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Systematic approach to develop an optimized nozzle design for up to date and future demands

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Abstract

The increasing size of support vessels and longer distances from shore to offshore oil, gas and renewable energy locations are leading to new – and in some respects contradictory – requirements on the performance of ducted propellers. This is a two-fold challenge. On the one hand, short travel times must be achieved while keeping fuel oil consumption low. On the other hand, the maximum possible thrust capabilities must be maintained at very low speeds during station keeping in harsh environments.

Using a systematic approach, a global and local hydrodynamic optimization of dedicated nozzle profiles and attachments was carried out. A preliminary CFD analysis of established nozzle designs served as a benchmark. Based on this analysis, an initial design was developed and digitally parameterized. With the assistance of a generic algorithm, these geometry parameters were varied and optimized in a closed loop CFD investigation. Using different objective functions, it was possible to generate new nozzle cross sections with clearly better overall performance than traditional shapes.

Thanks to a series of model tests and in full scale measurements the theoretical determined behaviour of the final designed nozzles was approved.

A follow-up local flow optimization led to an innovative anode concept in terms of shape and placement.

1. Introduction

In their early application, ducted thrusters were mainly used to increase available thrust at low speeds as well as for the bollard pull. Today, there is a high variety of vessel types and applications equipped with ducted thrusters as well as a diversity in terms of the intended purposes for the vessel and related performance requirements. This range runs from harbour tugs, where bollard pull still plays a major role, to an emergency towing vessel, which aims to achieve a very high maximum speed and a simultaneously large towing capability.

The requirements in the offshore energy support industry – based as they are on the different operational tasks – cover most of both extremes. Maintaining a ship's position requires efficient thrust generation at low inflow velocities. As a result, minimum power absorption is to be achieved without a reduction in thrust. At the same time, operation at service speed takes place with a significantly reduced thrust load coefficient for a substantial portion of operation. This leads to the equal requirement of low fuel consumption also at high travel speed. The logical consequence from these needs is a further step in the ongoing development of dedicated nozzle shapes through support from current research tools and methodologies.

The goal for the behaviour of the new nozzles can be summarized as follows:

- Achieve at least identical bollard pull to the previous nozzle WAG19A-mod.
- Increase performance at transit condition (save fuel).
- Make them suitable for a wide range of applications and operations.
- Minimize the installation space and the nozzle weight.

2. Nozzle optimization

2.1. Research sequence

The research sequence entailed the following:

- Analysis of existing nozzle designs and selection of global geometry parameters suitable for a compromise design serving a wide range of operation
- Definition of the target function for optimization
- Selection of an optimization strategy
- Defining best possible start design
- Setup of a computational model and evaluation with model tests
- Execution of automated workflow
- Validation of final geometry by model and full scale measurements

