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Fully Automatic Design Space Exploration by RANS Computations

Sebastian Uharek[1,2,*], Stefan Harries[1], Andrés Cura Hochbaum[2]

[1]Friendship-Systems AG
Benzstr. 2, 14482 Potsdam, Germany
[2]Technische Universität Berlin, Department Dynamics of Maritime Systems
Salzufer 17-19, 10587 Berlin, Germany

[*]Corresponding author, uharek@friendship-systems.com

ABSTRACT

The present paper presents the result of a design space exploration study for three design variables performed for a twin screw ROPAX ship performed with the Computer Aided Engineering (CAE) software CAESES and the RANS code Neptuno using the meshing software GridPro for the automatic generation of the computational grid for each design iteration step. The design space exploration is carried out using an ensemble design engine, which performs a systematic variation of the parameters in the desired design space. After the exploration, the results are used to set up a surrogate model for a subsequent fast optimization. It can be shown that the current approach allows an easy and fully automatic generation of a reliable surrogate model once the parametric model, the grid topology and the numerical computations are set up.

1 INTRODUCTION

In recent years numerical computations based on solving the Reynolds-Averaged Navier-Stokes (RANS) equations for viscous flows have become quite common for complex marine applications. At the same time, optimization projects are often performed using much simpler mathematical models, like potential flow theory. The two major reasons for choosing potential flow computations over RANS computations are the significantly lower computation time and the easier setup of potential flow computations. However, for some applications this approach is not suitable and it is necessary to consider the viscous flow.

The present paper presents an approach to couple the in-house RANS code Neptuno and the meshing tool GridPro with the Computer Aided Engineering (CAE) software CAESES using its Software Connector to reduce the effort of performing the numerical computations. The required computational grids are automatically generated and first attempts have been made on the automatic assessment of the quality of the generated grid and the computational results.

For optimizing geometries, as well as for the investigation of different variants, a new geometry has to be automatically generated based on the selected parameters. CAESES allows the generation of complex, parametric models for this purpose. After a parametric model has been set up, new designs can be easily generated.

Additional tools for the exploration of the design space defined by the selected design variables of the parametric model are provided by the included Dakota library. After the exploration, it allows to create a surrogate model of the investigated geometry using a response surface, which maps the target function onto the design variables.

After the surrogate model has been set up, the optimization can be performed based on this model, resulting in very low computation times. Since the designs required to set up the surrogate model are known in advance, all necessary computations can be run simultaneously if sufficient CPU power is available. The present approach thus would allow to use RANS codes in optimization projects without the drawbacks mentioned above. It is recommended to evaluate the optimal design obtained by the surrogate model again with the RANS code. If the computed value of the target function differs from the value obtained by the surrogate model, the additional data provided by the performed computation can be used to further refine the underlying model.

2 APPROACH

The key component of the proposed approach is the program CAESES, since it allows the easy coupling of all involved applications using its integrated Software Connector. It exports the geometry of the current design variant together with text based input files based on features of the geometry or other parameters defined. This allows to run numerical computations without any further interaction with external software, once the model has been set up. After the computations are completed, the postprocessed result data is loaded into CAESES and numerical data is being parsed and displayed in tabular form, whereas 3D information of the flow field is also imported and visualized.

The current approach employs three chained Software connectors. The first connector generates a block structured grid using GridPro. The second connector is a preprocessor for generating a block structured grid for calculations using the RANS code Neptuno and the third connector prepares the input data for the actual computation and some basic postprocessing, see Figure 1.

