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Trade-off between modularity and optimisation in the hydrodynamic design of high-speed electric ferries

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Abstract

The challenge of introducing "greener" alternatives to internal combustion engines in the maritime industry has led to the introduction of fully electric ships. However, serious challenges arise when a battery-driven vessel needs to operate at high speeds, due to the exponential increase in energy storage requirements and the corresponding battery weight. Hence, optimised hydrodynamic performance becomes the key design aspect. Meanwhile, modularity in the shipbuilding industry allows the production of systems using the same components and standard interfaces, which may be used in various applications, thus leading to potential cost reduction in design and production. Yet, hull form optimisation and modularity are sometimes two contradicting design approaches. H2020 European Union project "TrAM – Transport: Advanced and Modular" aims to introduce the benefits of modularisation in the design of battery-driven ships by implementing state-of-the-art "Industry 4.0" holistic ship design and production methods. In this paper, the trade-off between hull form optimisation and modularity is studied. Two design approaches –based on optimisation and modularity– are compared and their impact to the hydrodynamic performance of high-speed catamaran electric vessels is discussed.

Keywords: modular design; electric ship; battery-driven; industry 4.0; optimisation; hydrodynamics; high-speed catamaran

1. Introduction

Since the second industrial revolution, when mass production was introduced by Ford, modularisation has been promoting the use of standardised components and interfaces and is used for reducing the complexity of a system (Hounshell, 1985). Therefore, it differs from the practice of design optimisation, which promotes the production of systems consisting of special components and interfaces, designed and optimised for a specific use. One of the aims of the H2020 European Union project "TrAM – Transport: Advanced and Modular" is to develop cost effective design and production methods related to modular design concepts by utilising state-of-the-art "Industry 4.0" approaches (TrAM, 2018-2022). On the one hand, advanced design methods taking advantage of high performance computing and artificial intelligence, allow the development of detailed parametric modular designs that instantly provide essential information to the designer, such as weight per module and required energy storage capacity. On the other hand, smart manufacturing approaches support the production of modules that can be seamlessly combined to form the final product that reflects the owner's requirements. Hence, modularity offers the ability to design various system components in such a way that they are reusable across vessel types, thus leading to reduction in design and engineering hours, whilst versatility of the vessels is assured by verifying that a list of components and methods can be replaced after construction.

Although modular production methods have been widely applied in the automotive and aviation industries, there is still room for improvement in shipbuilding. However, the recent shift to "greener" technologies, such as the development of fully electric propulsion systems, perplex the further integration of the modular approach in ship design, where highly optimised vessels are now needed more than ever.

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In this study, the trade-off between modularity and optimisation regarding the hydrodynamic design of battery-driven catamaran ferries is analysed.

2. Background

2.1. Battery-driven ships

The maritime industry is being forced to reduce its emissions. International regulations are already in place, focusing on green industry practices, such as the reduction of sulphur percentage in fuel oil powered vessels to 0.5% or the introduction of indicators of the energy efficiency of each vessel, i.e. the Energy Efficiency Design Index (EEDI) (IMO, 2012). Koumentakos (2019) refers to the most recent developments in the evolution of alternative-fuelled ships. New technologies have been already applied in the other industries, such as the automotive. Battery-driven vehicles have been quite popular lately, providing a promising way of reducing greenhouse gas (GHG) emissions in land transportation (Himelic et al., 2011, Xiaoyi et al., 2019). The idea of introducing the same technology in shipping has become enticing in the recent years, with many countries opting for use of electric ships, especially in short sea shipping (Safety4Sea, 2018).

In TrAM, a modular all-electric high-speed ferry concept is being developed, with application cases covering the Norwegian fjords, the River Thames and the European inland water canals. Despite the benefits of reduced fuel consumption and decreased GHG emissions, design of battery-driven high-speed vessels is a convoluted process, with the minimisation of required power being the most significant challenge, due to the high weight-to-power ratio associated with batteries.

2.2. Modularisation in shipbuilding industry

Module is defined as a structurally independent building block of a larger system with well-defined interfaces (Holtta and Salonen, 2008). The design approach in which a system component acts as an independently operable unit, subject to periodic change is called modularity. Several parts within a ship system are already being developed and produced in a modular way. Main and auxiliary engine systems are available in certain models producing specific power output and defined by a standard set of dimensions. Wärtsilä has developed sales configuration principles and software, based on modularity (Sortland, 2001). Similar process has been followed by Rolls-Royce, which resulted in the increase of the range of possible product configurations available to customers, as well as in the reduction of the development time for new products (Andreassen, 2005). Batteries used in electrically driven ships are also available in modules with a predefined shape and size, while their density depends on the supplier. Based on the power requirements, modules are combined to form battery stacks able to cover the energy demands. Arora et al. (2018) underline the importance of modular design in battery packs for electric vehicles to reduce the manufacturing costs, while Wang et al. (2017) suggest that modular battery configurations can reduce the overall vehicle weight.

Bertram (1998) studied the producibility in ship design. He compared the effect of different shapes of hull surfaces on building and operational costs, while he suggested that the concurrent and interactive work between design and product engineers in the shipbuilding industry can lead to the establishment of unit breaks in ship design. These units can be fabricated as modules, which can reduce the total building costs. The location of these unit breaks can be critical to the cost reduction.

