A two-stage optimization approach for propellers with unconventional blade shape in a wake field using BEM

Jan Clemens Neitzel-Petersen, Daniel Ferreira González, Roland Gosda*, Moustafa Abdel-Maksoud

Institute for Fluid Dynamics and Ship Theory, Hamburg University of Technology, Hamburg, Germany

ABSTRACT
This paper presents an approach for an automated optimization to design a propeller with an unconventional blade shape such as a tip rake feature. The evaluation of the blade geometries is carried out with the in-house boundary element method (BEM) panMARE in a wake field to consider a realistic operational condition. The blade geometry is defined parametrically in a framework called HYKOPS1, where the blade surface is generated by locating profile curves in a three-dimensional space, providing a skeletal base for a loft.

In a first stage, several parameters defining the propeller blade geometry are handed over to a numerical optimization tool applying an evolutionary algorithm to identify adequate shapes for the design task, influenced by the averaged thrust, efficiency, the area of cavitated region and the variation of thrust and cavitation area. A consideration of the cavitation area with pressures below vapor pressure, its variation, and the variation of the thrust over a blade passage represents an approach to reduce the underwater noise and induced structural vibrations.

In a second stage, the geometry parameters are optimized within smaller ranges to aim for a local optimum within the design space. The reduction of the parameter ranges is based on the results of the ten best blade shapes. The optimized propeller is analyzed using the RANS solver STAR-CCM+ for detailed information about open water characteristics and for verification purposes.

Keywords
Propulsor optimization, parametric propeller, unconventional shape, HYKOPS

1 INTRODUCTION
The designer of modern ship propellers is confronted with a wide spectrum of requirements such as high efficiency, underwater noise levels and limits for induced structural vibrations. The task for the designer has become more difficult over the years to generate an appropriate blade geometry. Relying on data from well-known propeller series, a decision support tool based on genetic algorithms can support the identification of suitable propeller shapes for the design case (Suen & Kouh 1999). A parametrization of the propeller blade facilitates the option to utilize numerical optimization methods for a search in a broad range of blade shapes to reduce cavitation and increase efficiency as shown by Takekoshi et al. (2005). Mola et al. (2019) introduced a method to reduce the design space by identifying a linear combination of the geometric shape parameters, leading to a simplified design model for the designer. Including the ship hull in the optimization for a more realistic operation condition, Berger et al. (2014) introduced a method for an automated two-stage optimization of a marine propeller in full scale.

Widening the spectrum of design parameters to consider propellers with unconventional shapes, as shown by Praefke et al. (2015), increases the complexity and the variety of considerable geometries.

The present paper focuses on the automated optimization of marine propellers with an unconventional blade shape in the wake field of a ship. Initially starting with the propeller geometry of the KRISO container ship (KCS) in the corresponding wake field (Hino 2005), the propeller blades are deformed by utilizing the framework HYKOPS1 where the blade surface is generated by locating profile curves in a three-dimensional space, providing a skeletal base for a loft. The flow simulation is carried out with the in-house BEM code panMARE, where the incoming velocity is manipulated to address the changes of a homogeneous flow due to the ship’s wake.

In a first stage, a set of parameters to describe the unconventionally shaped propeller blade with wide ranges of values are handed over to the evolutionary algorithm to identify adequate shapes for the design task, influenced by the averaged thrust, efficiency, the area of cavitated region and the variation of thrust and cavitation area. Whereas meeting the required thrust at high efficiency is a common

* Corresponding author. Email: roland.gosda@tuhh.de
1 HYKOPS is available at https://collaborating.tuhh.de/m-8/HYKOPS
goal, a consideration of the cavityation area with pressures below vapor pressure, its variation, and the variation of the thrust over a blade passage represents an approach to reduce the underwater noise and induced structural vibrations. Analyzing the ten best propellers from the first optimization stage, a second optimization with a reduced parameter set and a smaller range of the values is initialized. The optimized propeller geometry from stage two will then be analyzed using the RANS solver STAR-CCM+ for detailed information about open water values and for verification purposes. A detailed comparison to the initial KCS propeller demonstrates the achieved improvements and induced disadvantages.

