



ASSESSMENT OF UNDERPOWERED PROPULSION MACHINERY IN ELECTRICALLY DRIVEN SMALL INLAND WATERWAY PASSENGER SHIPS FROM CLASSIFICATION SOCIETY POINT OF VIEW

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Abstract

Paper presents short operational and engineering analysis of underpowered propulsion in small electrically propelled small inland passenger ships. There is evidence that in certain weather conditions the phenomena of added aerodynamic resistance of small water crafts may have serious influence on their speed and manoeuvrability. Existing regulations like class societies rules for ship classification and construction or EU Directive 2006/87/EC do not provide any requirements or guidelines on prediction of air or hydrodynamic resistance or propulsion power computations to be assessed by third party in design process. In the opinion of authors, the case is particularly important when electrical or hybrid propulsion is considered as prime mover. Existing knowledge allows for engineering analysis to be conducted to provide better knowledge on the selection and construction of innovative propulsion machinery for ships where passengers safety is major factor of concern by waterways administration, class societies and insurance institutions.

Key words: *inland waterways, passenger ship, electrical, hybrid, propulsion power, aerodynamic resistance*

Introduction

Design of inland waterways crafts is considered easy even for students and freshly graduated engineers. The use of existing knowledge and relatively simple computation leads to fast design and selection of certain equipment quite easily as it is often available from the shelf. The use of more advanced analytical tools in case of novel ship hull and propulsion designs is often neglected. Operational experience shows that in some cases the fact of underpowered designs will happen. In worse cases, there is no possibility for design improvement without investment in more powerful propulsion system. Alternatively, calculations similar that are performed for bigger ships should be performed using knowledge accumulated by naval architects. In this case, the main obstacle is budget limit.

Decisions to use propulsion machinery selected on principle of lowest computed power installed may lead to operational problems in reality like inability to sail forward in windy conditions or poor maneuverability. Consequently, small or light crafts scheduled for

operation in restricted waters or rivers could experience navigation problems in case of combined wind action and waves. A practical example in PRS experience could be fact of crafts repowering and change of initially installed electrical propulsion to diesel drives. The paper is an attempt to collect some recent class society and engineering experience on operational consequences of underpowered waterborne crafts. More engineering effort and use some more advanced design tools could lead to partial solution to this problem. Authors suggest possible solution to predict and take right measures to improve ship design either by aerodynamic drag reduction or by increase of power and/or propulsion efficiency.

Short outline of class society requirements and other legal regulations

Classification rules do not impose requirement on ship hydrodynamic performance. The speed of small recreational or commercial boats with electric propulsion is within range of 6-8 km/h [3]. In case of commercial ships built to comply with class rules general requirement is that minimal speed of inland waterway ship or watercraft is not to be less than 13 km/h. [5]. Such requirement is also present in EU Directive laying down minimal technical requirements for inland waterway vessels [1].

The current state of the class requirements is that the applicable class rules (LR, BV, GL, PRS or RRR) do not contain any formula that allow to define ship power requirements. On the other hand there is given requirement for of 70% of nominal thrust to be available during minimum of 30 min in case of astern movement maneuvering. In general all new ships are to be subjected to maneuverability testing where ship speed is to be measured. Dedicated requirements are pending for all ships that are navigating on EU inland waterways according to the requirements of the 2006/87/EU Directive [1].

Small ship design and engineering in practice

In Poland, during last 12 years number of design projects of small passenger crafts with electrical propulsion has been conducted and some resulted in construction of prototype vessels. It is common in some circles to claim that design and construction of small ship, particularly for use on restricted waters is easy and unproblematic. That is not true and there is real evidence that numerous problems may appear. Some originates from improper design input data or wrong assumptions and omitting of engineering computations. Lack of design experience is also a potential risk for design process quality. Selected vessels are listed in the table underneath. As demand for such crafts is limited there are only few example of ships for more detailed analysis. For this study only polish designs were taken into account.

Class requirements for operational area and wind loading

A summary of environmental requirements present in class rules for ships navigating in different operational areas is presented in Table 1. Compliance with that regulations is a part of ship class notation.

