully autonomous. The selection of different operational profiles depending on the situation will allow for the effective use of electricity stored in batteries on ships.

Abbreviations

ACB	Acceleration, constant, braking
ACGB	Acceleration, constant, gliding, braking
AW	Wetted area
B	Breadth
D	Depth
L	Length
Lwl	Waterline length
T	Draft
W	Total energy demand
η_{clutch}	Clutch efficiency
η_{gear}	Gear efficiency
η_{mot}	Motor efficiency
η_{prop}	Propeller efficiency
η_{shaft}	Shaft efficiency

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