2 METHODS FOR HYDRODYNAMIC ANALYSIS

2.1 Potential theory-based boundary element method

Let the fluid domain \( \mathcal{F} \) in which the propeller is located be defined with respect to a Cartesian coordinate system \( \mathbf{x} = (x, y, z)^T \), with \( z \) pointing upwards against the direction of the gravitational acceleration \( \mathbf{g} \) (const.). Assuming the fluid to be incompressible \( (\rho = \text{const.}) \), irrotational and inviscid, a potential \( \Phi \) which describes the flow velocity field and which matches Laplace’s Equation can be written as follows:

\[
\Delta \Phi(\mathbf{x}, t) = 0, \text{ for } \mathbf{x} \in \mathcal{F}. \tag{1}
\]

Here, \( t \) is the time, \( \Delta \) denotes the differential operator. The pressure \( p \) in the fluid is given following to the Bernoulli equation:

\[
p + \frac{1}{2} \rho \nabla \Phi^2 + \rho \frac{\partial \Phi}{\partial t} + \rho g z = \text{const.}. \tag{2}
\]

According to the linearity of the Laplace Eq. (1), the velocity potential \( \Phi \) can be superposed by two solutions:

\[
\Phi = \Phi_e + \Phi_v \tag{3}
\]

where \( \Phi_e \) denotes a predefined potential from external influences and \( \Phi_v \) defines the hydrodynamic presence of a regarded propeller in the flow field.

According to Green’s third identity, the velocity potential \( \Phi_i(\mathbf{x}_0) \) at an arbitrary position \( \mathbf{x}_0 \) can be substituted by sources and doublets on the boundary surfaces \( S = \partial \mathcal{F} \). Defining the source strength as \( \sigma(\mathbf{x}) = \partial \Phi_i(\mathbf{x}) / \partial n \) (with \( \partial / \partial n = n \cdot \nabla \)) and the doublet strength as \( \mu(\mathbf{x}) = -\phi_i(\mathbf{x}) \) the velocity potential can be derived as follows:

\[
\phi_i(\mathbf{x}_0) = \frac{1}{4\pi} \int_S \left( \mu(\mathbf{x}) \frac{1}{r} - \sigma(\mathbf{x}) \frac{1}{\partial_n r} \right) dS, \tag{4}
\]

with \( r = ||\mathbf{x}_0 - \mathbf{x}|| \).

Hereby, the potential flow field \( \phi_i \) can be solved as a boundary value problem. Therefore, a set of boundary conditions are defined:

- The Neumann boundary condition ensures that there is no flow through the solid boundary \( S_b \) of the propeller:

\[
(\nabla \Phi - \mathbf{u}) \cdot \mathbf{n} = 0 \text{ on } S_b, \tag{5}
\]

Here, \( \mathbf{u} \) and \( \mathbf{n} \) are the motion velocity and normal vector of the surface \( S_b \).

- The Dirichlet boundary condition guaranties that the induced potential is spatially constant outside the fluid domain:

\[
\phi_i(\mathbf{x}) = \phi^* = \text{const. for } \mathbf{x} \notin \mathcal{F}. \tag{6}
\]

- The Kutta boundary condition sets the pressure jump between suction and pressure side at the trailing edges of the rotor blades to zero:

\[
\Delta p = 0 \text{ on } S_w, \tag{7}
\]

where \( \Delta p \) is the pressure difference at the trailing edge and \( S_w \) denotes the surface of the propeller wake.

In addition to this, the far-field condition, which is not referred to a specific boundary, demands that the hydrodynamic influence of the body has to vanish towards infinity:

\[
\lim_{x \to \infty} \nabla \phi_i = 0. \tag{8}
\]

This condition is already matched by the formulation of the induced potential \( \phi_i \) in Eq. (3).

It has to be mentioned that it is further assumed, that the propeller is deeply immersed so that the free water surface does not have an influence. Otherwise, the dynamic and kinematic boundary conditions at the free water surface have to be considered as well.