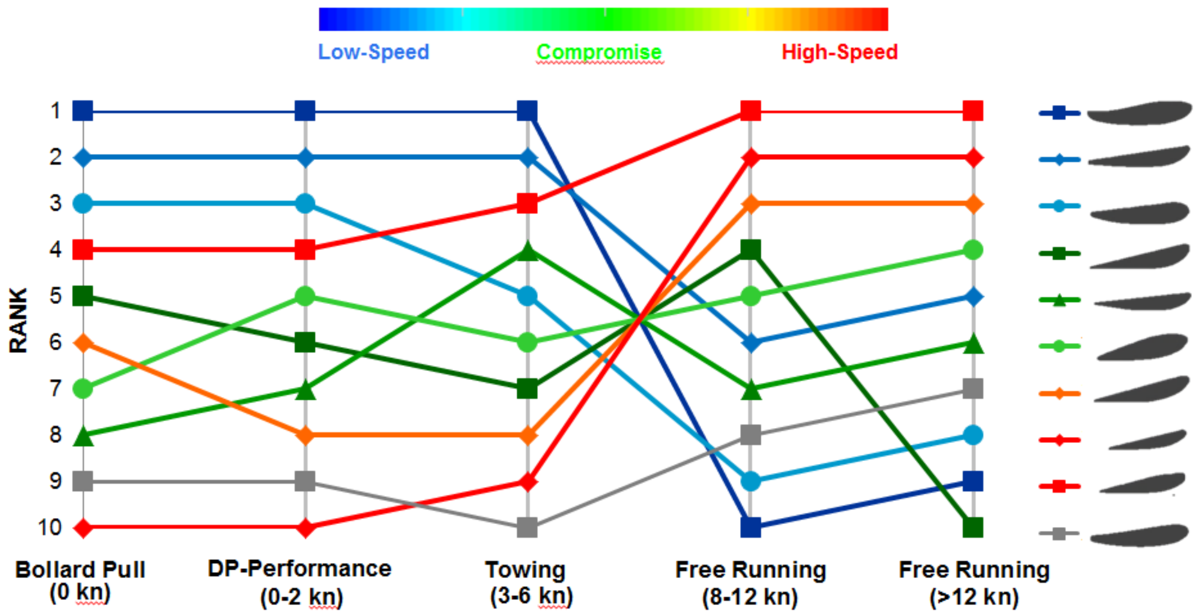
2.2. Optimization technique

In the past, a common approach has been to carry out an appropriate parameter study at model scale. By modifying a carefully chosen set of parameters, a general understanding of their influence could be obtained. For these experiments, model manufacturing and testing was mandatory and this, obviously, lead to a very limited number of setups. Based on the knowledge gained from this, an optimized version could then be selected and tested. This procedure, however, is very time-consuming and expensive – and the chance to miss the global optimum is still high.

To avoid the above disadvantages, the current research project is based on a high share of computational fluid analysis. Meanwhile flow simulation can be performed on computers within a reasonable amount of time and with an affordable hardware footprint. An optimization must still be carried out with a limited amount of geometry parameters. However, the most obvious difference here is the high number of combinations that can be analysed. CFD provides the basis for fast analysis of many designs in a standardized manner. The additional use of an automatic modification ensures an efficient optimization procedure. The likely outcome, when compared to previous methods, is a significant shorter timeline and a result much closer to the optimum solution.

2.3. Market study and pre design

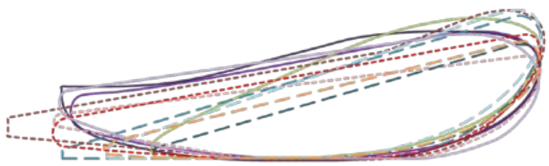
A study of existing nozzle designs was carried out to provide further insight concerning performance at different operation points. This provided clear evidence that the shape of the nozzle must take the special performance requirement into account. Hence, a wide range of operation requires a different nozzle compared to a bollard pull layout.



From the marked study below, the mentioned characteristics turned out to be promising for the general layout of a high performance compromise nozzle.

The selection of suitable geometry parameters include:

- Moderate opening angles
- Integrated cylindrical inner part
- Reduced nozzle length L/D 0.40 – 0.45
- Small diffusor



A pre design was carried out and tested in model scale. This verified good correspondence between the CFD results and the measured values in the towing tank. The free-running curve of the pre-design already promises a comparable bollard pull and an obvious improvement towards higher advanced ratios.

2.4. Optimization task

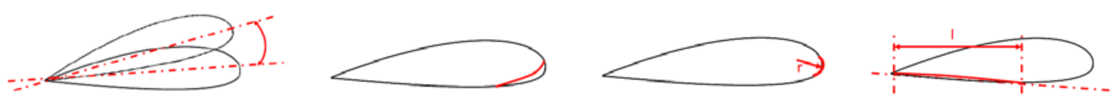
The optimization refers to the physical quantities of thrust and torque at a certain inflow velocity. The target function compromises to the relation of total unit thrust and consumed propeller torque – which must be increased since this represents the efficiency gain. The rating of a wide range of nozzle needs to consider at least two different operation points (where the power consumption must also be observed).

2.5. Parametric nozzle model

The parametric model for the future nozzle contains the main adjustment fields listed below. Their combination generates a good number of design variations. For all these parameters, a sensible domain had to be selected beforehand.

