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Development of hub caps fitted with PBCF

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ABSTRACT

This paper is concerned with optimizing the efficiency of ship propulsion systems by minimizing hub vortex-induced losses. Therefore, a fully automated optimization process has been developed. The process modifies the hub cap geometry in order to influence the hub vortex intensity.

This article includes an overview of previous developments on the vortex structure at marine propellers, focussing particularly on the hub vortex. The principles of the optimization process are presented and its components are described. The application of the process for a ship propeller is demonstrated and the results of the optimization are discussed.

Keywords

Propeller Boss Cap Fins PBCF, propeller geometry, hub vortex, computational fluid dynamics, optimization, evolutionary algorithm

1 INTRODUCTION

The importance of environmental protection has greatly increased in the past few years. In regards to marine propulsion systems the output of sulphur and carbon monoxide has been of particular concern. Further, fuel prices have significantly increased in recent years. Taken together, these factors have motivated ship owners to reduce the fuel consumption of their merchant fleet and so to improve the efficiency of their propulsion systems. Finally, acoustic aspects are also becoming an area of interest for international environmental regulations.

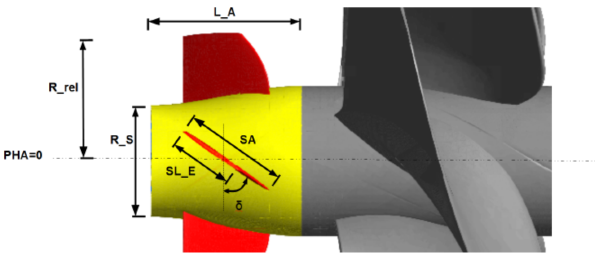

Figure 1: Variation parameters of the *PBCF* geometry.

As a result of this *Efficiency Saving Devices - ESD* for marine propulsion applications are getting more and more popular. *ESDs* also include hub caps fitted with hub cap fins, so-called *Propeller Boss Cap Fins - PBCF* (see also Figure 1). Well designed *PBCF* can reduce the intensity of the hub vortex.

A fully developed hub vortex has several effects on the performance of a marine propulsion system. In the center of a hub vortex there is a low pressure zone. Normally, the hub vortex induces a force on the surface of the hub cap, which is directed in the opposite direction to the thrust. Therefore, a reduction in the efficiency of the marine propulsion system should be expected. To overcome this problem, it is important to find a technical solution that reduces the intensity of the hub vortex as well as the thrust loss caused by the hub vortex.

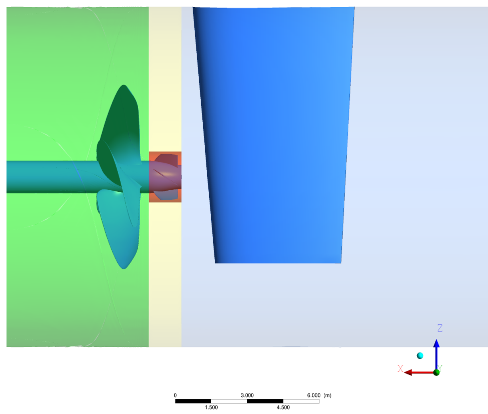

Figure 2: Decomposition of the simulation domain.

In the following sections, a procedure is presented that is able to reduce the intensity of the hub vortex. This is achieved by a modification of their geometry, which leads to four challenges:

- specification of the geometrical configuration of the considered system (see Figure 2),
- parametric description of the hub cap geometry,
- simulation of the flow around the hub cap geometry,