In the present method, the boundary value problem is numerically solved using a set of \( N \) low-order boundary panels as discretization of the solid body boundaries \( S_b \) and the propeller wake \( S_w \). On each body panel a constant source \( \sigma \) and doublet strength \( \mu \) is distributed whilst on the wake panels only a doublet strength distribution is applied as the wake does not induce any displacement. According to Katz & Plotkin (2001) the following influence

\[
A = \frac{1}{4\pi} \int_S \frac{\partial}{\partial n} \frac{1}{r} dS, \quad B = -\frac{1}{4\pi} \int \frac{1}{r} dS, \tag{9}
\]

can be used to establish a linear equation system in conjunction with Eq. (4) and the Dirichlet boundary condition from Eq. (6):

\[
\sum_{j=1}^{N_b} (B_{ij} \mu_{b,ij} + A_{ij} \sigma_{ij}) + \sum_{k=N_b+1}^{N_b+N_w} B_{ik} \mu_{w,ik} = 0 \tag{10}
\]

Here, the source strengths \( \sigma_{ij} \) on the body panels follow from the Neumann boundary condition and the doublet strengths on the wake panels \( \mu_{w,ik} \) can be substituted using the Kutta condition in Eq. (7). Hence, the remaining unknowns are the doublet strengths at the body panels which are obtained from the solution of the linear equation system.

The hydrodynamic loads can be derived by the integration of the pressure taken from Bernoulli’s Eq. (2) over the body surface. Due to the fact that the solution does not cover viscous effects, the resulting forces are corrected
using semi-empirical equations to consider the friction within the simulation.

2.2 Viscous method
The flow simulations for viscous fluids are carried out with the commercially available numerical code Simcenter STAR-CCM+. Applying a finite volume approach, the code solves the Reynolds-averaged Navier Stokes equations (RANSE) with a spatial discretization of the transport equations. The continuity equation and the momentum equation can be written as follows:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{11}
\]

and

\[
\left( \frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla \right) (\rho \mathbf{u}) = \nabla p + \nabla \cdot (\boldsymbol{\tau} + f), \tag{12}
\]

where \(\forall x \in \Lambda\) with \(\mathbf{u}\) as the Reynolds-averaged velocity vector. The formulas consist further of the Reynolds-averaged pressure \(p\), external forces \(f\), the Reynolds-averaged molecular stress tensor \(\boldsymbol{\tau}\) and the Reynolds stress tensor due to the Reynolds-averaging \(\tau_r\). To solve the equations, the components of the Reynolds stress tensor are approximated by using the SST k-ω turbulence model by Menter (1992).

3 FRAMEWORK HYKOPS FOR PROPELLER SHAPE

3.1 Framework HYKOPS
The HYKOPS framework was developed in the research project HYKOPS (Stoye et al., 2019b) to provide an alternative description for profile-based hydrodynamic surfaces that archives to describe shapes like tip rake propellers that are not realizable using existing standards for hydrodynamic devices (Praefke et al. 2017). Detailed information on the design of the implementation of HYKOPS may be found in Stoye et al. (2019a) and Friedhoff et al. (2019).

Each blade of a propeller is represented by an object denoted as loft. Each loft consists of a coordinate system, a loft path, an interpolation method for the lofting and a discrete set of loft elements.

Each loft element defines a two-dimensional profile on a surface defined by the two primary coordinates of a three-dimensional coordinate system. In general, the profiles may lie anywhere on the surface of their loft element. For NACA-series profiles the origin is defined to coincide with the leading edge and the trailing edge is on the primary axis where the axis coordinate equals one.

The loft path is the path, the profiles on the loft elements are interpolated along to generate the lofted surface.

3.2 Propeller shape generation
In order to optimize a propeller the shape of the base propeller is extracted from a PFF-file\(^2\). The PFF describes profiles of a blade on cylindrical surfaces centered at the axis of rotation. Assuming, that the surface is lofted with cubic splines, PFFs can be fully represented in a HYKOPS geometry.

During the optimization process the geometry is changed using the HYKOPS framework. Based on the given geometry, scalar values are incremented. The increment itself is calculated as a sum of two functions

\[
h(s) = f(s) + g(s), \tag{13}
\]

where \(s = r/R\) is the relative radius of the loft path in a cylindrical coordinate system \((r, \phi, z)\). \(r\) and \(R\) are the radial coordinate and the maximum radius of the loft path respectively.

\[
f(s) = a + bs + cs^2 \tag{14}
\]

is a quadratic polynomial with parameters \(a, b\) and \(c\). The parameters are calculated from values at the hub \(f(s_{\text{hub}})\), the tip \(f(s_{\text{tip}})\) and at an intermediate position \(f(s_{\text{mid}})\), \(s_{\text{mid}} \in (s_{\text{hub}}, s_{\text{tip}})\).

\[
g(s) = k \left( 1 - \cos \left( \frac{s - s_{\text{hub}} \pi}{s_{\text{tip}} - s_{\text{hub}} 2} \right) \right)^p \tag{15}
\]

is an exponential function with the factor \(k\) and the exponent \(p\) as parameters. The base of the exponential function is a damping function that is zero at the hub and one at the tip of the propeller.