Table 1

Area Notation	1	2	3	4	PRS Rules Part I [5]
Wind [°B]	5 - 6	Up to 6	3 - 4	-	3.6.3.4
Wind speed [m/s] - max	10	10 - 12	7	-	3.6.3.4
Wave height [m]	2	1.2	0.6	-	3.6.3.2
Minimal ship speed [kn(m/s)]	6 (3)		7	-	3.6.3.5
Distance from shore [miles]	Up to 6		3°B/6 4°B/1.5	-	

Wave height ($h_{1/10}$) is measured from trough to the crest representing value of 10 % of highest waves during the particular – not to long measuring period. This corresponds 5%

probability of exceeding that height.

Ship resistance and propulsion system design

In majority cases, designers conduct in practice very simple calculations, not taking all engineering parameters into account. During ship design process for assessment of ship performance, it is typical to assess water resistance. Usually omitted, determination of resistance resultant from aerodynamic forces is to be done to be able to select prime mover power to comply with area. The importance of wind knowledge about resistance is in often critical and could result in serious financial penalties for shipyard and costs for ship owner. Recently done combined shipping industry project resulted in elaboration of new guidelines for bigger ships. With the assistance of the Sea Trial Analysis-Joint Industry Project (STA-JIP) and ITTC, the new IMO EEDI rules to reduce CO₂ emissions. As a result, there is validated and approved method to consider the effects of wind on the resistance given in the ISO Standard 15016 (2002) and the ITTC Procedure 7.5-04-01-1.2.

For preliminary design of small ships, majority of calculations done are based on simple formulas. Performing full resistance assessment with model testing for hull and propeller require substantial budget and this is performed very rarely in case of small inland crafts. The analyzed ships discussed here possess relatively small electrical motor power in comparison to similar size crafts powered by diesel engines.

Assessment of ship aerodynamic resistance

The computations of the ship aerodynamic resistance is usually performed when necessary – for mooring analysis or on big fast ferries – HSC (High Speed Crafts), container ships or on naval vessels. There is no any information that aerodynamic resistance calculations were performed in the discussed inland waterways passenger ship examples. In case of windless weather conditions, the wind resistance acting on a ship sailing forward can be determined using the formula:

$$F_d = \frac{1}{2} \cdot \rho \cdot V_s^2 \cdot A \cdot C_d$$

where: - F_d - the drag force,

- ρ - the density of the air,

- V_s - the speed of the ship relative to the air,

- A - the cross-sectional area of the ship,

- C_d - the dimensionless coefficient of resistance, dependent basically on physical parameters, ship hull and superstructure shape and spatial dimensions and on ship speed relative to the air.

Majority of the wind resistance is due to eddie-making type, and therefore it varies roughly with V_R^2 (V_R is the relative velocity of air to a ship) what is presented in Fig. 1.

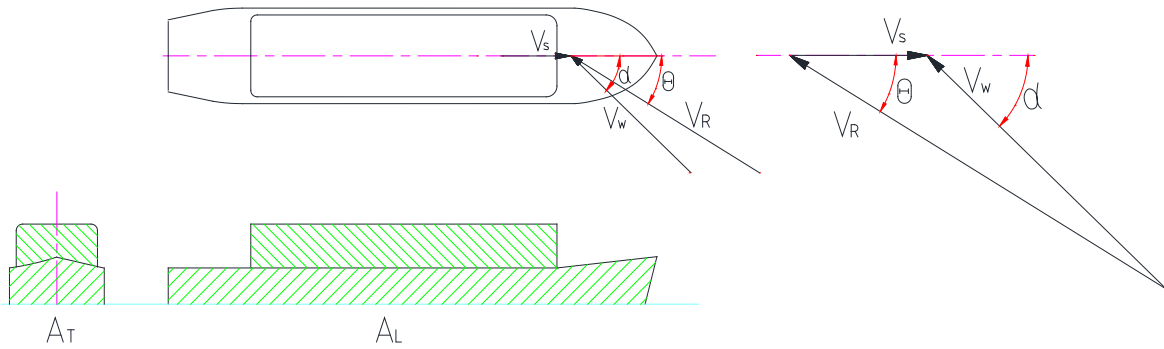


Fig. 1 Wind force acting on a ship and ship area used for assessment of wind resistance

A_L – longitudinal projected area,

A_T – transverse projected area,

V_w - wind speed,

V_s – ship speed,

V_R – wind velocity relative to ship,

θ – angle of wind direction relative to the longitudinal centre line of a ship measure from the bow,