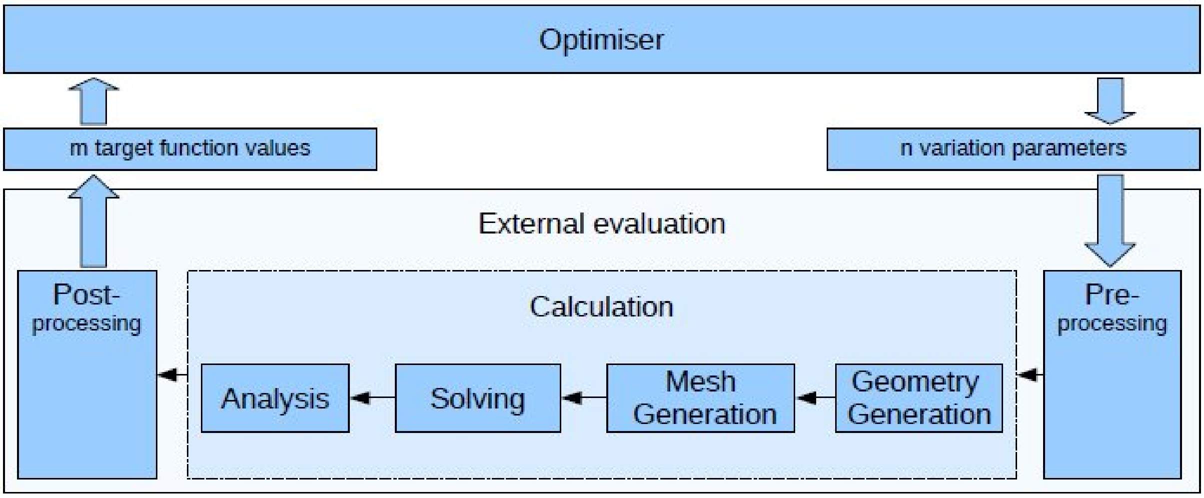

Figure 3: Developed process for the optimization of hub caps fitted with *PBCF*.

- optimization of the hub cap geometry.

In the following, the developed process will be introduced. Then the four challenges are characterized individually, including their integration in the developed optimization process. The investigated case is then described, and finally, its results are evaluated.

2 THE OPTIMIZATION PROCESS

The aim of the present work is to develop an optimization process for the automized design of hub caps with *PBCF*. The optimization process is designed as a cycle (see Figure 3). To begin the optimization the process generates hub cap geometries based on a predefined parametric geometry definition. Then the geometries are transferred into grid based geometry description, which are necessary for the simulation of the flow around the hub caps. After this these geometry grids are passed to the flow solver. At the end of the flow simulation the results are evaluated, and significant parameters are exported and are given to an optimization algorithm responsible for adapting the geometry. The optimization algorithm changes the geometry definition. The cycle is now closed so the process may start again. The optimization process runs through the cycle as long as a stop criterion is fulfilled.

The basic architecture of the process is flexible and can be used for other geometry optimizations. Several authors have used similar or even identical processes in order to optimize other marine propulsion components.

Benini (2003) has presented an optimization of an propeller of the Wageningen B-series. The propeller geometries of this series are defined analytically and investigated in detail by model tests. The results of these model tests are presented in form of a number of propeller performance diagrams in relation to number of blades, pitch and area ratio. The author uses selected parameters of the analytical propeller description for the variation of their geometry. The propeller performance diagrams of the model tests are used to perform the evaluation phase of the optimization. The author considers propellers with 3-6 blades and three Reynolds numbers ($2 \cdot 10^6$, $2 \cdot 10^7$ and $2 \cdot 10^8$). In each optimizations both parameters are kept constant. This means that a total of 15 optimizations are carried out. The aim of the optimizations is to maximize two target functions: thrust coefficient k_T and efficiency η. The results of the optimizations show that the two target functions compete with each other.

Hundemer et al. (2006) have also introduced an optimization of propeller geometries. In contrast to the publication of Benini (2003), the work of Hundemer et al. is not based on a propeller series. Instead, they developed their own parameterized geometry definition for the description of the propeller geometries. The aim of the optimizations is to maximize efficiency and to minimize both thrust fluctuations and risk of cavitation inception. Therefore, the geometries are evaluated by a *Computational Fluid Dynamics - CFD* software. The in-house simulation software *ISThydro* is also used, which is a 3D panel code.