![Figure 1: Function g for different exponents p](https://www.caeses.com/blog/2017/introduction-to-pff-propeller-free-format/)

Figure 1 shows \(g\) for different exponents \(p\) and Figure 2 illustrates the geometric changes due to a modification of \(p\) for the propeller rake.

The following traditional profile and propeller parameters are modified: Chord length, thickness, camber, pitch angle, rake and skew. For the definition of these parameters

---

\(^2\) The Propeller File Format (PFF) was first defined in Schulze (1995) and used in the German ship-building industry. The interested reader is referred to https://www.caeses.com/blog/2017/introduction-to-pff-propeller-free-format/ for an introduction.
Please consult a textbook like Carlon (2018). In addition, tilt and spiral angles can be modified as well.

The tilt angle is defined by the rotation of the profile on the \((x, r)\) plane, while the spiral angle is the rotation in the \((\phi, r)\) plane. The origin of the rotation is chosen on the profile plane. The spiral rotation is performed after the tilt. Both spiral and tilt angles may increase the propeller radius compared to the maximum loft path radius \(R\). To avoid similar behavior at the hub, \(f(s) = 0\) is prescribed for tilt and spiral. The exponential function \(g\) has no effect on the hub, as it is zero for \(s = s_{\text{hub}}\). Large changes in spiral and tilt angles may lead to intersecting profiles of different loft elements and should be avoided.

![Figure 2: Influence of the exponent \(p\) on blade rake (from left to right: \(p=0.5, 1., 2., 4.\) and original geometry)](image)

4 AUTOMATED OPTIMIZATION

4.1 Automated optimization method

The choice of an adequate optimization approach to successfully address the design problem is a challenging task. Being confronted with many different algorithms, an identification of key requirements reduces the options. In case of parametrical propeller design, the interaction of the parameters and the influence on the hydrodynamics cannot be clearly identified, excluding gradient-based methods to avoid a restriction by heading in the wrong parametrical direction. As the shape of the result space is unclear, an optimization method to identify a global minimum by evaluation of the whole design space is another key requirement. Combining these two key aspects, a random variation of parameters might enhance the search for a global minimum.

A differential evolutionary algorithm addresses the key requirements by applying selection, recombination, and mutation on the design space (Storn & Price 1997). As the name suggests, the algorithm mimics the evolutionary survival-of-the-fittest mechanism. Starting from an initial set of individuals with randomly generated parameters, the optimizing algorithm evaluates the fitness of each parameter combination within a generation and applies the mentioned mechanisms to create a new generation. Repeating these steps continuously allows the search for a global minimum within an unknown result space.

The optimization process can be controlled by several settings with the most relevant as follows:

- Population size: number of individuals per generation
- Mutation rate: Ratio of the components to be randomly mutated
- Crossover rate: Ratio of the components to be recombined
- Maximum iterations: Number of individuals to be evaluated until termination

An implementation of a differential evolutionary algorithm called \textit{coliny-ea} can be found in the DAKOTA framework as provided by the Sandia National Laboratories (Adams et al. 2022). The \textit{coliny-ea} algorithm is a script-controlled optimizer, allowing parallel computation of several individuals to accelerate the optimization process.

4.2 Fitness evaluation

The definition of the fitness function is a crucial part of the optimization process because it specifies the main goal of the optimization and therefore influences the quality of the result. This means, that the propeller shape after optimization will not necessarily lead to a better performing propeller, if the fitness function was bad or not appropriately chosen.

