Hydrodynamic optimisation of a zero-emission fast catamaran

RESEARCH PROJECT A current study conducted by the Hamburg Ship Model Basin (HSVA) focuses on the hydrodynamic hull form optimisation of a zero-emission, battery-driven, fast catamaran. Part of the Horizon 2020 European Research project "TrAM – Transport: Advanced and Modular", the aim of the project is to demonstrate that electrically powered ferries can be fast and competitive in terms of service, environmental impact and life-cycle cost, write HSVA's Apostolos Papanikolaou and Yan Xing-Kaeding.

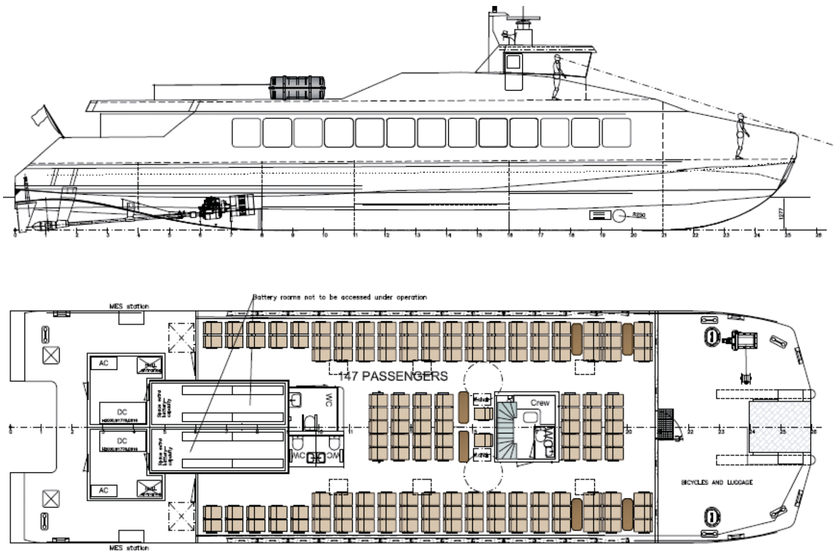

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Figure 1: Preliminary general arrangement of the Stavanger demonstrator

In a project relating to the hydrodynamic optimisation of a zero-emission fast catamaran conducted by Germany's Hamburg Ship Model Basin (HSVA), a two-stage optimisation procedure has been implemented. In the first stage (global optimisation), the optimum combination of the vessel's main dimensions are to be identified. In a later second stage (local optimisation) the optimal ship hull form, minimising the required propulsion power for the set operational specifications and design constraints, will be determined. Numerical results of speed-power performance for a prototype catamaran, intended for operation in the Stavanger area of Norway, were verified by model experiments at HSVA, proving the feasibility of this innovative, zero-emission urban transport concept.

The project is conducted within the framework of the Horizon 2020 European Research project "TrAM – Transport: Advanced and Modular", which is a joint effort of 13 stakeholders of the European maritime industry [9]. The aim of this project is to develop zero-emission, fast passenger vessels through advanced modular production, with the main focus on electrically powered vessels operating in coastal areas and inland waterways. The project is innovative for the introduction of zero-emission technology and design and manufacturing, while it should prove that electric-powered vessels can be fast and competitive in terms of service, environmental impact and life-cycle cost.

Intensive research was carried out on the hydrodynamic optimisation of a battery-driven catamaran's hull form, in order to minimise power requirements and energy consumption, while introducing new propulsion and hull systems suitable for electrically-driven fast vessels. It should be noted that hydrodynamic (and structural design) optimisation is imperative for fast vessels and even more so for battery-driven vessels with limited range. A demonstrator of the catamaran concept will be built and start operations on a multi-stop commuter route in the Stavanger area before the end of the project in 2022.

Hydrodynamic optimisation

A preliminary general arrangement of the Stavanger demonstrator vessel (Figure 1) was elaborated by Fjellstrand AS, the shipyard participating in TrAM, where the physical demonstrator will be built. The external dimensions of the vessel providing the required passenger transport capacity were set equal to 31.0m for overall length and 9.0m for the beam. The vessel has to have capacity for 147 passengers with a service speed of about 23 knots, depending on loading condition and fitted e-motors.