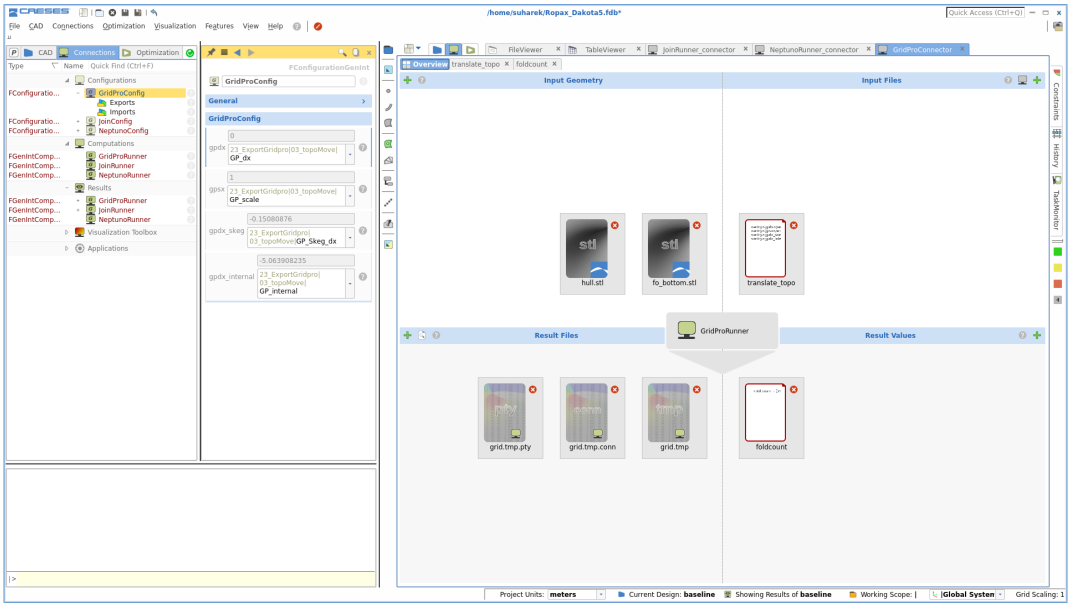

Figure 1: Setup of software connectors in CAESES

The coupling of the Software Connector functionality with the sshResourceManager software allows to run all jobs on external hardware. In the current application, the High Performance Cluster (HPC) of the Technical University Berlin is being used to run all computations required for the surrogate model simultaneously.

2.1 Parametric Model

The software program CAESES allows the automated shape optimization by coupling its robust CAD capabilities and powerful optimization algorithms with external computation tools [1]. The use of parametric models allows a reduction of the design space to the most important design variables. Multiple different strategies to explore the design space are included. The most simple one is the ensemble investigation, which just considers all possible combinations of the chosen design variables with a prescribed step size. More sophisticated options include the Sobol algorithm, which is a quasi-random sequence allowing an efficient design space exploration with significantly less designs compared to the ensemble investigation [2]. Another efficient alternative is the Latin Hypercube Sampling (LHS) from the Dakota optimization package. Similar to the Sobol algorithm, it generates equally distributed, near-random sequences of the design parameters in the selected design space [3].

The present method is applied to a twin screw ROPAX ship, for which a fully parametric model with 23 design variables to control the shape of the hull, including bulbous bow and skeg, was created in the scope of the HOLISHIP project [4]. In the present case only three of the 23 design variables are used for proving the capabilities of the selected approach rather than performing a full optimization. The used parameters are the length between perpendiculars, the length of parallel midship and a parameter which controls the position of the parallel midship. The total resistance of the ship was chosen as the objective function.

The design study of the ROPAX ship is performed at a fictive model scale with $\lambda = 25$. The length between perpendiculars for the initial (baseline) design is $L_{PP} = 162$m. The considered full scale speed is $u = 21$kn, which corresponds to a Froude number $Fn = 0.27$. A total of 120 designs were generated using an ensemble investigation considering all combinations of the following parameters: three ship lengths (L_{PP}), 10 lengths of the parallel midship (L_{MS}) and 4 positions of the parallel midship (x_{MS}). Since the current study is a proof of concept, no additional constraints are taken into account, which would usually be the case. All computations were performed on the computational cluster overnight, using only one core per design.

2.2 Computational grid and automatic adaption

The automatic evaluation of the objective function requires a robust meshing tool for the fully automatic generation of a high quality block structured grid for each design. For this purpose, the commerical meshing tool GridPro has been selected, because it separates the topology (grid structure) from the geometry. Thus, after building the topology, a structured grid for each design can be generated easily, while maintaining the basic structure and cell distribution of the original grid. This feature is desirable, since it reduces the dependence of the result of the numerical computation on the mesh resolution and mesh quality. The required geometry description is a watertight, error-free STL file, which is generated by CAESES for each design.

