Resistance tests with 3D printed models in the early ship design stage of high speed vessels

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ABSTRACT: Resistance prediction for high speed vessels \((Fn > 0.5)\) is a challenging task in the early ship design stage. On the one hand, model tests deliver satisfying results, which are on the other hand expensive and time consuming. Testing of different versions of the hull form using model tests in the design process is nowadays not economical. In the last years, 3D printing gained in importance in industrial applications like rapid prototyping. The enhancing quality makes the technology suitable for the production of ship models, as cost and production time can be reduced significantly. Hence, towing different versions of the hull design becomes an alternative to usual approaches. In this paper the application of 3D printed ship models is presented exemplary for a new hull design of a high speed vessel operating at a Froude number of 0.912 using the results of a bachelor thesis.

1 INTRODUCTION

The resistance prediction for high speed vessels, which by definition operate at Froude numbers \(Fn > 0.5\), is a challenging task. Many CFD solvers which base on potential flow theory are not able to produce reliable results at these high Froude numbers. The calculation time of viscous flow solvers, like e.g. RANS, is too high for the application in the early design. Furthermore, effects like dynamic trim and hydrodynamic lift require specialised numerical methods and high computational effort to achieve reliable numerical resistance predictions. Due to that, systematic series are developed and published to be used for resistance prediction, see e.g. (Grigoropoulos 2005). Nevertheless, the usage of systematic series is time consuming as well and is limited to the boundaries of parameters used in the series, for example the slenderness \(L/\sqrt{\lambda}\). Moreover, parametric series just give a basis for a new hull form and more optimisation has to be performed to obtain satisfying results and a competitive design. Before the production, expensive model basin tests are carried out to predict the resistance and performance of the final hull form. Due to high costs, it is not economical to perform an analysis of many different designs or hull form variations in the towing tank. To obtain a more cost efficient solution, the use of 3D printed ship models is presented in this paper exemplary for a new hull form design of a high speed waterbike using the results of a bachelor thesis. As the production for different variations and appendages using 3D printing technology is cheap and fast, it is possible to carry out more variations in the model tests.

The human powered waterbikes, which have been presented and analysed by Georgiev et al. (2014), are designed and built by naval architecture students from all over Europe. They compete at the yearly International Waterbike Regatta (IWR) which takes place since 1980 at changing locations. The vessels are developed by students with modern methods from the studies like CAD, CFD and FEM. The waterbikes are operating at speeds of up to 7.0 m/s in sprint discipline. The length over all is limited to 6 m in the rules of IWR. This results in Froude numbers of up to 0.912, which categorises the boats clearly as high speed vessels. Hamburg naval architecture students’ currently best performing waterbike is called ‘Reynold’. It is a monohull with simple frame lines (see Fig. 1). The latest lightweight carbon fibre hull version was built in 2018. The target of the under-
lying bachelor thesis was the development of a better hull form, as the initial design was simple and not further optimised before built.

The paper presents the initial design and the subsequent optimisation of the waterbike. Afterwards, the fabrication of the 3D printed models is discussed. At the end, the model tests carried out at the Hamburg Ship Model Basin (HSVA) are presented. The results of the model tests of the 3D printed models are validated for the initial hull form using model tests carried out earlier with the full scale version of the boat. Moreover, the model tests for the optimised hull form are compared to the initial design.

2 HULL FORM DESIGN AND OPTIMISATION

In this section, the hull form of ‘Reynold’ is presented before the optimisation of the new hull design using the methods available at the Institute of Ship Design and Ship Safety is discussed. Furthermore, typical appendages of fast ships, like e.g. spray rails, are designed and described for both hull forms under consideration to investigate their influence in the model tests.

2.1 Hull Form of Boat ‘Reynold’

The newest boat ‘Reynold’ (see Figs 1 and 2) of the Hamburg Waterbike Team is used as vessel of comparison for the presented investigation. The hull has been towed in full scale in 2014. The results of these towing tests are well-suited for the validation of the model tests presented in this paper. Additionally, the video data of the model towing tests can be used for a qualitative comparison with drone footage from last year’s IWR exemplified by figure 2.

The hull form of ‘Reynold’ (see Fig. 1) is digitised from a frame plan of the built boat. The resulting numerical model is used for hydrostatics calculations with the in-house software E4. The results show satisfying accordance with the measurements from 2014. The prior towing tests showed that the minimum resistance can be achieved in a floating position with a large positive trim (trim by bow). Due to this large initial trim no CFD calculations can be performed for this hull as the results do not converge.