Naujoks et al. (2007a), Naujoks et al. (2007b), Steden et al. (2009) and Steden et al. (2007) all describe an optimization of the geometry of a marine propulsor. This multi-component propulsor is also called linear-jet and consists of rotor, stator and a duct. The stator is located downstream of the rotor and both components are surrounded by the duct. As part of the optimization the geometries of all three components are varied. The diameter of the propulsor, inflow velocity and total required thrust are considered as input parameters. For the evaluation of the geometries *CFD* simulation are also applied. The process is designed as a two-stage concept. In the first section rotor and stator geometry is optimized using potential theory. The aim of the second section is to adapt the pressure level in the duct in order to minimize the risk for cavitation inception. At the same time the duct resistance is minimized. Therefore, a *CFD* method is applied.

Berger et al. (2013) and Berger et al. (2014) also present a two-stage optimization process for propeller geometries. The process is able to optimize the geometry of marine propellers. In addition to fulfilling the thrust requirements, the process is able to maximize the efficiency as well as to minimize the pressure fluctuations of the hull surface.

3 DESCRIPTION OF HUB CAP GEOMETRIES

The classic geometry of a hub cap is based on an axisymmetric body. The contour of that body may be conical, divergent or a combination of both. Figure 4 shows an exemplary contour of the basic hub geometry. For the optimization of the hub cap a parametric description is necessary. Therefore, the whole geometry mapped in Figure 4 is divided up in two parts, which are both described by a polynomial each, $F(x)$ and $G(x)$. For more information about the mathematical definition of the basic hub contour see Druckenbrod et al. (2012).

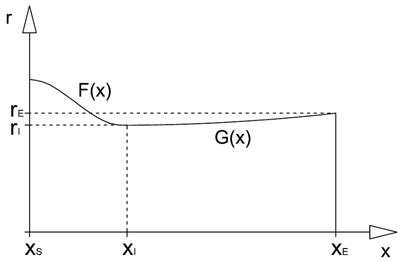

Figure 4: Decomposition of the basic hub cap geometry.

As the aim of the research project is to optimize hub caps fitted with *PBCF*, this basic geometry is extended to consider the case hub cap with fins. The geometry of hub cap fins is similar to the geometry of a propeller blade (see Figure 5). As a result of this, a parameterized description of a propeller blade geometry is used. Figure 1 and Table 1 show all variation parameters considered in the geometry definition of the hub cap with *PBCF*.

Table 1: Summarization of all variation parameters.

	description	max. no.	no.
1	length of basic geometry	1	1
2	radius of end plate	1	1
3	radius of PBCF	1	1
4	pitch	4	1
5	camber	4	0
6	phase angle	1	1
7	chord length	4	2
	total number	16	7

Table 1 lists a total number of 16 variation parameters considered in the geometry definition. For some geometrical variable more than one parameter is listed, such as the pitch. In this case the variation variables are described by a two-dimensional function which can be characterized with more than one variable.

Figure 5: Picture of a mounted hub cap fitted with *PBCF*.

As the optimization needs to work efficiently, the number of variation parameters has to be reduced to a minimum. As a result of this, the total number of 16 variation parameters have been reduced to 7, which are listed in Table 1.

4 FLOW SIMULATION

During the optimization process the quality of each hub cap geometry has to be determined. Therefore, a Computational Fluid Dynamics simulation is performed. The turbulent flow around a marine propeller as well as a hub cap is characterized by a complex vortical structure. In the present study the commercial simulation program ANSYS CFX ANSYS (2010) is used. For all numerical simulations the SST turbulence model is applied. For more information, see Ferziger and Peric (2001), Cebeci et al. (2005) and Pozrikidis (2009).