Smoothing algorithms are used to automatically generate grids with a high quality. However, there is one drawback to this approach: sharp edges, for example at the transom, lead to a so called mildly severe singularity in the numerical grid. This singularity can be resolved by arranging surfaces guiding the block faces adjacent to the sharp edges, called internal surfaces. These surfaces are also used in regions with a high resolution, e.g. near the free surface, to prevent the smoothing algorithm from moving the cells out of this region. These internal surfaces are also generated using CAESES based on a parametric meta surface and exported to GridPro.

Since the topology and geometry are separated, it is necessary to project all cell faces to the corresponding internal or external surfaces. For designs in which this projection could not be achieved, a nonzero value of the so called surface folds is returned from the meshing program. There are additional mesh quality parameters, which are returned. In the current study, the only two considered values were surface and volume folds, which are implemented as a constraints in the optimization process, thus excluding designs with insufficient grid quality.

For some designs, it was necessary to slightly translate the topology of the grid as well. This was done using tools like `trf` provided by GridPro. The parameters needed for the translation were evaluated using the parametric model.

For viscous computations it is important to ensure a sufficient resolution of the turbulent boundary layer. In the current application wall functions were used at the ship hull in order to reduce the required grid resolution in the vicinity of the wall. However, they are only valid in a certain range of non-dimensional wall distances (y^+). The used meshing tool allows to prescribe the required wall distance for using a so called clustering tool. However, for some designs the resulting wall distance lies outside the valid range. A postprocessing script run after the computations calculates the actual average y^+ value on the hull and marks computations with failed clustering as invalid.

In the present application the whole meshing process is done using a shell script, which is called with all required parameters from a Software Connector. The bash script includes the necessary conversion of the geometry, the meshing process itself, which is run for a fixed number of 2500 sweeps, as well as the required preprocessing, e.g. merging of blocks to reduce the computational effort. Due to the relatively low computational effort, the grids with about 800.000 cells are generated at a usual workstation, allowing to run 6 meshing processes in parallel.

The block structured grid for the current application has 1085 blocks before and 89 blocks after. The average time to generate such a grid is roughly six minutes. A screenshot of the used topology, the corresponding surfaces and the resulting grid can be seen in Figure 2.