The main adjustment fields are:

- Opening angle
- Inflow contour
- Radius leading edge
- Diffusor geometry (Diffusor length and angle)



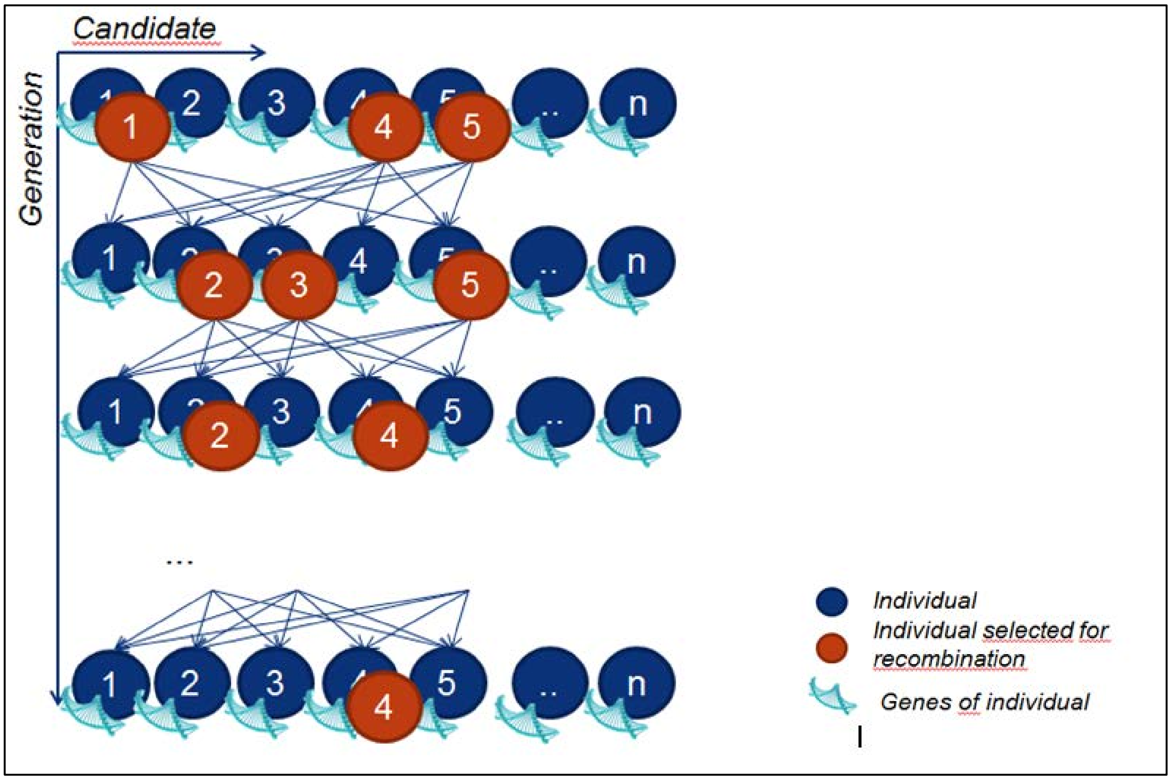
2.6. Optimization model – Evolutionary strategy

Evolution is the change in the inherited characteristics over successive generations caused by recombination and mutation. The main idea applying this strategy into computer science dates back to the 1970’s and is based on the work of I. Rechenberg and H.P. Schwefel.

The general approach is described below, and the attached graph illustrates this procedure.

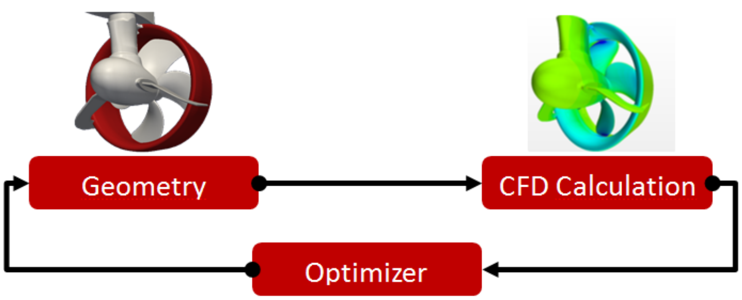
A first number of possible designs are generated (in most cases, at random). Each possible design is assessed and receives a value for the “fittest function”, depending on its performance. A selection of suitable designs is then used for a new combination. A randomized mutation is then executed, followed by an assessment of their characteristics.

This sequence described above must then be repeated until a defined abortion criterion has been obtained.