Developments have also taken place in the ship production phase regarding modularisation. World class shipyards have been exploiting build strategies which have led to considerable cost savings, construction quality improvement and extension and further development of ship design features. According to Deschamps (2008), these strategies are categorised in the following groups; (a) improved manufacturing and assembly methods, (b) improved procurement and material control, (c) improved business processes and (d) improved ship designs and engineering. Erikstad (2018) suggests that modularity is important not only for the supply chain design and production outsourcing, but also for the production and early outfitting and procurement packaging.

Apart from the newbuilding phase, modularity introduces flexibility in retrofitting applications. According to Schank et al. (2016), the US Navy considers modularity as one of the primary strategies for reducing time and cost of in-service vessels' modernisation. In addition, a decrease in the uncertainty associated with future operating scenarios can be achieved through the utilisation of replaceable mission modules in combat ships (Doerry, 2016).

2.3. Modularisation in ship design

The build strategies regarding improved ship designs and engineering, mainly involve integrated design and engineering systems, standardised, repeatable components and interim products and simplified ship and ship systems designs (Deschamps, 2008). A major challenge emerging in the development and integration of modular applications in ship design is the utilisation of parametric modelling methods on the definition of ship modules, as well as the coupling of parametric ship design with modularisation approaches. Modularisation techniques in ship design have already been applied in naval design, featuring various approaches and focusing on different steps of the process. For instance, a modular technical architecture, applied in naval design, involves the design steps presented in Table 1.

Table 1: Design steps for a modular technical architecture (Abbott, 2010)

1. Requirements analysis/acquisition plans	4. Zone allocation	7. Zone development
2. Technology market surveillance	5. Ship adjacency issues	8. Module station development
3. Functional partitioning/ship arrangements	6. System engineering trade-offs	9. Ship weight management

Different classification systems are available, on which the modularisation techniques can rely on. The ship's requirements are influenced by the SFI classification, use cases and scenarios. The SFI Group System is the most used classification system for the maritime and offshore industry worldwide (Manchinu and McConnell, 1977). It is an international standard, which provides a highly functional subdivision of technical and financial ship or rig information. SFI consists of a technical account structure covering nearly all aspects of ship/rig specification. Building on generic categories, such as hull, ship equipment, or machinery, it can be used as a basic standard for all systems in the shipping/offshore industry. The current functional SFI coding is an ideal basis and starting point for the early system models used to derive the modularisation methods.

3. Methodology

3.1. Parametric ship design

Parametric modelling offers increased flexibility in ship design. Depending on the level of parameterisation, a design can be partially or fully parametric. The definition of points, curves and surfaces using CAD software in a parametric way increases the efficiency in creating design variants, contrary to traditional modelling, which involves the manual definition of a single geometry. In partially parametric modelling, an existing shape is used as baseline geometry and specific elements are defined by parameters which affect the overall shape. For instance, shift transformation (point movements by a specified amount in the principle directions of a chosen coordinate system) or morphing (interpolation between two or more baseline geometries) techniques can be applied to an initial design, resulting in small changes which reflect the requirements set by the designer regarding the final shape. In a fully parametric design, the entire geometry is determined by parameters.

Essentially, a parametric model can be regarded as a system which takes as input a set of parameters and produces a specific shape. Design cases which involve flow-related objects, such as ship hulls or propellers, contain information that can be described in two distinct directions (Harries et al., 2015).

Parameterisation also allows the development of modules that can be adapted to the overall ship design. A common group of main parameters, such as those related to the main particulars of a ship, controls the connection of different modules (e.g. stern module connection with the rest of the hull form), while individual groups of parameters can affect the shape of each module.

3.2. Challenges related to parametric ship modules

Considering the state-of-the-art developments in ship design, effort is made in TrAM to combine the modern design methods, involving parametric Computer Aided Design (CAD) modelling, with modular approaches. Yet, several restrictions can be identified when creating a modular parametric ship model. These restrictions are mostly related to geometrical or operational constraints. In addition, restrictions may originate from the methods used in the development of the parametric ship design.

Nevertheless, they need to be addressed to understand how their effects on the application of modular design in parametric modelling. Below, each type of restriction is described in more detail.

3.3. Geometry constraints

The overall hull shape governs the applicability of modular design methods. Different ship types require different hull forms depending on their operational characteristics. In the present study the hull of a high-speed catamaran ferry is examined. Catamaran hull forms are characterised by slender designs, able to operate in high speeds. Contrary to large merchant vessels, whose hull shape remains constant for nearly half their length, catamaran passenger ships feature hulls whose shape changes constantly along the length of the vessel. Therefore, the introduction of longitudinal repetitive hull modules becomes challenging.

The flexibility of incorporating hull modules becomes smaller when the different propulsion systems are investigated in the design process. The aft part of the hull highly depends on the selected propulsion system. Use of propellers or waterjets greatly affects the shape of the stern and consequently the definition of a single module for the aft section of catamaran hulls. When batteries are considered for the development of an all-electric catamaran ferry, additional constraints emerge. The location of the batteries on-board can potentially affect the hull shape, as minimum dimensions are required at specific hull parts, such as the demihull breadth or the length of the battery compartment.