5 SPECIFICATION OF THE CONSIDERED SYSTEM

The main task of the flow simulation is to capture the vortical structure in the investigated flow field. In this case the most important aspect is the quality of the simulation, with a special focus on the simulation of the hub vortex. This results in a simulation mesh with a high number of cells in the flow regions of interest here.

Further, the flow around the propeller as well as the downstream located hub cap is very complex and is characterized by strong vortical structures. Due to the high interactions between several propulsion components, the hub cap geometry cannot be considered as isolated from the rest. Rather, the interaction between the hub cap geometry and other components must be considered.

An accurate calculation of the flow in the vortical regions and on the rudder leads to a high computation time of each single geometry, which has to be avoided. As for the optimization, a high number of hub caps has to be calculated.

6 GRID GENERATION

For the Computational Fluid Dynamics simulation the geometry needs to be represented by a numerical grid. If a viscous RANS simulation has to be done, a volume grid has to be generated. In the optimization process the numerical simulation has to be executed automatically. Structured grids are used for all numerical simulations. The complete simulation domain is divided up into four parts (see Figure 2):

- green part (propeller section),
- yellow part (hub cap section),
- red part (hub cap surrounding section) and
- blue part (rudder section).

The green section is static, so it does not need to be modified. As the length of the hub cap is also a variation parameter the red, yellow and blue parts have to be adapted to the hub cap length.

For the generation of the numerical basic grid ANSYS icem is used. The numerical grid of the hub cap fins is generated with ANSYS TurboGrid.

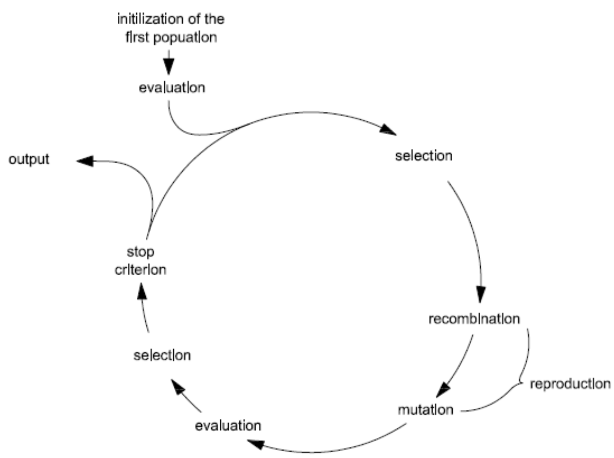

Figure 6: Process of an evolutionary optimization algorithm.

7 OPTIMIZATION TOOL

The actual optimization is done by an optimization algorithm. The algorithm has to be able to find a global optimum for a variety of variation parameters in a complex environment. For this task an evolutionary optimization algorithm is applied.

An evolutionary algorithm is based on the *Darwinian theory of evolution*. In the theory of evolution the performance of an individual is characterized by its genes. For an evolutionary algorithm the genes are replaced by variation parameters (see in Figure 7 the round-, rectangle- and triangle-elements). In addition to this, each individual is a single hub cap geometry in our case.

The basic principles of the *theory of evolution* are compressed within in several operators (see also in Figure 7):

- *selection*
- *recombination*
- *mutation*

At the beginning the evolutionary algorithm has to determine an initial population. In most cases this happens by using random values. This population is now the parental generation. Next, the optimization algorithm has to *select* some individuals of the parental generation for the next evolutionary step, which is called the *parental selection*. After that the characteristics of the chosen individuals are *recombinated* with each other and new individuals are created. Now their variation parameters are changed a little bit to enable new influences - the *mutation* process. Finally, all individuals are evaluated and the best ones are selected to create the next parental generation. This last step is also called the *environmental selection*.