In the present work, one major aspect of the optimization is the noise reduction of the propeller. There are different factors which influence the noise level of a propeller. Following Carlton (2018), the hydrodynamic impact of the ship wake, namely the inhomogeneous wake field, and the tendency of the propeller to cavitate in the design condition are two of the strongest influences on the noise level of a propeller. Hence, the thrust variation regarding one propeller revolution and the estimated cavitation area are evaluated within the field function. Considering the operational profile, the optimized propeller must match the condition for which the original propeller has been designed and the efficiency should not be decreased significantly. Hence, the efficiency and the thrust compared to a target thrust which is based on the thrust of the original propeller are considered in the fitness function as well. The resulting fitness function is:

\[
    f_{\text{fit}} = \frac{1}{\eta} + c_1 \frac{\bar{A}_{\text{cav}}}{A_0} + c_2 \frac{\bar{A}_{\text{cav}}}{A_0} + c_3 \frac{\Delta T}{T_0} + c_4 \frac{\bar{T}}{T_0}\tag{16}
\]

Here, the parameters of the field function are defined as follows:

- \(\eta\) is the propeller efficiency which follows from the evaluation of the mean thrust and torque.
- \(\bar{A}_{\text{cav}}, \bar{A}_{\text{cav}}\) are the mean cavitation area and the standard deviation of the transient variation of the cavitation area during one propeller revolution. The values for the area are non-dimensionalized with the surface of the propeller \(A_0\).
- \(\Delta T, \bar{T}\) denote the difference between the mean thrust and the target thrust \(T_0\) and the standard deviation of the transient variation of the thrust.
c_0, c_1, ..., c_4 are weights to increase or reduce the sensitiveness of the field function on the respective parameter.

To address the impact of the contributing parts of the fitness function, a set of weights are defined. They are listed in Table 1, where also the target values T_0 and \( A_0 \) are presented. Propellers with efficiency values outside the range of \( [\eta_{\text{min}}, \eta_{\text{max}}] \) are particularly punished within the evaluation to guarantee that the optimization does not follow an inefficient approach or unphysical results.

Table 1: Target values, limits and weights applied in the fitness function applied for the optimization

<table>
<thead>
<tr>
<th>Target values and limits</th>
<th>Weights</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_0 2028 kN</td>
<td>c_0 1.0</td>
</tr>
<tr>
<td>( \eta_{\text{max}} ) 0.9</td>
<td>c_1 1.0</td>
</tr>
<tr>
<td>( \eta_{\text{min}} ) 0.65</td>
<td>c_2 1.0</td>
</tr>
<tr>
<td>A_0 2 %</td>
<td>c_3 4.0</td>
</tr>
<tr>
<td></td>
<td>c_4 4.0</td>
</tr>
</tbody>
</table>

5 APPLICATION OF NUMERICAL METHODS

5.1 Setup for optimization algorithm

In the first stage, the following parameters are handed over to the optimization algorithm to evaluate variations of the KCS propeller:

- Change of pitch angle on the radius 0.6R
- Change of pitch near tip with value and exponent of exponential function
- Change of rake near tip with value and exponent of exponential function
- Change of tilt angle near tip with value and exponent of exponential function
- Change of chamber near tip with value and exponent of exponential function

The parameters are chosen without a reference study on the impact of the shape parameters on the hydrodynamics. Hence, the range of values appropriate for optimization is based on the feasible range for a physically appropriate, non-intersecting surface. The following table introduces the ranges set for the variation of the values:

Table 2: Variation of design parameters in stage 1

<table>
<thead>
<tr>
<th>Description</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Added pitch at 0.6R [\text{%}]</td>
<td>-4.</td>
<td>4.</td>
</tr>
<tr>
<td>Change of pitch near tip [\text{%}]</td>
<td>-15.</td>
<td>4.</td>
</tr>
<tr>
<td>Exponent for pitch change [\text{%}]</td>
<td>2.</td>
<td>20.</td>
</tr>
<tr>
<td>Change of rake near tip [m]</td>
<td>0.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Exponent for rake change [\text{%}]</td>
<td>2.</td>
<td>12.</td>
</tr>
<tr>
<td>Change of camber near tip [\text{%}]</td>
<td>-20.</td>
<td>200.</td>
</tr>
<tr>
<td>Exponent for camber change [\text{%}]</td>
<td>0.01</td>
<td>6.</td>
</tr>
<tr>
<td>Change of tilt near tip [\text{%}]</td>
<td>-70.</td>
<td>-30.</td>
</tr>
<tr>
<td>Exponent for tilt change [\text{%}]</td>
<td>0.01</td>
<td>10.</td>
</tr>
</tbody>
</table>

A total number of 2000 individuals are to be evaluated by the optimizer. A mutation rate of 0.3 is applied to allow multiple, random changes for a scan of the whole design space. A recombination rate of 0.1 is chosen to allow a reduced combination of parameters, as some parameters are sensitive to variations of others.