Parametric hull model

Based on a preliminary lines plan of a reference vessel, a parametric model for the demihulls of the Stavanger demonstrator was developed by use of the CAESES® software platform [1]. The model offers the designer the possibility to control/specify the main particulars of the demihull along with the hull form details within a reasonable range of variation in the variables, while at the same time ensuring adequate quality (fairness) of the hull. The designer can explore the huge design space of automatically generated hull forms and decide

L_{WL}	Waterline length
HB_{DES}	Demihull's half beam
T_{INIT}	Draught
$CHINEY_{ATS0}$	Transom width

Table 1: Main optimisation variables of hull geometry

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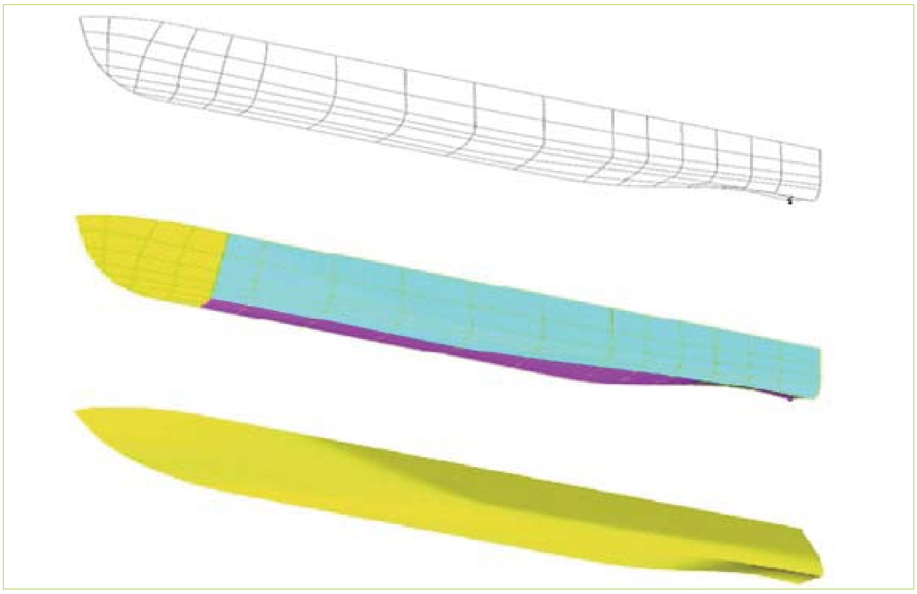

Figure 2 (from the top): Definition grid (a), resulting surfaces (b) and final demihull after Lackenby transformation (c)

on the most favourable ones on the basis of rational, holistic criteria [7].

A set of 20 design variables was first specified, defining the main dimensions, as well as local hull form details, such as the width, immersion and shape of transom, and the shape of the bow area of the vessel. From the set of 20 design parameters, the four most important referring to the catamaran's main dimensions and transom width were selected as design variables during the first round optimisation studies (Table 1). The overall beam of the catamaran was kept constant due to design/construction reasons (yard's specification of deck superstructure module).

Although increasing the separation distance of the demihulls would lead to lower wave resistance, the increase in lightweight and production cost is expected to outweigh this benefit. It is also noted that the vessel's operational Froude number will be close to 0.70 and therefore far beyond the last hump of wave resistance. Thus, viscous resistance will be dominant at the catamaran's service speed. For the definition of the stern region where a tunnelled form is fitted, the most important parameters are the transom height at centreline and the height difference from centreline to chine at transom.

Based on the specified values of the main optimisation variables and the default values for the remaining design parameters, a grid of parametrically defined curves was created in CAESES® (Figure 2a), which is the basis for the generation of a set of meta-surfaces (Figure 2b) and eventually leads to the final demihull hull form using Lackenby's transformation, through which the hull form's displacement volume and its longitudinal centroid can be adjusted to the desired values (Figure 2c).

If the battery racks are to be placed inside the demihulls, there must be sufficient space for installation and maintenance. Therefore the dimensions of the corresponding compartments need to be checked against the specified requirements.

The hydrodynamic assessment of each design alternative is based on HSVA's in-house tools, i.e., the panel code for wave resistance υ-SHALLO [3] and the RANSE code FreSCo+ for total resistance and the refined local flow simulations at the catamaran's transom [4]. Since these tools require considerable computing resources, it was decided to explore the possibility provided by CAESES® to pre-compute data for later usage. To this end, a series of so-called Design of Experiments (DoE) has been carried out, to obtain a large number of alternative hull forms which were then analysed by HSVA with the above-mentioned CFD tools.