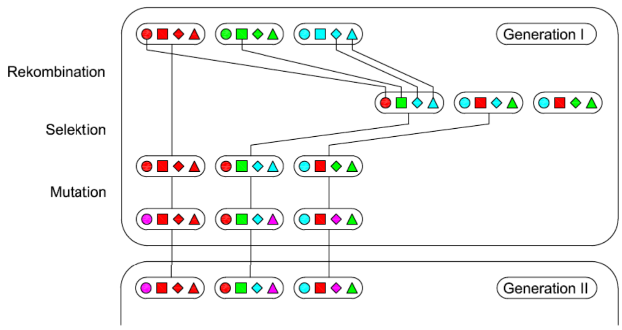

Figure 7: Visualization of the evolutionary algorithm operators.

An optimization algorithm is only able to optimize parameters in order to minimize one or several target functions. So the definition of the optimization problem has to be aligned to the requirements of the optimization algorithms. The optimization problem is reduced to an optimization of parameters. As a result of this, a parameterized geometry is needed and a target function has to be defined (see Formulas 1 - 4 and 8 - 10).

For the present investigations the Open Source tool DAKOTA Adams et al. (2012) is used. For more detailed information about evolutionary algorithms see Ahn (2006), Coello et al. (2007) and Yu and Gen (2010).

8 DESIGN OF HUB CAP GEOMETRIES

In the present work multiple optimizations have been conducted in two stages. In the following section both stages are introduced and all optimizations are characterized, after which the results of the optimizations are presented.

8.1 First-stage optimizations

In the first series of optimizations the target function considers three target function portions:

- thrust
- moment
- efficiency

For the thrust portions (see formula 1) the propeller thrust coefficient is slightly modified. As the aim of the optimization is to increase the efficiency of the whole propulsion system, including the force on the hub cap, the thrust force of the propeller in the classic thrust coefficient formula is replaced by the force of the whole propulsion system, which also includes the force on the hub cap (see Formula 5). Although, as already described, a hub vortex causes a pressure induced force on the hub cap surface that reduces the efficiency of the marine propulsion system, the pressure reduction can also induce the same force on the rudder surface in the opposite direction. In this case, considering the entire propulsion system shows that both forces eliminate each other. This means that the total force also contains the force on the rudder, including the costa bulb, which has to be considered.

A hub cap geometry fitted with *PBCF* also induces a momentum. For the momentum portion (see Formula 2) the propeller momentum coefficient is used in a slightly modified version. The propeller momentum is extended to the momentum caused by the *PBCF* (see Formula 6).

Finally, the efficiency itself is also included in the target function (see Formulas 3 and 7).

$$\epsilon_{k_T} = \frac{k_T^{Initial}}{k_T} \tag{1}$$

$$\epsilon_{k_Q} = \frac{10 \cdot k_Q}{10 \cdot k_Q^{Initial}} \tag{2}$$

$$\epsilon_{\eta} = \frac{\eta^{Initial}}{\eta} \tag{3}$$

All three portions are weighted and summarized in one single target function (see Formula 4).

$$\epsilon_I = \epsilon_{k_t} \cdot w_{k_t} + \epsilon_{k_q} \cdot w_{k_q} + \epsilon_{\eta} \cdot w_{\eta} \tag{4}$$

$$k_T = \frac{T_{total}}{\rho \cdot n^2 \cdot D^4} = \frac{T_{propeller} + T_{hub} + T_{rudder}}{\rho \cdot n^2 \cdot D^4} \tag{5}$$

$$k_Q = \frac{Q_{total}}{\rho \cdot n^2 \cdot D^5} = \frac{Q_{propeller} + Q_{hub}}{\rho \cdot n^2 \cdot D^5} \tag{6}$$

$$\eta = \frac{J}{2 \cdot \pi} \cdot \frac{k_T}{k_Q} \tag{7}$$

Table 2: Weighting of the target function - FIRST-STAGE.

OPTIM	total	w_{k_t}	w_{k_q}	w_{η}
01	470	0.33	0.33	0.33
02	470	0.60	0.20	0.20
03	470	0.20	0.60	0.20
04	470	0.20	0.20	0.60
05	470	0.00	0.00	1.00

The results of all first-stage optimizations are summarized in Table 2 including the associated weighting coefficients.