3.4. Operational restrictions

Different operational profiles associated with each design impose restrictions related to the definition of parametric ship modules. Depending on the profile, a ship may need to operate in open or inland waters. The structural or operational rules applied to each case may be different. Furthermore, a vessel may need to transport passengers, cargo or a combination of those. These differences in the operational profiles affect the design and, consequently, the definition of parametric ship modules. In addition, variations in the main dimensions result from the different areas of operation. For instance, a design may be affected by bridges, thus creating a restriction for the maximum allowed air draught. Local regulations set the baseline regarding the maximum allowed produced wave wash by boats cruising within specific areas. Moreover, low sea depth of inland waters, compared to open waters leads to a restriction regarding the maximum operational draught.

Different operational speeds affect the selection of the propulsion systems, which in turn affect the hull form and engine modules to be used. These parameters need to be considered in the design phase and constraints are therefore applied on the definition of parametric ship modules.

In general, use of modular parts for the hull definition could potentially be associated with main dimension variations based on fixed increments. The lack of free adjustment of specific dimensions in the hull form does not allow the production of a hull with an optimal performance (e.g. lowest resistance, energy consumption, battery requirements). This becomes an extremely important issue in the case of battery-driven vessels, where the energy requirements should be minimised to keep the required battery capacity as low as possible. High-speed catamaran designs are typically associated with low displacement values; high energy demands lead to high battery capacity requirements and, consequently, increased displacement.

3.5. Methodology constraints

The extent to which parameters are used in parametric ship modelling varies among different design methods. In modern methodologies, such as the state-of-the-art holistic design approach (HOLISHIP, 2016-2020, Papanikolaou, 2010), a wide range of computations are integrated in a single process, utilising a variety of software tools. The design procedure involves all the required calculations for the weight, resistance and powering estimation, as well as the structural design. Use of parameters allows the definition of these computations parametrically, thus enabling the evaluation of multiple design variants.

The definition of a single parametric ship model involving all the necessary calculations generates restrictions in the definition of ship modules. The weight estimation may be based on different approaches. For instance, the lightweight may be divided into three main weight groups; the steel weight, outfit weight and machinery weight. A different approach which works better with the modularisation concept is the application of the SFI group system. This classification system includes predefined categories for the weight break down (Table 2).

Therefore, the definition of the parametric ship modules should adhere to the classification system used for the weight estimation. The weight per module needs to be known and incorporated in the method to create a seamless design process which can be the base for a design optimisation study. This constraint affects both the hull and superstructure of a vessel.

Similarly, the structural design of the ship follows specific international rules regulations. Therefore, the type of components and their location in the ship structure are confined by regulations. In addition, the design of the ship structure is closely connected with the production process adopted by the shipyard. The extent and application of the modularity need to be the same in both cases to benefit from the advantages such an approach has to offer (i.e. design and production costs). For instance, solutions involving stretching of specific hull parts, may contradict with the modular production methods which are based on the fabrication of set modules. The former practice would require a change in the shape of the latter production modules, diminishing the overall benefits of modularisation.

Table 2: SFI system ship weight groups

Group number	System
100	General
200	Hull systems
300	Cargo equipment
400	Ship equipment
500	Crew and passenger equipment
600	Machinery main components
700	Systems for machinery main components
800	Common systems

4. Case study: parametric modular high-speed battery-driven catamaran ferry design

Taking into account the parametric ship module constraints outlined in the previous paragraphs, a parametric modular hull design is developed for a high-speed battery-driven catamaran ferry. Several design variants are produced and their calm water resistance is calculated and compared with the response of a similar, optimised hull form.

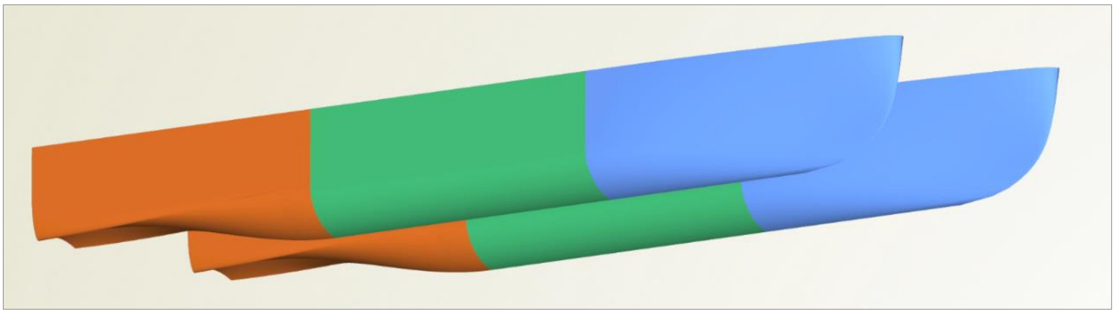

Fig. 1. Parametric modular catamaran hull model.

4.1. Definition of parametric modular hull form design

The developed parametric modular hull model is defined in CAESES® CAD/CAE software and consists of three independent modules; the aft, mid and fore (Figure 1). Different versions are designed for the aft and fore modules, which can be selected based on the overall design. For instance, two versions are developed for the aft module; one suitable for a vessel which has waterjets installed and one for a vessel that is fitted with propellers (Figure 2). Similarly, two versions are developed for the fore module, which have different stem profile and shape (Figure 3). Both the aft and the fore module can be scaled along the longitudinal x-axis.