Based on the pre-computed data, surrogate models can be developed, enabling the sufficiently accurate estimation of the quantities of interest during the optimisation study in practically zero time (in our case, the calm water resistance of each design variant at various displacements and service speeds [5]). Apart from significantly reducing the calculation time, surrogate models increase the robustness of the whole process by avoiding the need for remote computing.

Global optimisation studies

A global optimisation study was first performed in order to identify the best combination of selected design variables for the Stavanger demonstrator. The range of variation of the design variables was as follows: length at waterline, from 29.0m to 30.2m, halfbeam of demihull, from 1.0m to 1.3m, initial draught, from 1.2m to 1.6m and transom width at chine, from 0.8 to 0.85 (non-dimensional). The objective of the study was to minimise the calm water resistance of the bare hull in a range of displacements and speeds, which mostly represent the operational profile of the Stavanger demonstrator.

Therefore, it was decided to evaluate the calm water resistance of each design alternative at 21 knots, 23 knots and 25 knots and at three displacements Δ1, Δ2 and Δ3 are based on the results, to evaluate a weighted average of the calm water resistance. A set of constraints was also applied, in order to verify that each feasible design alternative had sufficient space for the installation of the battery racks and the fitting of large diameter propellers. The optimisation study was carried out by employing the NSGAII algorithm [8], already integrated in the CAESES® environment.

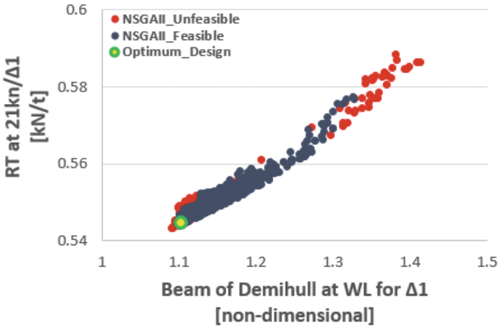

Figure 3: Calm water resistance per displacement tonne against non-dimensional beam at WL, 21 knots, displacement Δ1

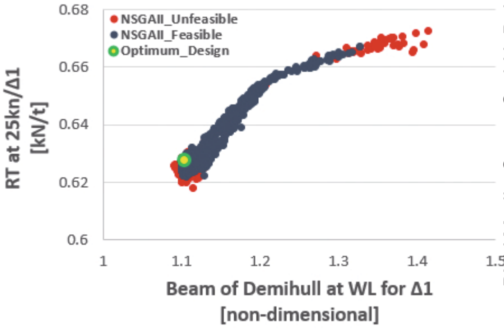

Figure 4: Calm water resistance per displacement tonne against non-dimensional beam at WL, 25 knots, displacement Δ1

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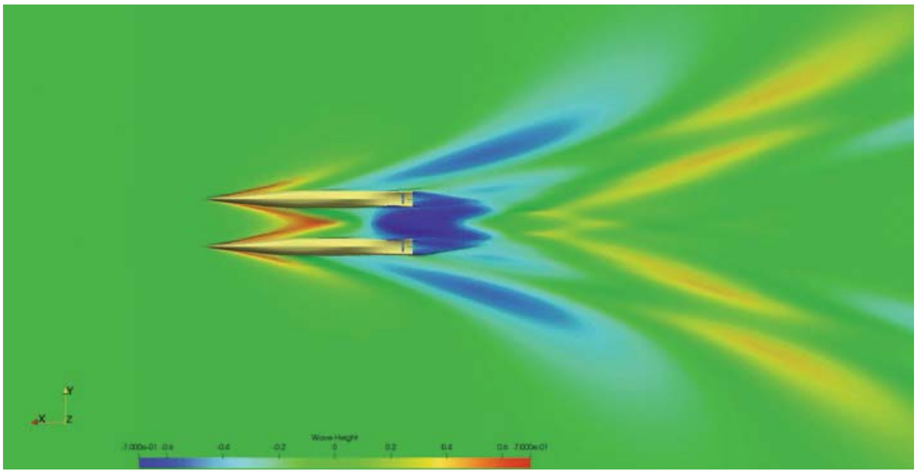