2.2 New Hull Form

For the new hull design, the EPROSYS research project (Grashorn 2005), which investigates a 50kn-high-speed RoPax ferry of 205 m length ($Fn = 0.573$), is used as initial hull. The main dimensions of the waterbike hull designs are summarised in table 1.

The optimisation of the new hull is carried out in E4 with the potential flow solver KELVIN, developed by Söding (1999). The calculations are performed up to a Froude number of 0.456 which corresponds to a speed of 3.5 m/s of the full scale waterbike. This speed is only the average speed for the slow long distance race, but higher Froude numbers cause numerical problems. In the sprint discipline Froude numbers of more than 0.78 are reached. Therefore, the CFD optimisation concentrates on the quality of the wave pattern and pressure distribution instead of the reduction of the absolute wave resistance value.

The optimisation in general is focussed for instance on the lengthening of the design waterline within the boundary of the permissible 6 m length overall of the waterbike. For this purpose, an axe-bow style foreship is used (Keuning et al. 2002). Furthermore, the large wave trough at the aftbody is a central point of the optimisation (see Fig. 2). A shift of the mainframe towards the bow is performed which is a recommendation of the EPROSYS project results (Grashorn 2005). In addition the mainframe is modified towards a homogeneous pressure distribution and the transom stern is widened to achieve a constantly broadening waterline in design and dynamic conditions. The resulting design is shown in figure 3.
2.3 Spray Rails

‘Reynold’ is already equipped with so called spray rails. Those serve to reduce the spray component of the towing resistance. On one hand, they lead the spray water away from the hull and thus reduce the wetted area in the foreship. On the other hand, they generate an additional dynamic lift at the bow. Spray rails are often recommended in literature for high speed vessels (Faltinsen 2010, Grigopoulos 2005). Guidelines for the optimum positioning and configuration of spray rails have been developed by Müller-Graf (1994). These guidelines are depicted in figure 4. It is recommended to always provide a combination of spray rails and a trim wedge to achieve a good distribution of the hydrodynamic lift. Therefore, spray rails are designed regarding the recommendations of Müller-Graf (1994) for both investigated hull forms (see Fig. 5). It is recommended to always provide a combination of spray rails and a trim wedge to achieve a good distribution of the hydrodynamic lift.

Therefore, spray rails are designed according to the recommendations of Müller-Graf (1994) for both investigated hull forms (see Fig. 5). The influence of these appendages is highly dependent of viscous effects and is hard to evaluate on basis of CFD calculations. Therefore, the calculation with KELVIN is not possible. Being able to analyse these effects is another benefit of the presented experimental tests.

2.4 Trim Wedges

Trim wedges generate a high pressure area at the stern due to the hard alteration of buttock lines. Thus, an additional lift develops and at best affects the trim in a positive way. The impact of trim wedges is difficult to analyse with CFD calculations in general and not possible with KELVIN either. For the model experiments various geometries of trim wedges are designed and produced. Design recommendations for trim wedges are found in (Müller-Graf 1991).

3 MODELS

In this section the tasks and realisation of the model production with a Fused Deposition Modeling (FDM) 3D printer are named and described. Polylactide (PLA) is used as material for the manufacturing. The time effort and costs are presented and compared to conventional model fabrication.

3.1 Scale

The model tests are carried out following geometric similarity and Froude’s law of comparison. Therefore, following relation applies:

\[
\lambda = \frac{L_S}{L_M} = \left( \frac{v_S}{v_M} \right)^2,
\]

where \(\lambda\) is the scaling factor. \(L_S\) and \(L_M\) are characteristic lengths of the ship and the model, respectively. \(v_S\) and \(v_M\) denote the velocity of the ship and the model, respectively.

On the one hand, a small scaling factor is desirable to minimise errors due to scaling effects. On the other hand, the model scale in the presented case is limited by two boundary conditions. One limitation is given by the maximum carriage speed at the towing tank. In the planned towing tank, the carriage has a maximum speed of 3.0 m/s. At the same time, the minimum velocity of interest in full scale is 5.2 m/s, which is the average speed in 100 m-sprint discipline of the waterbikes. The second limitation is the maximum build volume of the 3D printer. The model is printed in the upright position and should not be divided in transversal direction for a faster fabrication. Thus, the available print bed size of 305 mm × 305 mm limits the maximum frame area. The used 3D printer has a building volume of 600 mm in height. As the sections of the model are assembled by adhesive connections, this is no additional limitation.