α – direction of the resultant force relative to the centre line

According to Hughes formula

$$F_d = k \cdot \rho \cdot V_R^2 \cdot \frac{A_L \cdot \sin^2 \theta + A_T \cdot \cos^2 \theta}{\cos(\alpha - \theta)}$$

Where: - k – an empirical constant $k = (0,5 - 0,65)$

The additional propulsion power required to overcome the aerodynamic drag is given by:

$$P_d = F_d \cdot V_R = k \cdot \rho \cdot V_R^3 \cdot \frac{A_L \cdot \sin^2 \theta + A_T \cdot \cos^2 \theta}{\cos(\alpha - \theta)}$$

Design and construction problems in small ships design

Requirements and procedure for testing of the new build inland waterway ships is described in Rules [7] and is based on EU Directive requirements. As a result of analysis of published information about projects and existing inland ships and ferries [6], specifics of electrically propelled vessels could be summarized as:

1. Relatively small size - 6 to 24m,
2. Lightweight design with hull made of steel, GRP composites or aluminum alloys,
3. Number of passengers - 6 to 100 (150 max),
4. Mono-hull or quite often twin hull design,
5. Energy storage (battery) weight is substantial comparing to hull weight

As an example of design issues that are to be analyzed, enclosed are diagrams with analysis of power requirements and weight estimations:



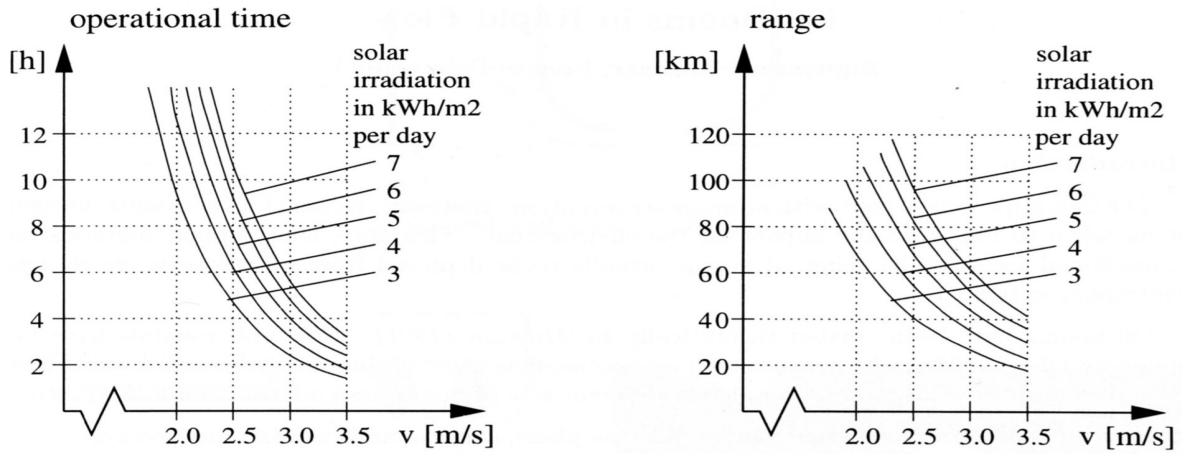


Fig.2 Operational time and range as function of solar craft speed – design analysis example. [3]

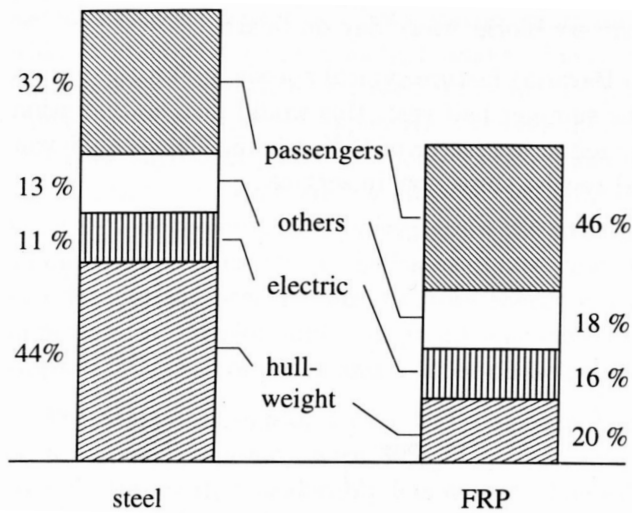


Fig. 3 Weight distribution in relation to construction material l in small water craft design [3]