The first column shows the number of the optimization and the second column shows the number of individuals of each optimization. The last three columns contain the weighting factors of the target function.

Table 3: Sorting of the individuals - FIRST-STAGE.

OPTIM	total	1. sorting	2. sorting
01	470	91	2
02	470	5	0
03	470	43	0
04	470	94	5
05	470	93	2

To evaluate the quality of the optimization results all individuals have been sorted. The results are summarized in Table 3. The first and second columns are identical to Table 2. The third column in Table 3 contains the number of remaining individuals after the first sorting, which refer to an efficiency improvement and a momentum reduction. A visual evaluation of that remaining geometries has shown that only a few also have a reduced hub vortex intensity. Thus, a second sorting has been necessary for thrust improvement. The number of remaining geometries after the first as well as the second sorting are listed in the fourth column in Table 3. That fourth column also shows that only very few geometries are able to fulfill the conditions of both sortings.

As a result of this, a second stage of optimizations have been carried out, with an improved target function system.

8.2 Second-stage optimizations

In the second optimization a target function has been used that is better to indicate the intensity of the hub vortex. The new target function considers the efficiency of the whole propulsion system and the force on a surface cutout $k_{Tfacemin}$ which is characteristic for the intensity of the hub vortex (see Formulas 8 - 10). For the second stage optimizations also various weighting of the single portions are used (see table 4).

$$\epsilon_{01} = \frac{1}{\frac{k_{TIsoclip} - k_{Tfacemin}}{k_{Tfacemax} - k_{Tfacemin}}} \tag{8}$$

$$\epsilon_{02} = \frac{1}{\frac{\eta - \eta_{min}}{\eta_{max} - \eta_{min}}} \tag{9}$$

$$\epsilon_{II} = \epsilon_{01} \cdot w_{01} + \epsilon_{02} \cdot w_{02} \tag{10}$$

Table 4: Weighting of the target function - SECOND STAGE.

OPTIM	total	w_{01}	w_{02}
07	180	0.8	0.2
08	180	0.2	0.8

8.3 Results

Taken together, more than 3000 geometries were simulated in the optimizations, which means that a highly efficient analysis is necessary in order to evaluate all the hub caps. Some very convenient possibility is to visualize each target function over the progress of the optimization. Another possibility is to plot each variation parameter over the target function. In order to combine both evaluation strategies in this case, a three-dimensional representation is used with the color.

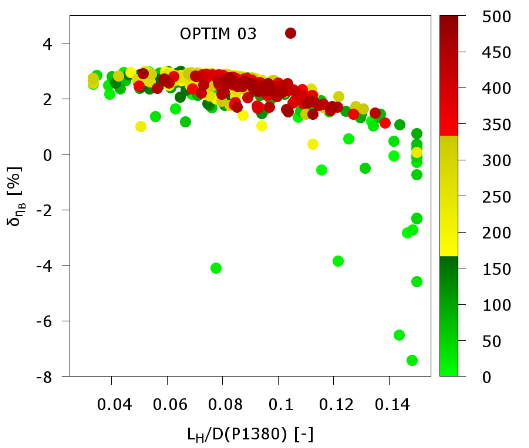

Figure 8: Improvement of the efficiency over relative hub cap length for *OPTIM 03*.

In this study the influence of the hub cap length on the efficiency is presented. Figures 8 - 11 show the length of the hub cap geometry on the x-axis. On the y-axis the change of the efficiency in form of a $\delta\eta$ is visualized. Finally, the color represents the chronology of the individuals during the optimization process. This evaluation is introduced for two optimizations - *OPTIM 03* and *OPTIM 05*. The first two, Figure 8 and 9, show all individuals. Figures 10 and 11 provide a detailed view of the interaction.