Figure 5: Free surface deformation at 23 knots

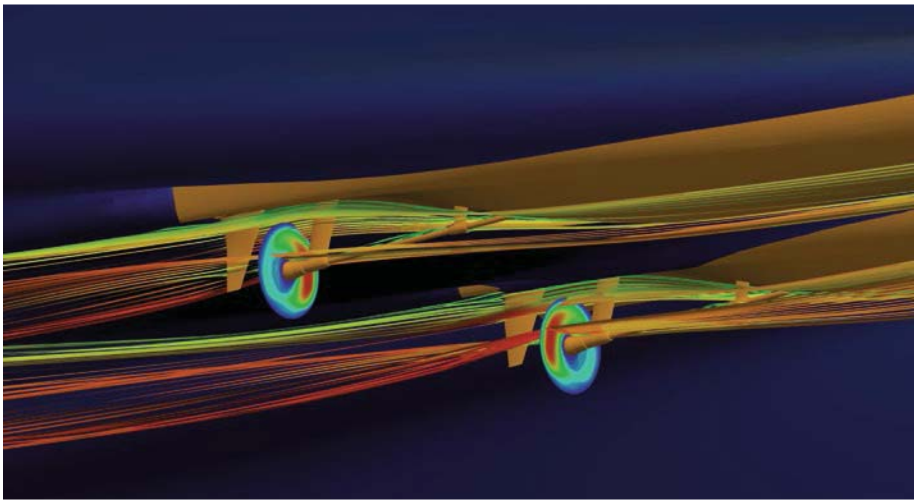

Figure 6: Streamlines through propeller disc and propeller body force distribution at 23 knots

In figures 3 and 4, some representative results of the global optimisation study are illustrated. Out of 1,000 designs, 824 were feasible, whereas 176 violated at least one of the constraints [6]. The optimum design is marked with a green circle. Based on the results, the overall optimum design has a very slender hullform with a length at waterline length close to the maximum, a beam close to the minimum and increased draught.

Local optimisation studies

With the best hull form resulting from the global optimisation, the study continued with more focus on the optimisation of the stern region aiming at high propulsive efficiency. While global optimisation had been based on calm water resistance and issues including simplicity of hull construction and outfitting/maintenance of the main equipment, the local hull form optimisation focused on the propeller tunnel area. This part of the hull form was mathematically captured by six local form parameters. A further five parameters relating to the propeller characteristics were introduced, such as diameter, position and shaft inclination.

The Dakota Optimisation Toolkit of Sandia National Laboratories disposed in CAESES® was used. This toolkit allows comprehensive exploration of the multi-parametric design space using proper sampling methods, such as Latin hypercube sampling, orthogonal arrays, and Box-Behnken designs. In total, nine design constraints were eventually specified, mainly for reasons of seamless fitting of the propeller, its shaft and brackets.

Generated designs were evaluated by use of HSVA's RANS-QCM coupled method [10], in which the RANSE code FreSCo+ and the propeller panel code QCM [2] are coupled through the actuator disk method at an iterative basis to evaluate the hydrodynamic performance at self-propulsion condition. In this procedure, the free surface, free sinkage and trim of the catamaran are considered as well. The numerical mesh applied had around 5.3 million cells in total, including a refinement around the free surface region and the propeller/ship transom stern region.

The identified best design with respect to the required power was further fine-tuned to minimise the risk of air suction in the propeller tunnel. For the selection of the best hull form, a range of displacements and speeds were evaluated to assess the performance of the hull variants at various off-design conditions. Figure 5 shows the computed wave field of the best hull form at a design speed of 23 knots viewed from the bottom. The propeller is simulated via a body force method, where the three-dimensional blade forces coming from the panel code QCM (RANS-BEM coupling) are incorporated, as can be observed in Figure 6.

Experimental verification: tested model and CFD validation

Numerical CFD simulations for the optimised hull form of the Stavanger demonstrator were verified by calm water resistance and self-propulsion tests at HSVA's large towing tank, enabling a firm prediction of the speed-power performance of the full-scale ship under trial conditions. The 5.34m-long catamaran (scale 1:5.6) was fully equipped with propellers, shafts, brackets and rudders, as well as with openings for bow thrusters. An aft view of the fully equipped model is shown in figure 7 and 8.

The conducted, systematic resistance and self-propulsion tests for various speeds, displacements and trims confirmed the numerical CFD predictions. A typical comparative speed-power diagram, with the delivered power scaled with the catamaran's displacement, is shown in Figure 9.