5.2 Setup for BEM evaluation of individuals

The reference propeller, on which the geometries from the optimization are based, is the well-known KCS propeller (Hino 2005). The propeller parameters are shown in Table 3. During the optimization process, for each individual a transient hydrodynamic simulation of the fully discretized propeller is conducted using the presented boundary element method panMARE. For the discretization of the individual geometries the same number of panels is used. Here, both sides of the blades are respectively discretized by 18 panels in chordwise and 25 panels in spanwise direction. Furthermore, the panel distribution is refined in the circumstance of the leading edge to capture the high-pressure gradients in this area. Exemplary, the grid for the original KCS propeller geometry is printed in Figure 3.

Table 3: Propeller Case Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter D</td>
<td>7.9</td>
</tr>
<tr>
<td>Number of Blades</td>
<td>5</td>
</tr>
<tr>
<td>Rotational Speed (n)</td>
<td>1.745</td>
</tr>
<tr>
<td>Advance Ratio (J)</td>
<td>0.896</td>
</tr>
</tbody>
</table>

Within the simulation the hydrodynamic impact of the vessel is considered by the ship wake. It is described by a stationary velocity field \(v_{\text{sw}}(x)\), which is illustrated in Figure 4. It is based on CFD simulations associated with the work by Berger (2018) for the regarded advance ratio \(J = 0.896\). In the present case, the Neumann boundary condition in Eq. (17) is modified in order to capture the influence of the in-homogenous inflow velocity field on the propeller behavior, as follows:

\[
(\nabla \Phi + v_{\text{sw}} - u) \cdot n = 0.
\] (17)
The simulation time step size is $\Delta t = 1 / (180 \pi)$, so that the blade rotation per time step is $2^{\circ}$. Each propeller simulation is run for $N_r = 1.3$ propeller revolution, which has shown to be sufficient for the convergence of the harmonically oscillating thrust. In the post processing of the hydrodynamic simulation, one full revolution of the propeller is evaluated regarding the specified values for the optimization.

![Figure 4: Ship wake field for advance ratio J=0.896](image)

5.3 Setup for RANS calculation
The numerical calculations of the optimized propeller and the original KCS geometry are carried out with the solver for viscous flows STAR-CCM+ in open water condition. The operation condition is equal to the values in Table 3, leading to an advance coefficient of $J=0.73319$ by considering the average velocity from the influence of the wake field. The computations are carried out in model scale with a factor of 31.6, which leads to a propeller diameter of 0.25 m.

The flow regime is specified as fully turbulent. The velocity inlet of the cylindrical domain is located 3 propeller diameters upstream of the propeller. The distance from the propeller plan to the pressure outlet is 6 propeller diameters. The surrounding free-slip wall of the cylindrical surface has a radius of 3 propeller diameters. The hub is modelled as a free-slip wall boundary condition reaching from inlet to outlet.

The mesh consists of 6.1 million cells for the KCS case and 8.8 million cells for the optimized propeller case respectively. The transient calculation run with a time step corresponding to $3^{\circ}$ of propeller rotation for 5 propeller revolutions.

6 RESULTS
6.1 Results from stage 1
The evaluation of 2000 parametrically generated modifications of the KCS propeller with the evolutionary optimization algorithm coliny-ea indicates an improvement of the cavitating area on the propeller surface and the thrust variations. Visualizing the fitness function over the individuals, the plot in Figure 5 shows a significant improvement of the lower boundary of the fitness function during the leading 500 evaluations, followed by 1500 individuals on a similar level with mutations leading to peaks of the fitness function.

![Figure 5: Fitness function for all individuals of stage 1](image)

Evaluating the parts contributing to the fitness function, the area below vapor pressure on the propellers and its standard deviation reach favoring values near their minimal values, hence there’s a strong dependence on each other (ref. Fig. 6).