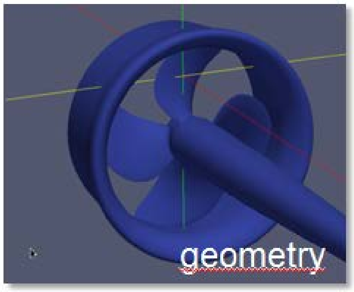
2.7. Workflow

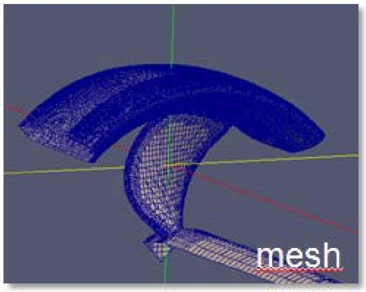
The graphic below shows the workflow in general. The optimizer provides the input data for a new nozzle shape. The geometry is automatically updated by using a dedicated geometry tool. A new 3D model of the nozzle is created and implemented in the computational model. The performance data for different operational points derives from CFD (OpenFOAM). The computational accuracy is evaluated with model test results obtained for different nozzle designs. The CFD results are post processed and handed over to the optimizer. The optimizer modifies the geometry as described above and a new generation is analyzed.

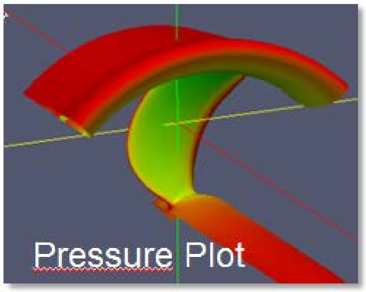


2.8. Computational model / analysis

The CFD model consists of the computational domain with a quarter of a cylinder. This means a sector model of the nozzle and one propeller blade is used for the 3D simulation. Mesh generation, modification and adjustments are performed using snappyHexMesh.







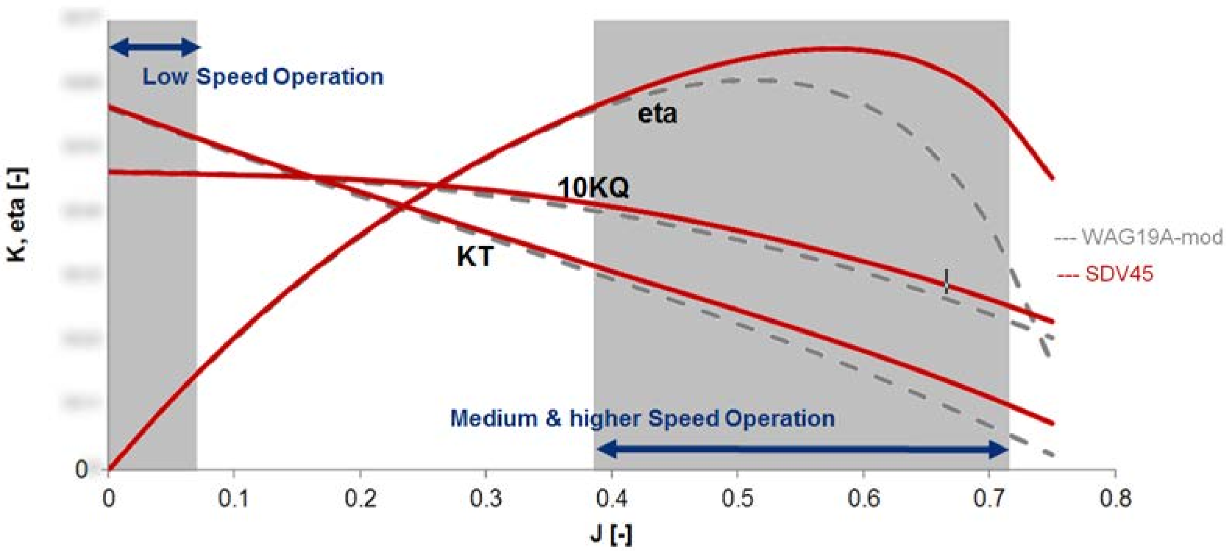
3. Results

The nozzle optimization, based on a genetic algorithm, was completed successfully. After one month of computing and 229 investigated variations of nozzle design, a final profile shape was selected.

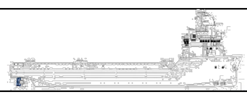
A model thruster was equipped with the “winner” nozzle and free-running tests were performed at the Potsdam model basin. The test results correspond very well to the predicted performance.

A direct comparison with the previous configuration (modified 19A nozzle) leads to the following results:

The bollard pull capability with the optimized duct is only slightly improved. The open water performance towards higher advanced ratios has improved significantly. This concerns not only the maximum obtained efficiency. The drop in efficiency deploys significantly later and less strong. Consequently, a wider range with high efficiency numbers for a ducted propeller was achieved.