As far as the mid module is concerned, it can be defined in two ways; as a set of repetitive sections of defined length, or as a continuous single module.

The definition of the hull as a combination of the previously described modules takes place in CAESES® using an automated process (known as "feature" within the software). The user selects which type of modules are required for the vessel being designed, provides the values of the parameters controlling the main particulars of the vessel and the hull surface is created automatically in the software (Figure 4).

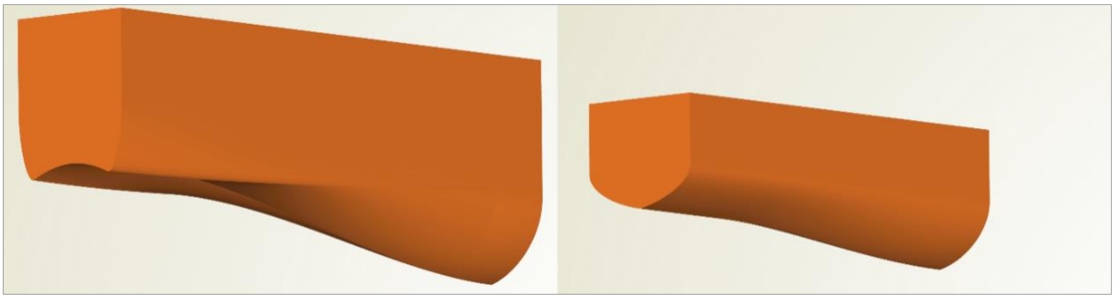

Fig. 2. Stern modules.

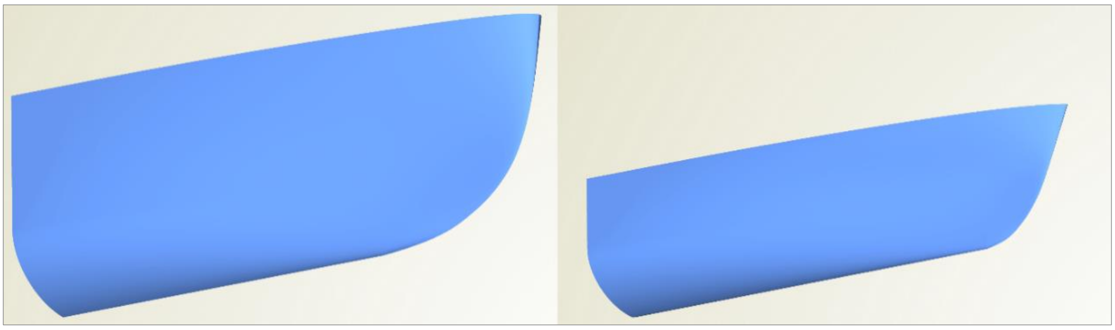

Fig. 3. Stem modules.

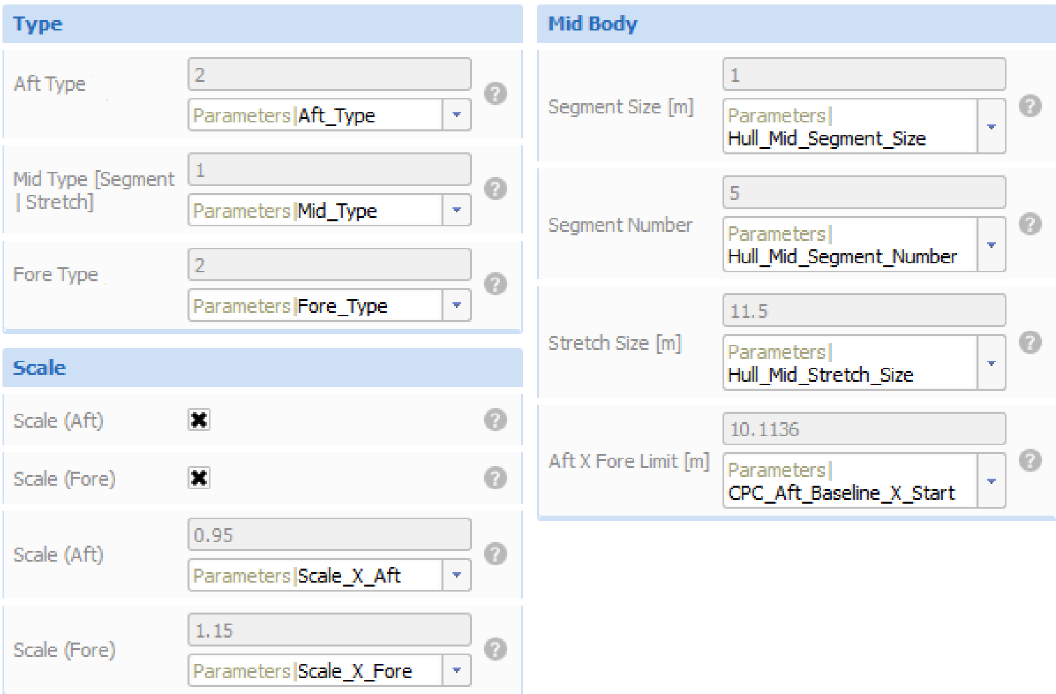

Fig. 4. CAESES® feature for parametric modular hull definition.