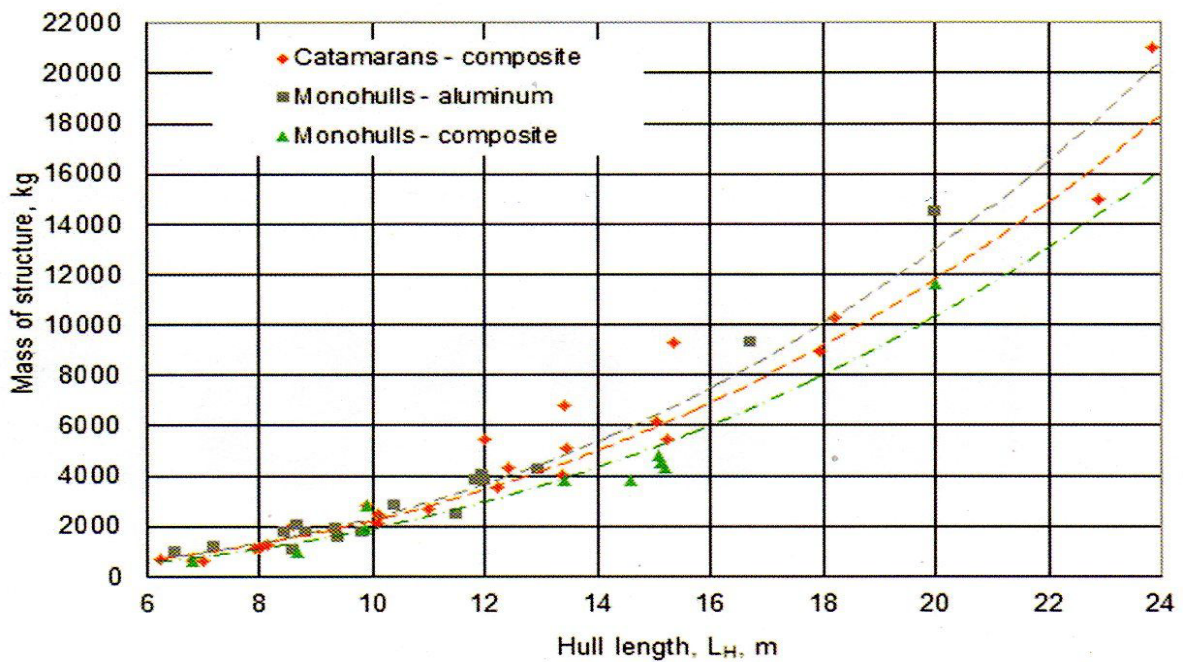


Fig. 4 An example of weight relation of catamaran crafts in a function of construction materials and ship length [8]

The above graphs point out that the hull and equipment weight of the small craft shall be kept at lowest possible value due to important influence on energy required for propulsion. Additionally, prediction of operational characteristics in case of battery powered should be conducted to analyze energy usage for planned usage timeframe. Excessive use of energy may lead to lack of propulsion power in case of change of weather conditions when additional aerodynamic drag require more energy to be used to keep speed or operation of the vessel systems. The safety measures are present in class society rules – usually spread in various parts of rules. Synergy of safety requirements is not always properly understand by designers, fresh ship owners and water administration.

Maneuverability testing is described in EU Directive Amendments [1] and the all requirements are included into PRS Rules [7]. The requirement for minimal speed at least 13 km/h is enclosed in Part III p. 2.2.1 of PRS Rules [5]. The requirement for astern thrust 70% of forward thrust by 30 min. is in part VI p.1.10.2. In certain cases, there could be request to increase the astern thrust due to safety or maneuverability reasons. Full maneuverability requirements are enclosed in PRS publication no 27/P-2010 [7]. The maneuverability requirements are not easily implemented by ship-owners due to budget reasons and sometimes due to lack of test area. Having in mind that, ship operational parameters should be constant during all day navigational scheme, it is very risky not to install additional energy power in case of battery powered ships. A solution requested by class society rules is to have additional source of energy i.e. diesel generating set.

Selected ship examples

Ship A.