![Figure 6: Contributing parts of the fitness function for cavitation area and its standard deviation on the surface of 2000 individuals](image)

A similar trend can be stated for the standard deviation of the thrust the standard deviation of the cavitating area during one propeller revolution as shown in Figure 7. A reduction of the variation in thrust due to a modification of the blade shape reduces the variation of the area below vapor pressure as the trend of the bandwidth of the results shows. The correlation of the contributions to the fitness function by the area below vapor pressure and the efficiency indicates that an optimum in efficiency is contradictory to a minimum in cavitation area (ref. Fig. 8) within the range of modifications.

The contributions to the fitness functions of the 10 best propellers from the optimization are shown in Figure 9. A comparison to the original geometry “KCS” indicates significant differences of the area below vapor pressure and of the standard deviations of thrust and area below vapor pressure, which have been reduced due to the optimization. The modifications during optimization increased the
contribution of the efficiency due to the weights in the fitness function (see Chapter 4.2), resulting in a smaller efficiency value. For all presented propellers in Figure 7, small differences of the thrust in comparison to the original KCS propeller are observed, since the contribution to the fitness function is large to achieve a propeller with similar thrust output.

The surfaces of the 3 best configurations are presented in Figures 10 and 11 with views on the suction and pressure sides. The propeller surfaces differ minimally in shape, which can be supported by a tabular summary of the modification parameters in Table 4.
The main changes visible in Figures 10 and 11 are due to the differences in the rake change applied near the tip. The exponential distributions attain different bending curves on the blades, leading to a visibility of the green surface in Figure 11 of the best propeller with the lowest value for the exponent of the rake change. The red surface of the third best propeller stands out with large values for the change in rake and the corresponding exponent, which makes it visible in Figure 11 with the largest bend to the pressure side near the tip.

The pressure distributions of the optimized propeller show similar patterns due to the similarity in shape (ref. Fig. 12). The upper blades in Figure 10 pass the low velocity region of the KCS wake, hence the pressure signature shows small values reinforced by the reduction due to hydrostatic pressure.

**Table 5: Variation of design parameters in stage 2**

<table>
<thead>
<tr>
<th>Description</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Added pitch at 0.6R [°]</td>
<td>0.245</td>
<td>0.689</td>
</tr>
<tr>
<td>Change of pitch near tip [°]</td>
<td>-9.07</td>
<td>-7.21</td>
</tr>
<tr>
<td>Exponent for pitch change [ ]</td>
<td>6.503</td>
<td>8.838</td>
</tr>
<tr>
<td>Change of rake near tip [m]</td>
<td>2.027</td>
<td>2.254</td>
</tr>
<tr>
<td>Exponent for rake change [ ]</td>
<td>2.902</td>
<td>4.154</td>
</tr>
<tr>
<td>Change of camber near tip [%]</td>
<td>93.84</td>
<td></td>
</tr>
<tr>
<td>Exponent for camber change [ ]</td>
<td>4.83</td>
<td></td>
</tr>
<tr>
<td>Change of tilt near tip [°]</td>
<td>-38.4</td>
<td>-31.0</td>
</tr>
<tr>
<td>Exponent for tilt change [ ]</td>
<td>7.849</td>
<td>9.309</td>
</tr>
</tbody>
</table>

**6.2 Results from stage 2**

For stage two, another 1000 propeller shape variations are numerically evaluated in the wake field of the KCS using BEM. The values of the fitness function for the individuals are presented in Figure 13, indicating a significantly smaller range of results in comparison to stage 1 (ref. Fig. 5). The reduced design variable space limits the shape variation, hence the result space is smaller.

The fitness functions for the 10 best individuals from optimization two are similar in value and in size of the contributing parts (ref. Fig. 14). In comparison to the KCS propeller, the area with pressure below vapor pressure as an indication for cavitation (blue) has decreased from 0.7% to 0.4%. The standard deviation of the cavitating area has significantly decreased (violet). A similar behavior can be stated for the standard deviation of the thrust during one blade period (yellow) by maintaining the thrust of the KCS propeller, because the red bar is not visible. The propeller efficiency in the wake field is lower, changing from 75.8% to 71.4%, which is a result of the large influence due to the priority in the fitness function evaluation of cavitation and thrust variation. Hence, the propeller from iteration 867 from optimization stage two represents the best individual for the objective with reduction of the fitness value of 18.74% compared to the original KCS propeller.
The propeller shape of individual 867 is visualized in Figure 15. The tip is significantly bent to the pressure side with a maximum rake value of 2.25 m. On the outer radius, the tilt angle rotates the profile sections to 33° with their faces oriented downstream, allowing the profile allocation to follow the rake-induced shape. The pitch is reduced near the tip from originally 14.85° to 6.44° and the pitch around 0.6R is increased by 0.33°.