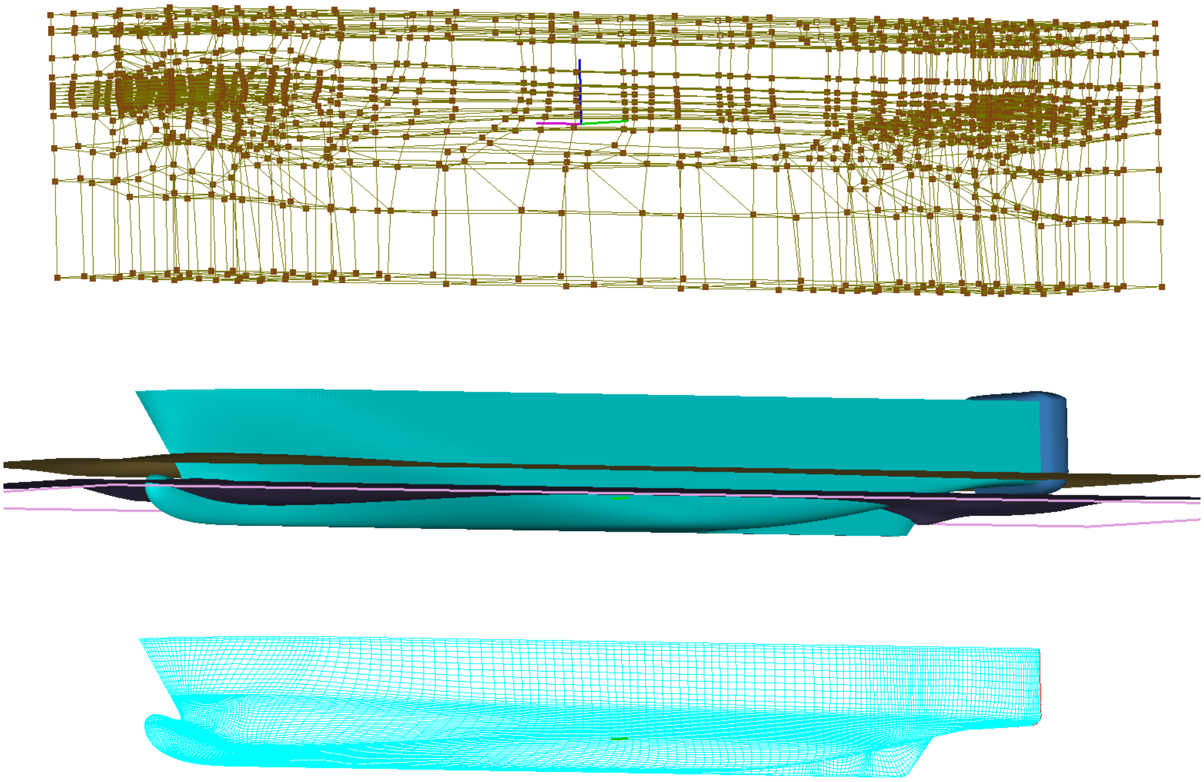

Figure 2: Topology (top), surfaces (middle) and resulting grid (bottom).

2.3 Coupling of viscous flow solver with CAESES

The used RANS code Neptuno uses a finite volume method on a non-matching block-structured grid to compute the viscous flow around the ships hull. The SIMPLE method is used for pressure velocity coupling, the turbulence is modelled using the standard k-ω turbulence model and a two-phase level set approach is used for the water free surface. Details on the numerical method can be found in previous publications of the authors, e.g. [5]. It has proven to yield accurate results and has been validated for many different complex marine applications, e.g. seakeeping [6] and manoeuvring [7].

In the current application the code is coupled to CAESES using two custom Software Connectors. The first connector includes the preprocessing commands needed to convert the grid to Neptuno and to set the boundary values of the considered case. This process is executed on the workstation which is also used for generating the grid. The second connector is for running the computation as well as for executing the postprocessing steps. It is set up using the CAESES sshResourceManager to be able to run up to 200 computations in parallel on a high performance cluster.

Since computations with free surface often show slight oscillations in the force traces due to reflections at the domain boundaries, an averaging is performed over the last two periods instead of taking the last value in the time history of the longitudinal force. This is done automatically using a script written in python. Further postprocessing actions include the conversion of the Neptuno result file into the Tecplot file format for importing the data back into CAESES.

3 RESULTS AND DISCUSSION

For the current design study, a total of 120 numerical computations were carried out, from which 20 failed due to problems generating the numerical grid or convergence issues. Note that no dedicated grid dependence analysis has been performed for the present case. However, numerous previous studies for similar applications have shown that the chosen cell distribution and resolution of features is sufficient for the present application case. Figure 3 shows the longitudinal force $Fx' = F_x/\rho u_0^2 L_{PP}^2$ made non-dimensional using the density of water ρ, the longitudinal speed u_0 and a reference length L_{PP}:

(1)

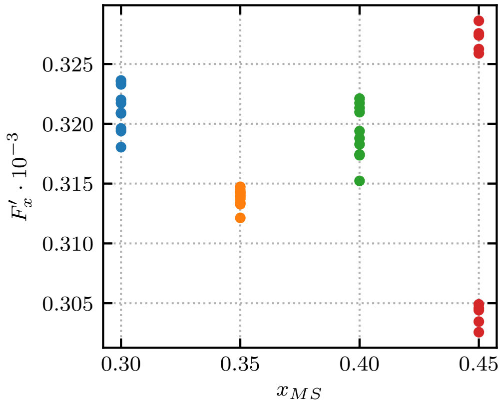

Figure 3: Outliers due to meshing difficulties

Especially for $x_{MS} = 0.45$ and $L_{MS} < 6\,\mathrm{m}$, outliers are clearly visible at the lower right bottom of the figure. A closer look reveals, that for these cases the clustering of cells in the boundary layer has failed, see Figure 4.