Mono-hull ship – The first bigger passenger ship in Poland equipped with electrical propulsion. The ship was used for short trips on lakes and river estuaries. According to the available information the design appeared to create some technical and operational problems – windy weather prevented to be used for tourist trips. Very soon operational use has been suspended. Ship owner decided to make major modification of the propulsion system and removed electrical drive into diesel drive. The vessel was prototype with limited funds and probably without detailed design that should include detailed calculations for battery powered ship propulsion system. We can assume that in case of this passenger ship having steel design with construction same as for typical inland waterway ship with diesel propulsion was to heavy. Battery powered vessel appeared to be uneconomical, slow speed, difficult to make maneuvers at slow speed so ship owner decided to conduct propulsion machinery conversion to diesel drive.

Ship B.

Twin hull small passenger ship used as river ferry or water tram used in restricted water areas like rivers and channels. Advanced design with solar cells appeared economical solution maximal speed during testing within range defined by Rules. Ship power system consists of two battery banks and diesel and solar generator. Electrical motors place in machinery compartment above waterline and power transmission to the propeller is made using “L” drive. The ship is in operation starting from Sept 2008.

Ship C.

Small solar powered boat of 6m length. Experimental design constructed by a team from University of Technology. Boat performed several trips on polish rivers and channels as well as some trips at sea in Gdańsk Bay. The electrical motors propulsion power is very low (2 kW) and in windy conditions some problems of not sufficient power has been observed.



Ship D

Mono-hull small passenger ship – river ferry. Solar powered ferry boat operated in restricted waters and channels. Ship power system consists of two battery banks and diesel and solar generator. Propulsion by two electrical underwater motors.

Ship E

Hybrid, electrically and solar energy powered passenger ship for inland waterways. Completed research project and selected engineering analysis. Model built and testing has been done. The craft designed to be operated in estuary of Vistula river inland waterway channels.

Assessment of wind resistance for selected ships with electrical propulsion

Evaluation of wind generated aerodynamic resistance has been done for sample ships using technical data available in literature and PRS Register of Inland Waterways Ships. Areas of wind action has been assessed using ship general plans and officially available dimensional data. Formulas used are those presented above. Results of computations are presented in Fig. 5.

Tab 2. Basic data of analyzed passenger ships

	SARA	Ship A	Ship B	Ship C	Ship D	Ship E
Design year	1998	2004	2008	2008	2009	2013
Hull material/shape	Cat/Steel	Monohull/Steel	Cat /GRP	Cat /GRP	Monohull/GRP	Monohull/Al
Passengers/crew	122	78+2	28+2	10+2	28+2	55 + 3
Length [m]	18.0	20.63	13.46/11.40	6	13.9/12,71	20/19.5
Beam max [m]	4,5	4.02	3.02/3.22	2.5	3.25	5.7
Height over waterline [m]	-	3.94	2.97	2,7-2,8	2,7	4.4
Hull height [m]	-	1,41	1,32			
Depth [m]	-	0.64	0.36		0.4	0,47
Displacement [dm ³]	33,3				7500	28000
Weight/Hull height	32.4			2500		?
Cross-section area over-water [m ²]		15.84	9.5	5.6	8.78	25.08
Cross-section area longitudinal [m ²]		36.35	26.4	9.1	31.65	56.63
Prop power [kW]	11	2 x 8	2 x 8	2 x 1	2 x 9.8	2 x 12 kW
Speed [km/h]	9.9	10	12	8-10	12	12-15
Battery	Yes	Yes	Yes	220 kWh	20, 48V/1000Ah	Yes
Autonomy min.	8-9	8-10	8h	8h	8h	
	Project [3]					Project
Curve no		Serie 2	Serie 3	Serie 4	Serie 5	Serie 5