Taking into account the aforementioned limitations, a model scale of \(\lambda = 3\) is chosen. This leads to model lengths of 2 m. Hence, the models each consist of four sections with a length of 500 mm.

3.2 Production

The numerical hull form design is exported from E4 as an area model in the stereolithography file format (.stl). Afterwards, the area model is post-processed for the fabrication with a 3D printer. In a first step, the post-processing of the model is done using the open source software Blender. At first, a volume model
with a thickness of the hull of 13 mm is generated from the area model. Moreover, constructional elements for the model tests are added, as e.g. elements to connect the model to the towing carriage and to outfit the model for testing. After the creation of the volume model, the model is processed by the manufacturer software IdeaMaker, which is used to set the parameters of the print and to generate the machine code (gcode) of the printer. Each printed part needs a tuning of the input parameters to reach satisfying results.

The models are produced with a nozzle diameter of 0.6 mm using a layer height of 0.3 mm. This combination is chosen as a compromise between accuracy and print speed. The infill percentage was 8% with a ‘Cubic’ infill pattern. Two outer shells were used, leading to a shell thickness of 1.2 mm. One fully equipped printed model weighs approximately 3.5 kg, while the target displacement is between 7.5 kg up to 8.9 kg. This leaves enough room for weights to set the floating condition in the towing tank.

Although a smaller nozzle diameter would improve the surface quality, the used nozzle diameter already leads to a satisfying surface quality. For a further improvement, the outer hull was sanded with waterproof sandpapers in grit size 80, 120 and 180. By using a yellow filament, a high contrast is reached in the towing tank without painting the model. For adhesive connection of the sections and other elements of the model professional plastic glue was used and the connecting areas were filled afterwards. Although being a quite simple way of post processing, a model of satisfying quality is produced for model basin experiments. Both completed models are shown in figure 5.

The production time of one 500 mm section varies between 22 and 30 hours. Smaller parts like trim wedges or similar parts are produced in less than five hours. In total, a model is produced within one week, which includes the printing of all elements and the sanding.

The material costs for one model can be estimated to 90€ based on a current price for filament of approximately 25€/kg. According to statements of employees of the HSVA, a similar carbon fibre reinforced plastic model from a third party company would cost approximately 10000€. Therefore, using 3D printed models gives the possibility to save immense costs.

4 EXPERIMENTS

In this section the execution of the model basin towing tests is described. The model tests are conducted following the recommendations (International Towing Tank Conference 2017a, International Towing Tank Conference 2017b). The setup is presented as well as the reproducibility and the final results. Moreover, a comparison to the available full scale test data is given.

4.1 Setup

The experiments are carried out at the large towing tank of HSVA. The model is linear guided at the bow by a stem and roll construction which limits the degrees of freedom of the model to heave and pitch motions. In the aft part a socket is mounted to the model which is then connected to the towing carriage with a load cell. The load cell itself is connected to a stem which is vertically mounted on roller bearings and thus as well allows heave and pitch but disables roll motions.

The dynamic trim and sinkage is measured with wires that are connected to the model at the bow by and stern at $y = 10$ cm on starboard side. The heeling moment of the wires is compensated with additional weights at starboard side of deck.

In general, the loading condition is realised with trim weights that are mounted to a T-slot bar on the inner bottom of the model (see Fig.12). The alignment, positioning and attachment of the T-bar is realised by
directly integrating it to the 3D printing model. The setup is exemplary shown in figure 6.

4.2 Reproducibility and Validation

Some of the measurement runs are executed twice for the same speed. These double measurements show a force accuracy of $2 \, g \approx 0.02 \, N$ in the measured force. Every run is carried out with 30 up to 60 seconds measuring time due to the high capability of acceleration of the towing carriage and the large length of the tank.

As mentioned before, the validation can be realised with a comparison to unpublished full scale towing tests from 2014. Therefore, the model of ‘Reynold’ is tested with the known loading condition from those full scale tests.