Figure 7: View of the tested Stavanger model

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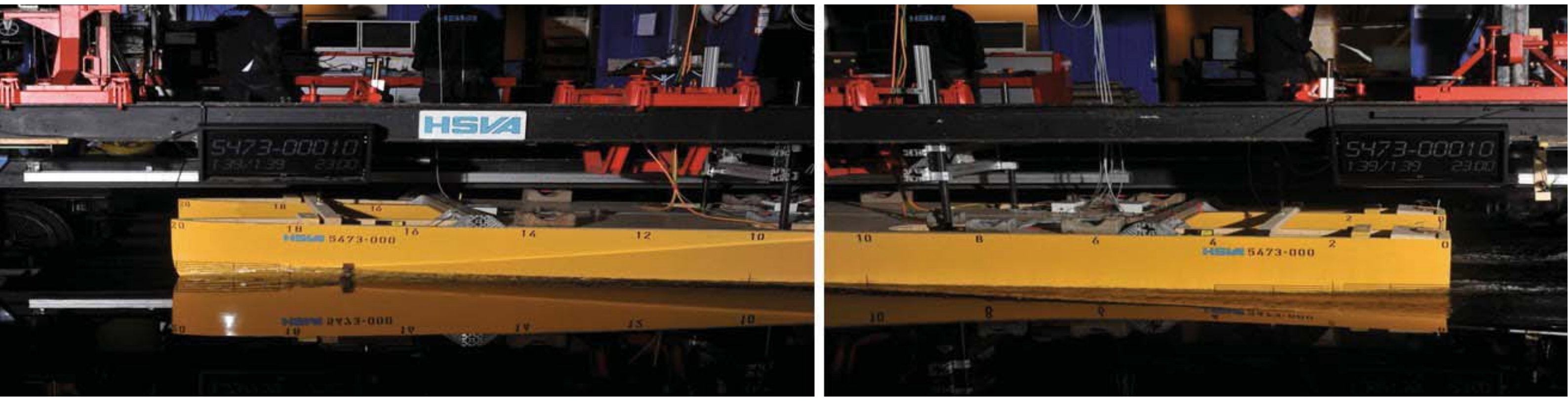

Figure 8: Self-propulsion model of the Stavanger demonstrator at 23 knots full scale speed

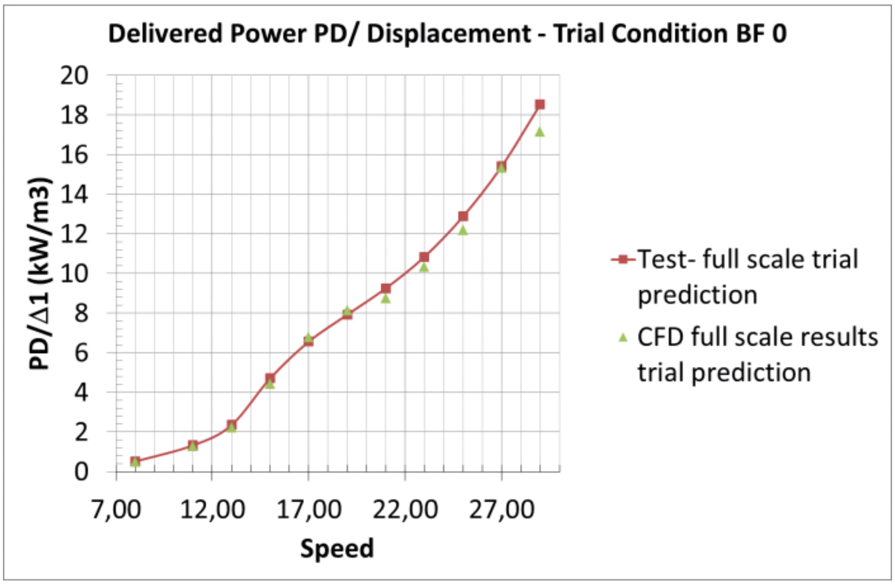

Figure 9: Delivered power per displacement for the full-scale trial condition by model tests and CFD

Summary and conclusion

A zero-emission, fast catamaran aiming to operate a multi-stop commuter route in the Stavanger area, the Stavanger demonstrator, was numerically and experimentally optimised by HSVA. Based on the hydrodynamic characteristics of the various designs and considering also construction and maintenance issues relating to available space in the compartments of the two demihulls, an overall optimum hull form has been selected for more refined optimisation. This hull form has been further optimised using HSVA's CFD tool FreSCo+, with a focus on the stern area and the propulsive efficiency that achieved a remarkable 78% at the design speed. Numerical predictions were verified by model tests at HSVA's towing tank, allowing the final selection of battery capacity and electric motors' power for the desired speed profile of the Stavanger demonstrator.

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