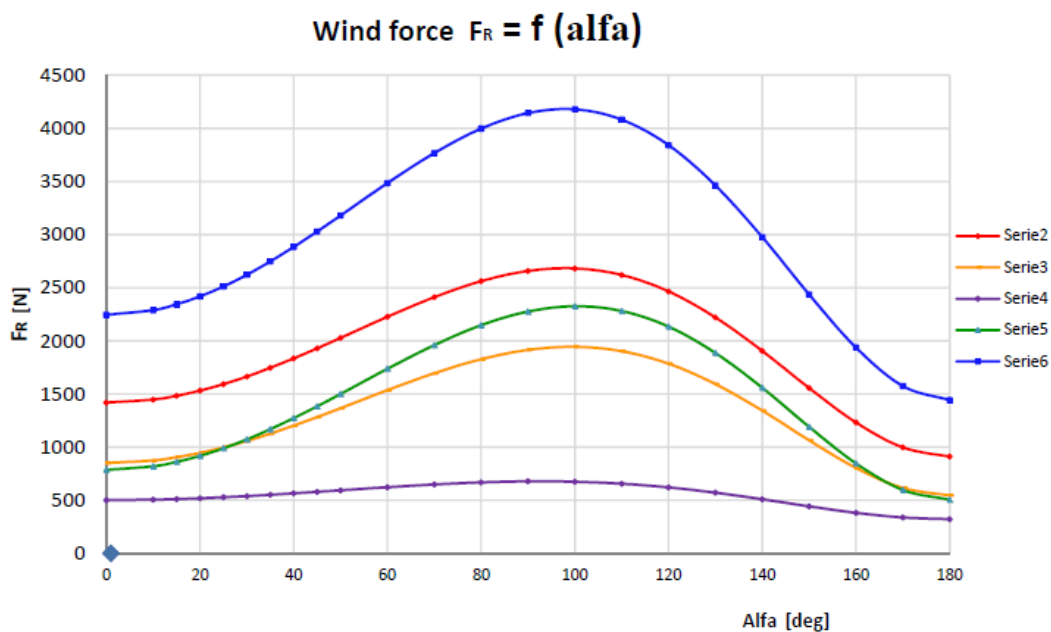


Fig. 5 a

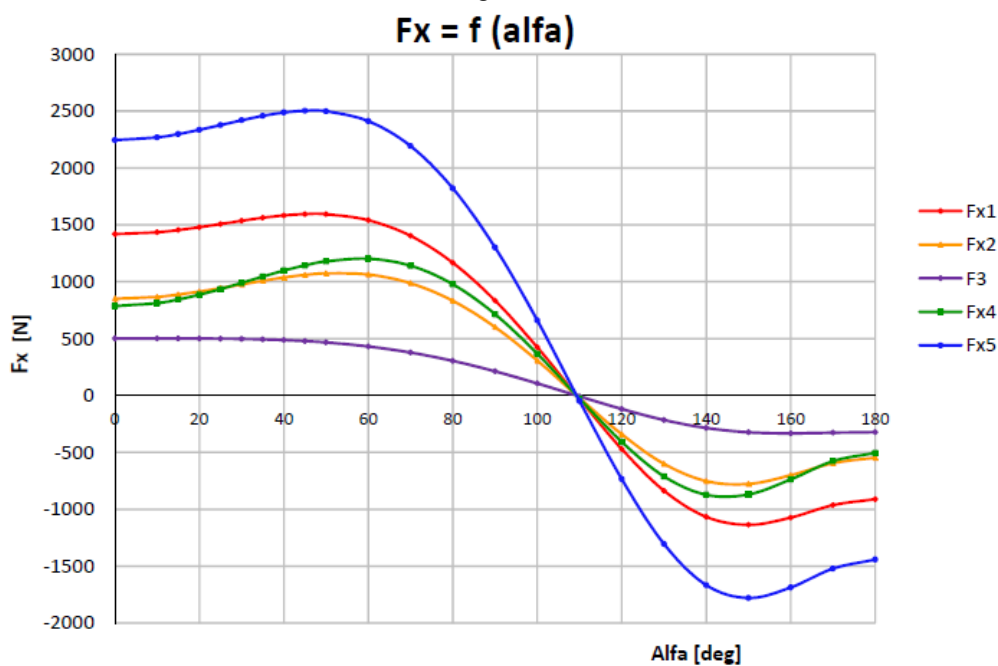


Fig. 5 Computation results of aerodynamic forces acting on the analyzed passenger ships for wind $5 \div 6^\circ B$ ($10 \div 12$ m/s) - Notation Area 2 – spatial wind speed has not been assumed. Fig 5a Total aerodynamic force acting on ship sailing in wind blowing from various directions. Fig 5b Wind resistance for wind blowing from bow. Marking: *Series 2/Ship A*; *Series 3/Ship B*; *Series 4/Ship C*; *Series 4/Ship D*; *Series 5/Ship E*

Risk of under-estimation of ship power requirements

Design calculations should be done bearing in mind all aspects related to the propulsion power requirements. In practice there are only draft calculations performed and analysis of hydrodynamic resistance assuming certain – roughly estimated efficiency or not taking into account all factors that have influence on resistance and propulsion system efficiency. An example of Solar Boat designed on Gdańsk University of Technology is rare example of complex design analysis that included also testing in model tank.