After the outliers are removed, a clear dependence of the non-dimensional resistance of the ship on the position of the parallel midship is visible in Figure 6 on the left-hand-side. It can be seen that the optimal position is somewhere in the region of $x_{MS} = 0.35$. Figure 5 shows the wave patterns for two different designs. The design shown on the right hand side has a resistance which is 8% higher than the one of the designs shown on the left. The symbols for each position of the parallel midship in Figure 6 correspond to the length of the parallel midship, which is displayed in the centre. The colouring scheme is identical to the one in the left figure. No clear trends are visible for this parameter. When investigating the influence of the length between perpendiculars, it is obvious that (as expected) the non-dimensional resistance gets reduced with increasing ship length.

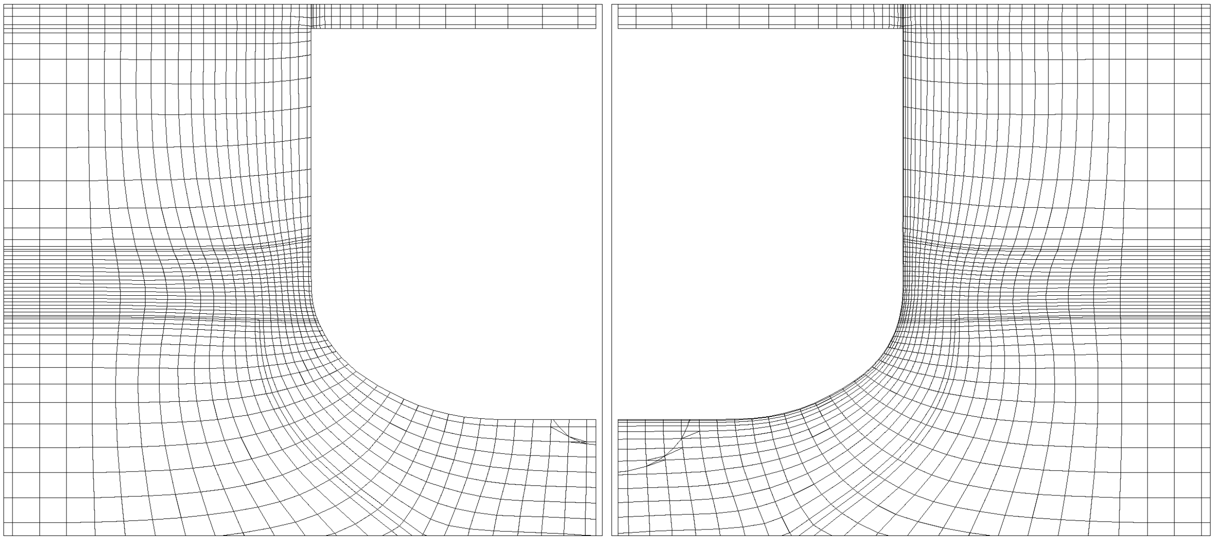

Figure 4: Failed (left) and successful (right) clustering in the near wall region.