A preliminary lightship breakdown for the parametric modular design according to the SFI system is shown in Figure 5. The breakdown is based on confidential data from a shipyard constructing high-speed catamaran vessels. The main contributors to the overall lightweight are the 100, 500 and 800 weight groups, which are related to the structural weight, the outfitting and the common systems, respectively. The latter includes the battery systems, hence the relatively large contribution in the lightship. This confirms the high impact of energy storage capacity in the design of electric ships and underlines the importance of the hydrodynamic performance in the development of such vessels.

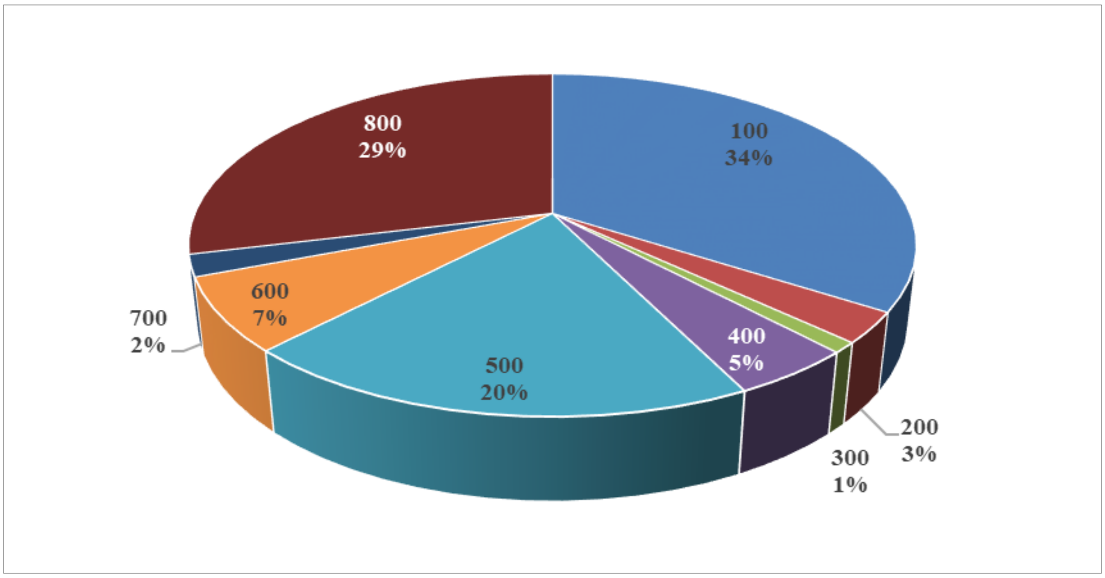

Fig. 5. Lightship breakdown for the parametric modular design, according to the SFI system.

4.2. Calm water resistance calculation

The method used for the calculation of the calm water resistance for the modular hull forms is the slender body method. The slender body method, based on the work of Tuck et al. (1999) and Couser (1996) is available in Maxsurf® Resistance. This method uses a Michell (1898) based approach to compute the wave resistance of a port/starboard symmetrical monohull. This method may be applied to many different hull forms, including multihulls. However, the individual hulls should be slender and should be symmetrical about their local centreline. Planing forces are neglected in the slender body method which limits speed range applicability for this method. In general, sensible results can be obtained for a wide range of mono- and multihull vessels operating at normal Froude numbers.

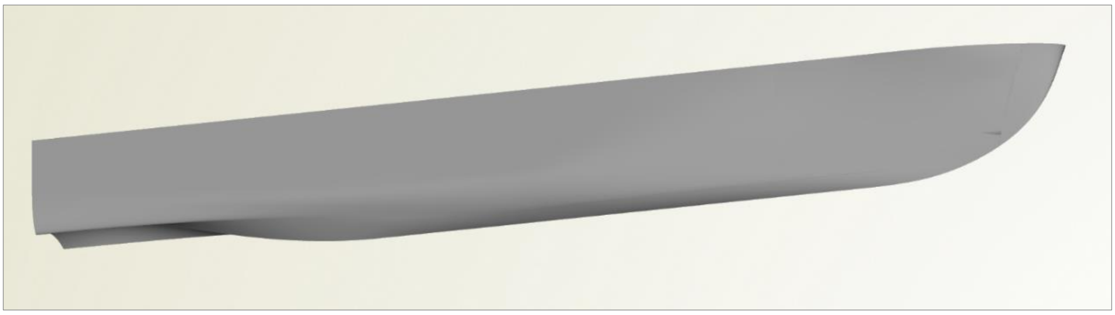

Fig. 6. Optimised vessel (catamaran demihull).

This analytical method computes the energy in the free surface wave pattern generated by the vessel and hence the wave resistance of the vessel. The viscous resistance component is found using the ITTC ’57 friction coefficient calculation method and the specified form factor. The sum of the two resistance components (wave and viscous) provides the final result.