The results in Table 7 for the KCS propeller and the optimized propeller P0867 are evaluated in open water conditions at an advance coefficient of 0.733 corresponding to the averaged inflow velocity with wake field. The results in Table 7 for the KCS propeller indicate that the operation in the wake field in full scale leads to a high efficiency. Applying a corresponding open water condition at an advance coefficient based on the averaged velocity in the wake field, the thrust coefficient decreases by 1.5%. Comparing the results from the calculation with wake field, kT is significantly reduced by 7%. Whereas the calculated efficiency in full scale during operation in wake field is calculated to 76%, the results in corresponding open water condition indicate a lower efficiency by about 10%-13%.

Table 7: Results from numerical calculations on KCS propeller

<table>
<thead>
<tr>
<th>Case KCS</th>
<th>kT</th>
<th>10kQ</th>
<th>η</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEM in wakefield</td>
<td>0.171</td>
<td>0.263</td>
<td>0.758</td>
</tr>
<tr>
<td>BEM open water J=0.733</td>
<td>0.168</td>
<td>0.294</td>
<td>0.667</td>
</tr>
<tr>
<td>RANS open water J=0.733</td>
<td>0.159</td>
<td>0.298</td>
<td>0.623</td>
</tr>
</tbody>
</table>

Similar results can be observed for the optimized propeller P0867, as the efficiency under corresponding open water condition is significantly lower by 10-14%. The thrust values are within a 3% range (ref. Table 8).

Table 8: Results from numerical calculations on optimized propeller P0867

<table>
<thead>
<tr>
<th>Case P0867</th>
<th>kT</th>
<th>10kQ</th>
<th>η</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEM in wakefield</td>
<td>0.171</td>
<td>0.279</td>
<td>0.713</td>
</tr>
<tr>
<td>BEM open water J=0.733</td>
<td>0.176</td>
<td>0.335</td>
<td>0.613</td>
</tr>
<tr>
<td>RANS open water J=0.733</td>
<td>0.171</td>
<td>0.351</td>
<td>0.569</td>
</tr>
</tbody>
</table>

Comparing the results for both propellers, the similar thrust coefficient at operation in the wake field is a result of the objective of the optimization. Comparing the results of the cases for both propellers, the optimized propeller has a reduced efficiency of about 5%.

7 CONCLUSION & OUTLOOK

The presented two-stage optimization approach by applying an evolutionary algorithm using the boundary element code panMARE for evaluation successfully designed an adequate propeller with an unconventional blade shape for the design objective. For the parametrical description of an unconventional blade shape, the framework HYKOPS is applied. Starting from the well-known KCS propeller geometry, a wide design space for several design parameters describing an unconventional blade geometry with a rake towards the pressure side is handed over to the evolutionary algorithm for identifying the best set considering thrust, cavitation, and efficiency. A reduction of the design space after stage one allows a detailed search of an optimized parameter set in stage 2, leading to an optimized geometry with a reduction of the objective function by 18.74% compared to the KCS propeller. A comparison of both propellers with the RANS
method STAR-CCM+ verifies the results from the applied boundary element method panMARE.

Analyzing the optimization procedure, a reduction of the evaluated propeller geometries makes the process more time-efficient without a loss of quality. The reduction of efficiency from the initial geometry to the optimized propeller is significant, resulting from the definition of the objective function. Emphasizing the importance of efficiency by redistributing the weights allows a more balanced solution. Applying the procedure to evaluate shapes with rake to the suction side or other peculiarities would lead to a more profound understanding of the resulting advantages of geometric modifications to conventional propellers.

Acknowledgements
The authors thank the German Federal Ministry for Economic Affairs and Climate Change for the financial support within the research project DEffProForm-ProptiForm as well as the German Research Foundation (DFG) for the funding from project 344826971.

References