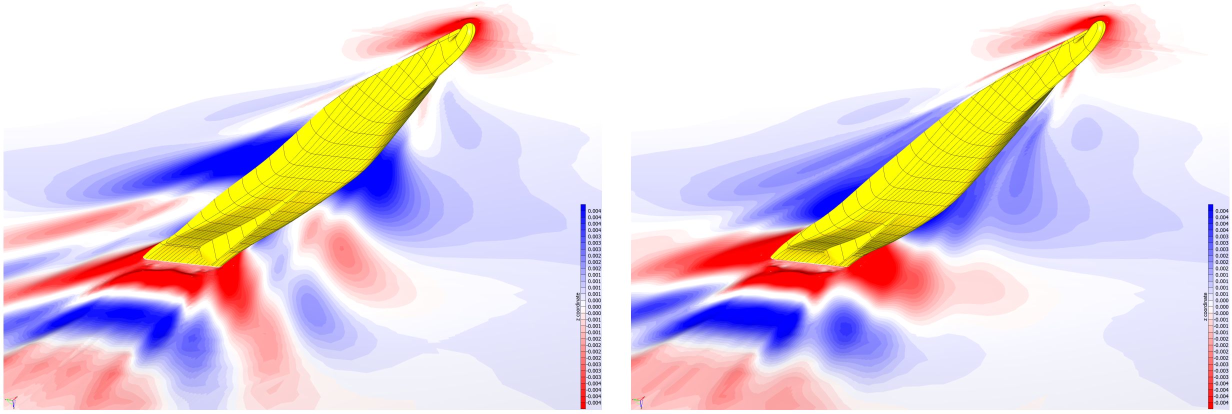

Figure 5: Free surface elevation for $L_{PP} = 155\,\mathrm{m}, x_{MS} = 0.45, L_{MS} = 1$ (left) and $L_{PP} = 155\,\mathrm{m}, x_{MS} = 0.3, L_{MS} = 2$ (right).

From the successful 100 computations, 16 equally distributed computations were selected for generating the response surface model used during the optimization process, which is displayed in Figure 7.

To validate the capabilities of the surrogate model, the remaining 84 designs that have not been used for the response surface are evaluated using the surrogate model and the difference to the corresponding value from the RANS simulations is computed. The resulting average relative error is 0.85%, the maximum difference being 3.1%. At the same time using the surrogate model requires only 16% of the original computation time.

4 CONCLUSIONS

A robust setup for a fully automatic design space exploration has been implemented and allows the quick determination of arbitrary complex response surfaces for parametric models created within the optimization software CAESES. The results of the study indicate clear trends for the dependence of the total resistance on the position of the parallel midship and length between perpendiculars, whereas no clear tendencies were detected for the length of the parallel midship.

The current method could further be improved by reducing the number of failed designs due to