Table 3: Main particulars of the optimised design

Description	Value
Displacement (c.m.)	80
Length overall (m)	30.60
Length waterline (m)	29.32
Breadth overall (m)	9.00
Breadth demihull (m)	2.44
Depth (m)	3.45
Draught (m)	1.26
Service speed (Knots)	23

Table 4: Design variables

Design variable	Min. value	Max. value
Breadth demihull (m)	2.00	2.60
Draught (m)	1.20	1.60
Mid module stretch size (m)	5.00	15.00
Longitudinal scale of aft module (-)	0.75	1.25
Longitudinal scale of fore module (-)	0.75	1.25
Deadrise (deg)	10	20

Table 5: Design constraints

Parameter	Constraint (min.)	Constraint (max.)
Displacement (c.m.)	75	85
Length overall (m)	30.1	31.1

4.3. Comparative study

For the comparative study an optimised high-speed electric catamaran vessel is used as the reference point (Figure 6). This design is the result of a multi-objective design optimisation, taking into account the calm water resistance response of a catamaran hull at various displacements and speeds. In particular, NSGA2 (Non-dominated Sorting Genetic Algorithm 2) was used to optimise a parametric catamaran design. The design variables included the waterline length, demihull breadth and design draught of the vessel. The objective was to minimise the calm water resistance at three different speeds and displacements. The different operational profiles were combined into a single objective function using the weighted sum technique (Sen & Young, 1998). The main particulars of the optimised design are shown in Table 3.

Based on the optimised design, a modular parametric model is developed (Figure 1) and a design of experiment (DoE) is conducted for the modular design. 5000 designs are produced using the Sobol algorithm (Azmin and Stobart, 2015). The design variables of the DoE are shown in Table 4. The overall breadth is kept constant and equal to 9 metres. On the other hand, the breadth of each demihull is variable, therefore, the distance between the demihulls is calculated based on the overall and the demihull breadth values. Similar procedure was followed in the design process of the optimised catamaran hull shown in Figure 6. Two design constraints are enforced to ensure that the valid modular designs are similar to the optimised hull. The displacement at design draught should be between 75 and 85 cubic metres, whereas the overall length should be between 30.1 and 31.1 metres (Table 5).

Following the DoE, 66 valid designs are produced and tested to calculate their calm water resistance using the slender body method described in paragraph 2.2. Calculations are performed for speeds ranging between 0 and 30 Knots. The form factor is calculated according to Molland et al. (2011). In addition, the wake height at various planes parallel to the centreline is calculated for the service speed, which is equal to 23 Knots.

5. Discussion of results

The results of the comparative study are presented in this section. Indicative data showing the average design variable and constraint values of the valid modular designs are shown in Table 6. The number of the valid designs produced during the DoE phase is 66, despite the overall population of 5000 variants. The high percentage of violated designs is related to the hard constraints regarding the displacement and the overall length. Nevertheless, the valid designs cover the design space adequately and prove sufficient for the purpose of the study which investigates the hydrodynamic performance of modular designs.

In Figure 7 the calm water resistance curves for the 66 valid designs, as well as the optimised vessel, are presented. In general, the response of the modular designs is similar to the one of the optimised hull, indicating an average percentage difference of 13% between the modular and the optimised versions. As far as the resistance at the service speed (23 Knots) is concerned, the response of the modular designs varies between 42 and 49 KN, with an average value of 45.2 KN and a standard deviation of 1.4 KN. The optimised vessel was tested using the same calculation method and the result of 45.9 KN was obtained (Figure 8).

One modular design is selected among the valid ones, matching the displacement of the optimised vessel, named Des1463. Information about this design is found in Table 7. Its calm water resistance response at 23 Knots is 44.2 KN, 3.7% lower than the optimised vessel.

Table 6: Valid designs information

Parameter	Average value
Breadth demihull (m)	2.19
Draught (m)	1.27
Mid module stretch size (m)	9.14
Longitudinal scale of aft module (-)	1.03
Longitudinal scale of fore module (-)	1.03
Deadrise (deg)	15.26
Displacement (c.m.)	80
Length overall (m)	30.5

Table 7: Des1463 information

Parameter	Des1463 value
Breadth demihull (m)	2.09
Draught (m)	1.26
Mid module stretch size (m)	11.57
Longitudinal scale of aft module (-)	0.91
Longitudinal scale of fore module (-)	0.91
Deadrise (deg)	19.00

Table 8: Wake height

Design	Displacement (c.m.)	Calm water resistance (KN)	Max. wake height at Y = 0.5L (m)
Optimised	80	45.9	0.389
Des1463	80	44.2	0.357
Des0149	84	48.8	0.412
Des3215	75	42.3	0.354

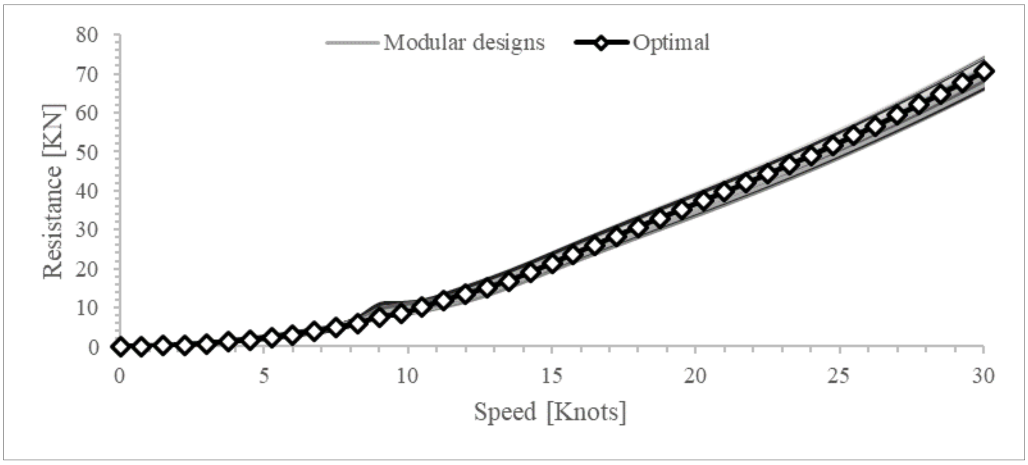

Fig. 7. Calm water resistance curves.