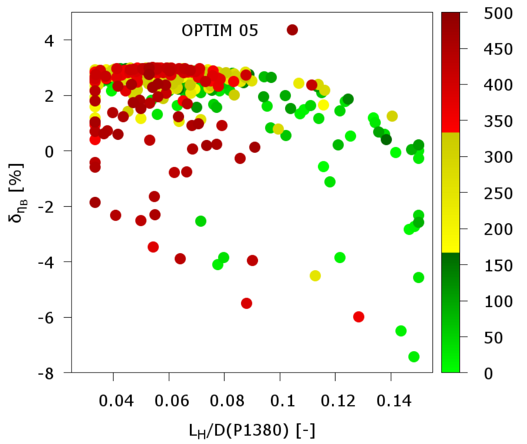

Figure 9: Improvement of the efficiency over relative hub cap length for *OPTIM 06*.

All illustrations show a clear contour on the upper front of the points cloud. A pairwise comparison of the Figures (Figure 8 with 9 as well as Figure 10 and 11) also indicates that the location, such as the progress of this contour, is identical.

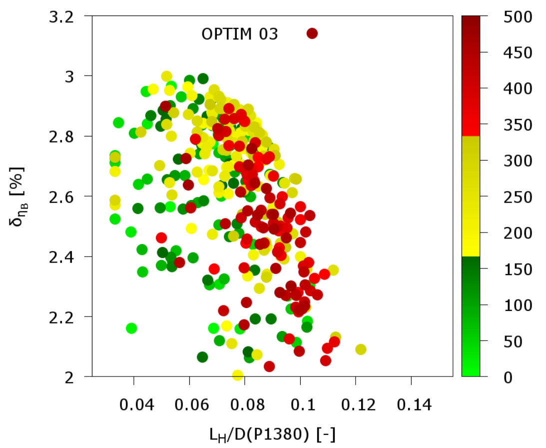

Figure 10: Improvement of the efficiency over relative hub cap length for *OPTIM 03* - detailed view.

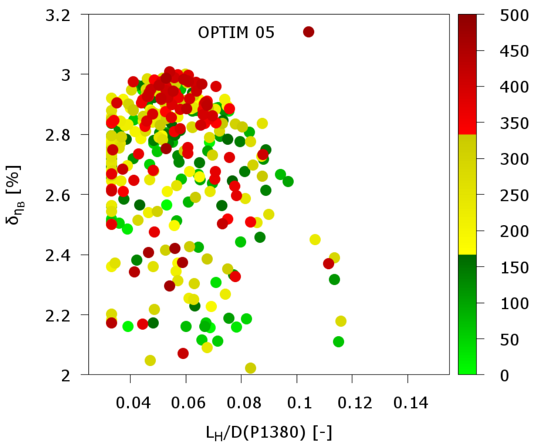

Figure 11: Improvement of the efficiency over relative hub cap length for *OPTIM 05* - detailed view.

The red dots show the latest 150 produced individuals and their location indicates the optimum for the optimization algorithm. Table 2 shows for *OPTIM 03* a weight on the efficiency of 20%. This is also seen in Figure 10, where the maximum efficiency is not the optimum for the optimization algorithm. *OPTIM 05* has a weight on the efficiency of 100%, and in Figure 11 the red dots indicate that the maximum efficiency is the optimum for the optimization algorithm. The maximum efficiency is for all optimizations (*OPTIM 01* - *OPTIM 05*) between $4 - 6\%$ of the propeller diameter.