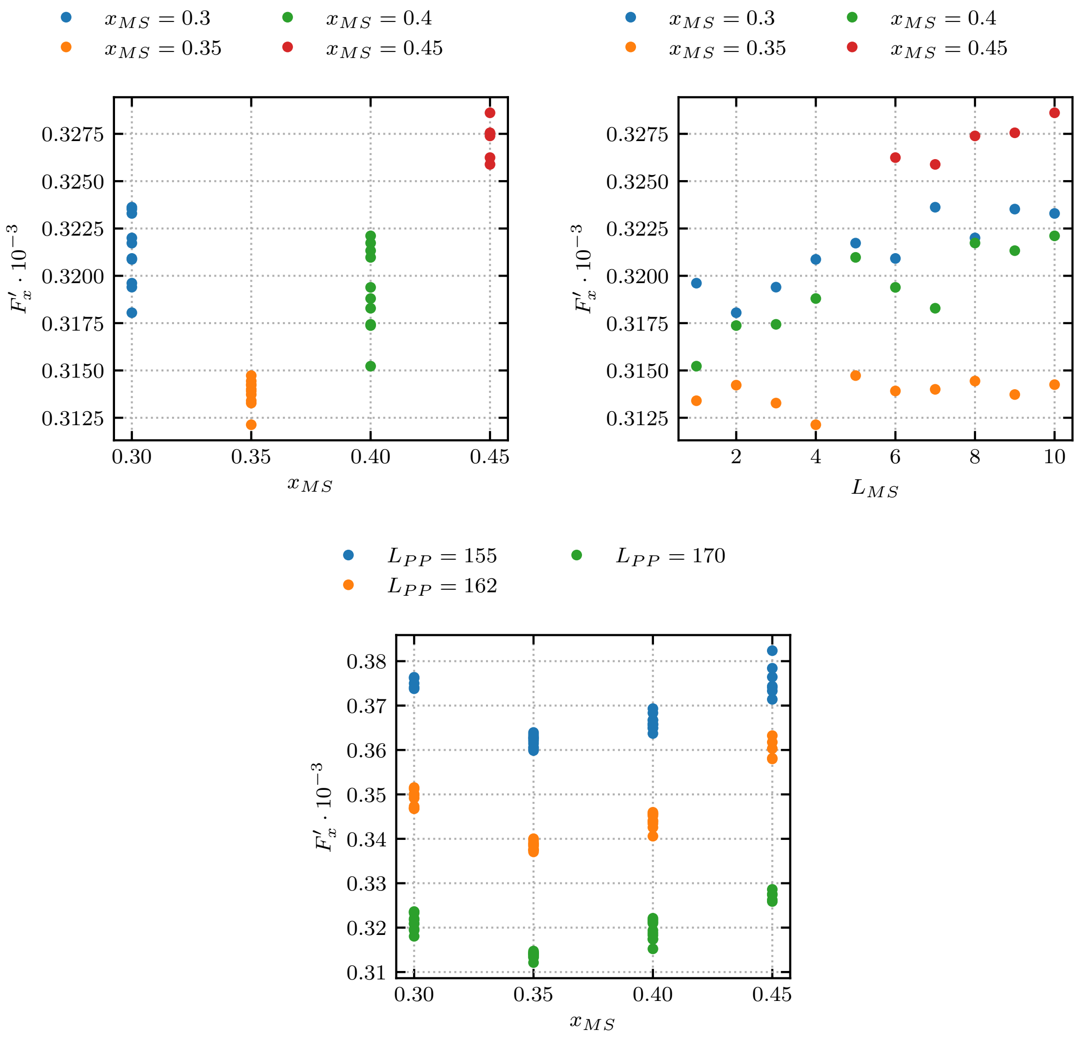

Figure 6: Computed non-dimensional longitudinal force for different combinations of design variables.

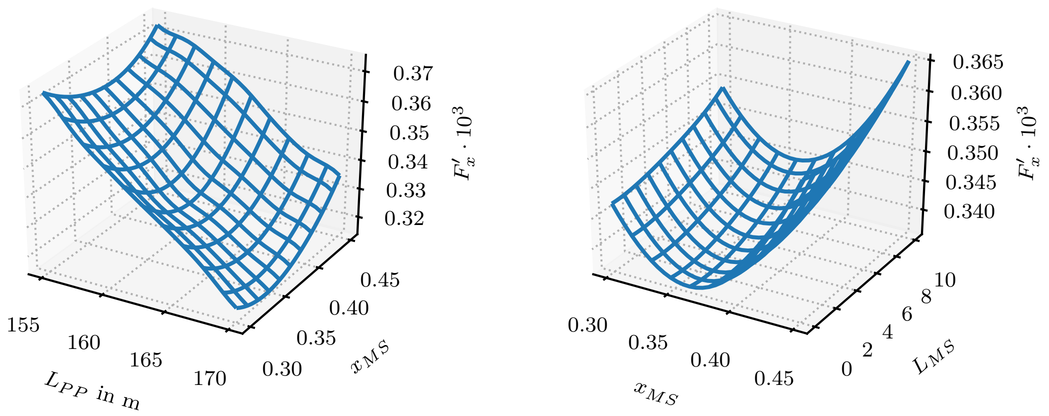

Figure 7: Surrogate model: dependence of F'_x on x_{MS} and L_{PP} for $L_{MS} = 1$ (left) and on x_{MS} and L_{MS} for $L_{PP} = 162\,\mathrm{m}$ (right)

meshing issues, a work that is currently carried out by GridPro. Furhter, it is planned to include an API to allow for a closer integration with external programs. The time for the RANS computations could be reduced as well by monitoring the convergence parameters throughout the whole simulation and implementing a suitable stopping criterion instead of performing the computation always up to a predetermined number of steps.

The current study is to be seen as a proof of concept and further computations with additional parameter variations are planned. Further, the use of a proven RANS solver coupled with sufficient user experience also allows more complex computations as for example the optimization of the skeg of the ship in oblique inflow conditions.

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