The example application below shows the potential gains.

	**Offshore Supply Vessel** **(Free-running-design, SRP430 FP, 1600 kW, D_P=2.3m)**	
nozzle	*WAG19A-mod*	***SDV45***
DP-thrust (1kn) [t]	47.1 (100%)	***48.5 (+3%)***
max. vessel speed [kn]	14.8 (100%)	***15.1 (+0.3kn)***
power @ 14.8kn [kW]	1571 (100%)	***1410 (-10.2%)***

In a last step, the theoretically acquired knowledge as well as the data generated in the model test are validated in full scale measurements. The performance of the first vessels equipped with SDV45 nozzles is satisfactory. All evaluations of measurement data matched very well with the outcome of the research and development project. This concerned bollard pull and free running.

Bollard Pull Test - Harbor Tug - Geta Coast Guard

Speed Trial Escort Tug - Dux

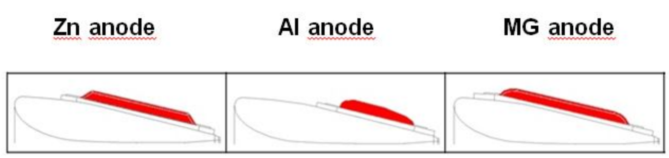
4. Consequential development

During the course of this work, the discrepancy of the behaviour of plain designed nozzle profiles as used in CFD as well as model tests compared to real-life performance came into focus again. Even the best profile shape gets counteracted by the use of blunt-shaped anodes in terms of flow disturbance. These additional bodies applied on the plating of the profile have a significant impact on the overall efficiency, especially at increasing ship speed. The additional anodes might also explain why full scale predictions for ducted systems sometimes seemed too optimistic and the obtained maximum speed during trials was lower than expected.

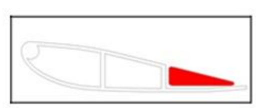
The loss in efficiency depends on ship speed as well as the number, volume and shape of the anodes in relation to the thruster size. Smaller nozzles with an unfavourable ratio of necessary anode to thruster volume consequently show a more distinct reduction in open water efficiency. The use of zinc or magnesium and the demand for a long protection period lead to particularly bad performance. Another way of applying cathodic corrosion protection was the logical consequence.

From the various CFD results, the pressure gradient on the profile surface was well known. The upper surface towards the trailing edge is especially insensitive to geometrical modifications. As a result, this area was designated to be adopted in order to allow for the application of integrated anode bodies. An additional sequence of CFD calculations proves that the efficiency of the new SDV 45 nozzle profile is not significantly affected by the omission of the rearmost plating.

As a result, the operator can expect a continuous performance regardless of the actual anode condition. In contradiction to the traditional arrangement, there is no negative impact on performance – neither with anodes nor without them. Furthermore, the available space is sufficient to integrate such a volume of material so as to allow the exchange period to be extended considerably. On common anode concepts, the required amount must be placed somewhere in the surrounding areas.



A subsequent investigation validated the structural strength and the manufacturability. As a result, this option is now a standard within the SCHOTTEL portfolio.



Conclusion

A new ducted thruster for supply vessels with multi-purpose operation was developed.

The influence of the nozzle geometry was examined via CFD analysis. The CFD results were validated using a well-established model test technique. Design objectives were defined and expressed by appropriate parameters. A qualified start design and suitable influence parameters were detected through an extensive study of existing nozzle cross sections. Investigations on this first geometry already showed a wide range of efficiency at different inflow velocities. Thanks to an automated closed loop research methodology, a time saving and high quality optimization strategy was established. After approximately one month of computation time and with more than 200 variations, a "winner" design was detected. A new nozzle based on that design was manufactured in model and full scale. Tests in a towing tank and in real application proved the predicted performance data. The efficiency of the new system was compared to the former "standard" layout. A significant improvement was obtained – especially at higher ship speeds.

A follow-up project developed an integrated anode concept and established this as an additional feature. The placement of the anodes in pockets at the rear end of the nozzle offers reduced efficiency losses at higher ship speeds and longer replacement periods regardless of the anode material. Finally, a complete new standard nozzle type complements the SCHOTTEL portfolio – particularly for applications with a wide range of operations.