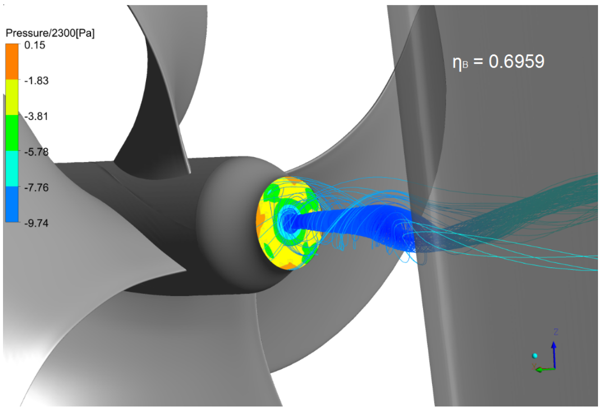

Figure 12: Streamlines and pressure contours for a short hub cap geometry without *PBCF*.

Following the global evaluation a detailed analysis of some selected geometries has been carried out. This study presents three characteristic geometries - all with the same basic hub cap geometry.

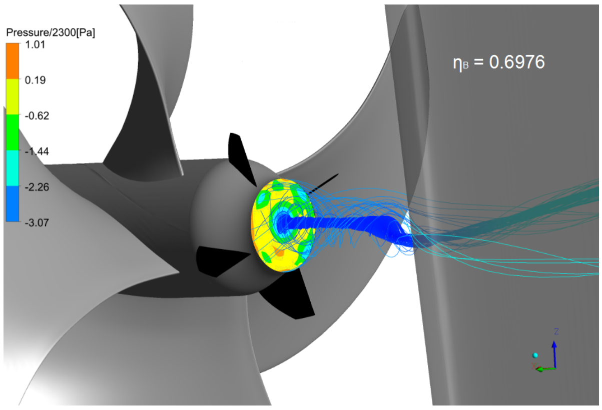

Figure 13: Streamlines and pressure contours for a short hub cap geometry with *PBCF*.

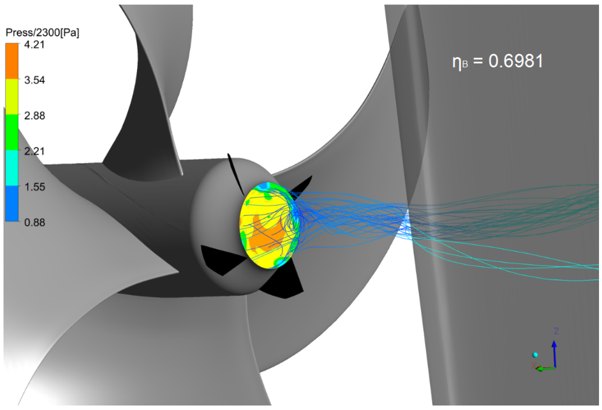

Figure 14: Streamlines and pressure contours for a short hub cap geometry with an optimized *PBCF* geometry.

Figure 12 shows only the basic hub cap geometry without hub cap fins. On the plate surface the pressure is visualized. Additionally, the figure also displays some streamlines starting at the plate surface. Especially the streamlines but also the pressure contures show the intensity of the hub vortex. In Figure 13 the same basic hub cap geometry is fitted with *PBCF*. The optimization of the hub cap fins is based on an initial fin geometry. Figure 13 shows the basic hub cap geometry fitted with the initial *PBCF*. The streamlines as well as the pressure level contour lines indicate that the intensity of the hub vortex is reduced but still existent. Finally, Figure 14 presents one of the optimum geometries. Here, streamlines and the pressure contour indicate that the hub vortex is almost negligible.

9 CONCLUSIONS

An optimization process was introduced which is able to develop hub caps fitted with *Propeller Boss Cap Fins (PBCF)*. The development of the process with its two stages was described. A number of optimizations were carried out and a total number of more than 3000 geometries were simulated and analyzed. The evaluation of the optimization results shows that the process is able to maximize the efficiency as well as to minimize the intensity of the hub vortex. A visualization of streamlines and pressure contours for some selected geometries brings the same result and thus helps to evaluate the quality of the optimization results.

The results show a strong interrelation between variation parameters and efficiency or intensity of the hub vortex. Special attention was given to the influence of the length of the hub cap on the efficiency.

10 ACKNOWLEDGEMENTS

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