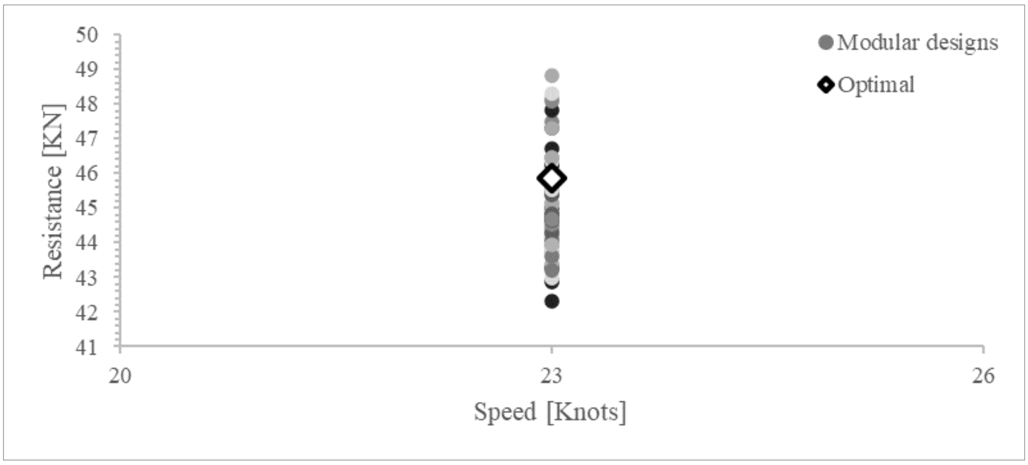

Fig. 8. Calm water resistance at 23 Knots

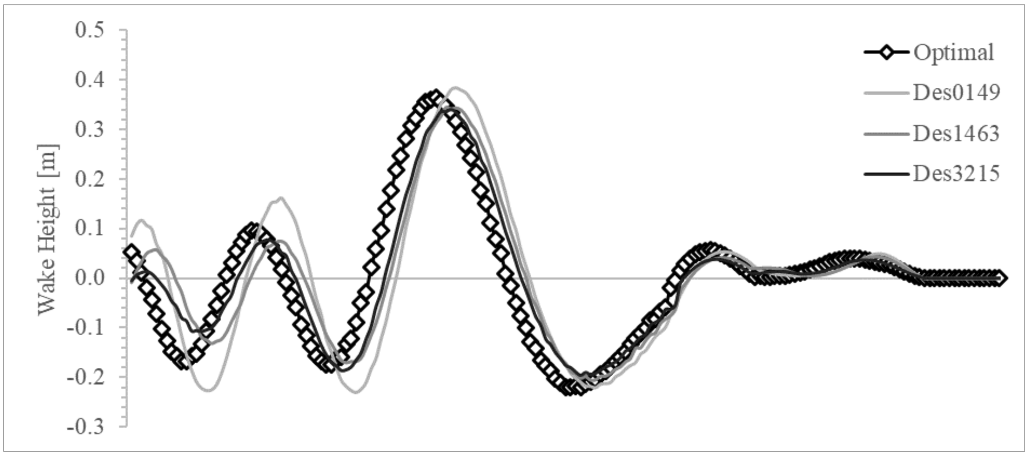

Fig. 9. Wake height at 23 Knots at Y = 0.5L (m).

The wake height at the service speed (23 Knots) is calculated for the optimised vessel and three modular designs which cover the examined displacement range and the results are presented in Figure 9 and Table 8. Des0149, which features the highest displacement and resistance, marks the highest wake height at 0.412m, followed by the optimised design, which marks a maximum wave height of 0.389m.

On the other hand, Des1463 and Des3215 achieve similar maximum wave heights at 0.357m and 0.354m respectively. However, all four designs create a similar wave pattern at the presented longitudinal plane overall.

Finally, a wake field comparison between the optimised design and Des1463 is presented in Figure 10. The area directly behind the transom is reserved for a “virtual appendage”, used to account for the immersed transom. This method has been found to give good results for catamaran forms with transom sterns (Couser, 1996). The virtual appendage is not included in the wetted surface area calculation. It is only used to artificially close off the numerical model to calculate the wave resistance.

The overall wave height values for Des1463 range between -0.409m and 0.357m, while for the optimised design values range between -0.437m and 0.389m. In general, no major differences are spotted between the two wake fields, however, the one corresponding to the optimised hull is overall smoother than that of Des1463. In particular, the optimised design features a milder wave pattern close to the centreline, while the wake produced near the bow is lower than that of Des1463.