The predicted full scale resistance from the 3D printed model testing is compared to the full scale measurements in figure 7. The results show a satisfying qualitative accordance with a deviation of $-4.2\%$ to $-6.7\%$. The raw data of the tests from 2014 shows a variance of $+1.4 \, N$ ($+1.76\%$) and $-2.5 \, N$ ($-3.14\%$) from the mean value of $79.5 \, N$ for a speed of $3 \, m/s$ for repeated measuring. The time of measuring is relatively low compared to the towing tests presented in this paper. At low speeds of $3 \, m/s$ it is about $25 \, s$ whereas at $6 \, m/s$ it is only $8 \, s$ and at maximum speed of $7 \, m/s$ only $6 \, s$.

Taking into account the shortcomings of the full scale measurements, the difference between the full scale measurement and the prediction of the present model tests is satisfying. Thus, for all other resistance results the reliability is regarded as proven.

The dynamic trim angle is analysed using the same procedure. Again the qualitative curve shapes (see Fig. 8) of both tests show good accordance. The measuring from 2014 shows again a variance when tested twice and the measuring time is equally low like for the resistance data. Hence, the conformance of the trim angle curves can be considered satisfying and the information gained in the model tests of other loading conditions and hull forms can be transferred to the full scale version with certainty.

4.3 Results

Compared to ‘Reynold’ with bare hull the new hull form design shows a reduced towing resistance in the whole speed range. The best results can be achieved in floating position with trim towards stern compared to the initially tested floating position. All tested versions of trim wedges as well as the spray rails increase the towing resistance. The hull seems better suited for trim towards stern which explains why the trim wedges increase the resistance. In general the spray rails decrease the resistance due to the additional lift at the bow, but the spray of the new hull apparently is too small to generate enough lift. That is why the combination of spray rails and a trim wedge is not investigated. The comparison between the described versions is shown in figure 9.

The positive influence of the trim towards the stern
is also shown in the results of CFD calculations in figure 10 and in the images from the model tests in figure 12 comparing the centre to the right image.

The floating position showing the reduced resistance is now considered to be the design floating position. Therefore, the results of this version are compared against ‘Reynold’ in figure 11 and table 2.

For the ‘Reynold’ hull it turns out that spray rails increase the resistance in the common speed range of the waterbike. Only at the speed of 7 m/s, which is normally not reached by a waterbike, they show a reduction of 1.24% in towing resistance. The plausibility of these results is approved when comparing the drone footage of the real vessel in figure 2 and the

Table 2: Comparison of towing resistance in full scale prediction.

<table>
<thead>
<tr>
<th>( v_S ) [m/s]</th>
<th>new hull to ‘Reynold’</th>
<th>new hull to ‘Reynold’ w/ SR</th>
<th>‘Reynold’ w/ SR to ‘Reynold’</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.46</td>
<td>-1.70%</td>
<td>-5.89%</td>
<td>+4.46%</td>
</tr>
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<td>5.20</td>
<td>-5.05%</td>
<td>-7.55%</td>
<td>+2.71%</td>
</tr>
<tr>
<td>7.00</td>
<td>-1.33%</td>
<td>-0.09%</td>
<td>-1.24%</td>
</tr>
</tbody>
</table>

5 CONCLUSIONS

Two numerical hull models were successfully post-processed and prepared for printing of four 500 mm sections and additional components. For each 3D printed part the setup was adjusted to reach maximum quality at acceptable printing time. The adhesive connection could be generated and tested successfully. With simple sanding by hand an acceptable smoothness of the outer hull surface was achieved.

Model tests at the large towing tank of HSV A were performed with the comparatively small models of 2 m length. The towing speed up to 4.04 m/s resulted in the ability to investigate Froude numbers of up to 0.912. All tests could be carried out without any problems especially regarding the 3D printed models or the setup at the towing carriage. The small measurable forces were no problem either. The accuracy could be proven to 0.02 N.

Different hull form variations with spray rails and trim wedges were realised and evaluated regarding their effect on towing resistance and dynamic trim. The comparison to available towing test results of full scale experiments showed the reliability of the measured results. Thus, the new hull form was shown to be about 3.6% averaged more effective towards the current boat in the current configuration.
Figure 12: Wave pattern at \( v_S = 5.2 \text{ m/s} \): ‘Reynold’ w/SR (left), new hull form (centre) and new hull form at trim optimum (right).

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REFERENCES