Solution to the problem of under-powered propulsion of small inland waterway crafts.

Class society acceptable solution to the problem of under estimation of power requirements could be proposed based on:

- Introduction of requirement to provide classification society with computation results for propulsion system to verify correctness of selection of prime mover. Data needed for verification could be minimal power for still water, minimal power for maximal environmental loads that are used by class as figures placed in all ship safety documents – Class certificate. Class society can verify if input data used for selection of propulsion power are satisfactory from rules point of view.
- Introduction of certain formulas into the rules for ship classification and construction. In this case the formulas should be based on naval architecture and experimental experience i.e. using agreed ITTC guidelines and formulas.

Additionally, we can summarize practical aspects of underpowered vessel to the following conclusions:

1. The ship smaller speed than value set by ship owner could have negative effect (i.e. financial) on project compliance with figures set as design data,
2. Achieved speed lower than 13 km/h could cause a problem with obtaining of EU inland waterways class certificate. Minimal speed required by Council Directive 82/714/EEC is forward speed. It is obvious that astern speed and in fact effective thrust will be smaller as well.
3. Worse manoeuvring characteristics measured during trials (normally to be done on still water) in fact will be worse when combined action of wind and waves will occur.

As the minimum speed for inland ships is a part of class requirements the non-compliance with that regulation is usually a reason for derogations. Real consequence of underpowered vessel may result in the necessity of replacement of specific machinery of components. Propulsion upgrade may include:

- installation of stronger motor as well as modification of propeller,
- installation of more efficient batteries.

In case of small craft with limited space and buoyancy, some of such activities may be a tough task. Change of whole drive may be very expensive and could pose number of additional modifications and will cost extra money, time and also loss of reputation.

Summary

1. Innovative ship design with electrical propulsion and new energy sources require more knowledge to perform design due to the fact that detailed computations or simulations ought to be conducted. There is no such requirements in the existing ship classification rules for inland waterway crafts. EU Directive 82/714/EEC do not have requirements for propulsion calculations and only minimal vessel speed is required to be checked by class or inspection bodies to allow Navigation Documents to be issued. It is recommended, to provide such data to the ship classification society for verification purposes on voluntary basis for all ships. Using the results of our study, such approach ought to be mandatory for passenger ships and ferries, especially of innovative design.
2. Taking into account the trend towards propulsion efficiency, the available knowledge and engineering tools approach should be formally included into Rules. Action to implement new requirements for checking vessels propulsion efficiency and energy conservation measures to obtain efficient propulsion shall be promoted. Having

requirements for manoeuvrability prediction or testing included into the requirements of EU Directive, the extra effort and related cost to perform such calculations for new ships can be neglected as minor. Now-days it is not complicated to conduct such quite complex calculations due to availability of software design tools and quite large amount of data for design analysis.

3. The proposed new requirements should be mandatory for all ferries or passenger ships with hybrid or pure electric electrical propulsion where batteries are used for storing energy for propulsion. Propulsion calculations (power, thrust requirements, energy consumption or conservation) with additional aerodynamic resistance calculations should be required for estimation of the ships manoeuvrability performance in extreme and possibly all operational conditions. Maximal values should be calculated and included into booklet for the use of ship master.
4. Elaboration of digital model of electrically propelled ship aerodynamic resistance during navigation could be further used for development of complex vessel energy conservation and management system for electrical battery powered surface craft or ship. The energy management system will be an essential part of ship propulsion control system allowing to compute and process data necessary for optimal navigation, operational planning and final decision taking either by ship crew or by automatic energy management system.
5. The presented findings of short study of underpowered propulsion system in small electric powered crafts is an example of identification of potential problems that may occur in case of omitting some environmental phenomena in design phase in case of innovative ship design. The problem is worth of further exploration using better selected resistance coefficients as well as real information describing ship structure and resistance/power data used for computations. The elaborated solution should be implemented into engineering guidelines.

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