6. Conclusions

In this paper, a study was carried out to investigate the application of modular concepts in the design of a high-speed electric catamaran vessel. Following the analysis of the restrictions associated with the implementation of such methods in parametric ship design, a parametric modular design of a catamaran hull was developed and multiple design variants were tested to estimate their calm water resistance using the slender body method. Their response was compared with an optimised catamaran hull to identify the potential losses in performance over the aforementioned benefits of modularisation. Overall, the results suggest a similar response between the two design approaches with respect to the examined performance indicators. A modular and an optimised catamaran design with identical displacement values have a similar hydrodynamic performance, as far as the calm water resistance is concerned. In addition, the maximum wake height at their service speed (23 Knots) is comparable.

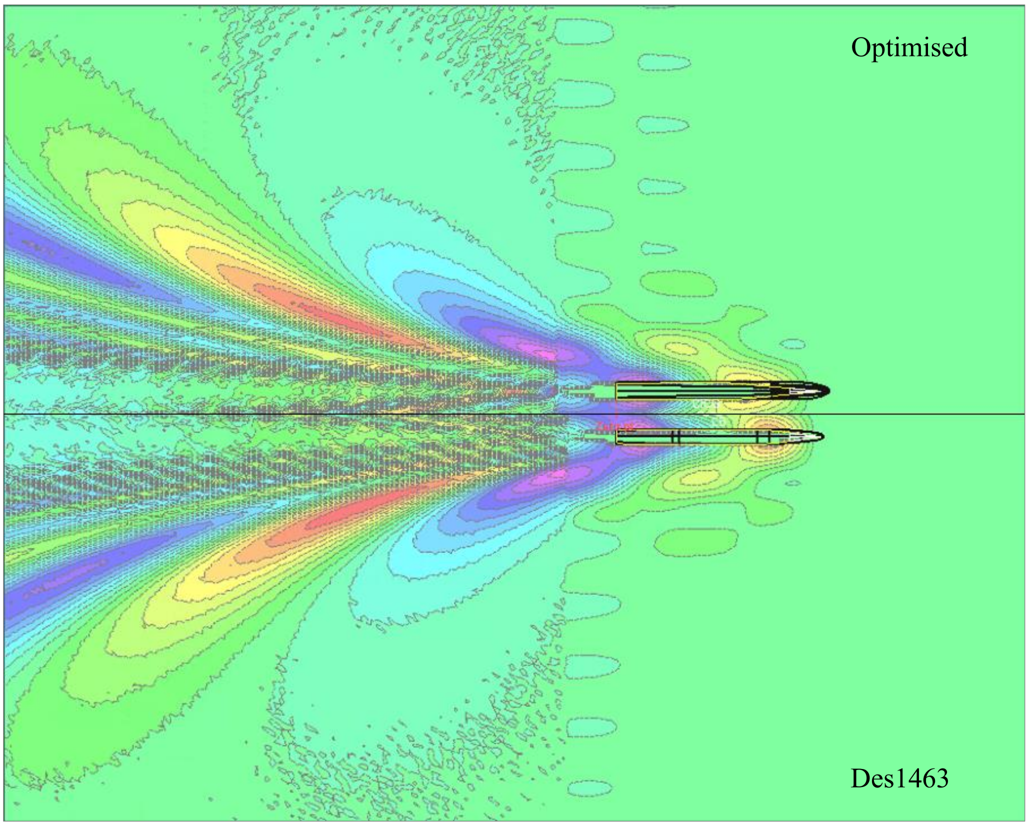

Fig. 10. Wake field comparison between optimised hull (top) and Des1463 (bottom) at 23 Knots.

Yet, it is worth mentioning that the analysis was performed for a specific operational profile (displacement, service speed). The optimised hull form used is the result of a multi-objective optimisation study, which involved several displacement and speed values as part of the evaluation process. Therefore, a single-objective optimisation study, focused on a specific displacement and service speed combination, could potentially produce an optimised design, which performs better than the modular designs demonstrated in this paper.

The results of the study indicate that modular hull forms can potentially achieve similar performance with optimised hulls, which are designed for one specific operational profile, provided that the individual modules are optimised. The cost and effort associated with the design process of a modular design can be mitigated by the broad use of the initial development in various cases utilising the same hull form type. Capital cost for high-speed ferries, similar sized to the investigated vessels of this study, account for roughly 4% of the total ownership cost, including operational costs for the ship's entire lifecycle. However, repair and maintenance costs, accounting for 10% of the total ownership cost, are anticipated to be reduced if modular design is adopted (Schank et al., 2016). Such practices have already been applied to other industries, such as the automotive and the aviation industry. On the other hand, the effort spent to develop a design, which is optimised for a specific purpose, cannot be transferred to further applications.

However, recent developments in the ship design industry have introduced advantages similar to the ones deriving from the application of modularisation. Fully parametric ship designs allow the development of several design variants based on a parent design, which could potentially correspond to different operational profiles. The traditional ship design process has evolved though such practices and more recent design tools and methodologies (Harries et al., 2015, Papanikolaou, 2010) have introduced a more flexible approach to ship design. The combination of parametric design and modularisation could potentially increase the flexibility and result in lower development costs.

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