OPTIMAL DESIGN OF MARINE PROPELLERS USING MULTI-OBJECTIVE EVOLUTIONARY ALGORITHMS

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ABSTRACT

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Marine propeller design is defined by competing objectives. The transportation industry has a unique challenge in designing new equipment because of its constant use. Poor designs are paid for upfront and continue to cost the operator throughout the part's entire service life. Propeller design is a complex process attempting to maximize factors, minimizing others while operating within material and equipment constraints. With these considerations, marine propellers are an ideal candidate for advanced computerized optimization. The evolutionary algorithms chosen for this review are specifically designed to solve such problems. The high dimensionality of the input variables and multiple nonlinear constraints make finding feasible solutions complicated and finding an optimal set impractical without computerized methods to evaluate and compare results. The utility of evolutionary algorithms is demonstrated effectively with this analysis and review of the marine propeller design problem.

This thesis is dedicated to my wife, Valerie.
Thank you for your calming influence when I needed it most.

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CHAPTER 1 INTRODUCTION

Marine propeller design is heavily dependent on balancing objectives for performance. Just like many design problems, propeller design is determined by how well-balanced competing objectives are. Therefore, the advancement of design techniques is worth a review. Transportation equipment is unique in the regard that it is always part of the operating cost. For a brief example, if a propeller is more efficient, the less energy the vessel needs to move its cargo. The less energy the ship needs, the less fuel the vessel's operations require. This factor is multiplied repeatedly with repetitive use. The operational efficiency goes right to the vessel's cost-effectiveness. The propeller is unique in its intricacy because it has all the complexity of an airfoil but operates in a medium with changing phases, velocities, and pressures that is also highly corrosive. The uniqueness of the parts attributes results in the complex numerical analysis necessary to quantify the propeller's performance. In addition to fluid complexity, the manufacturing process requires that these propellers be made entirely out of one piece. The details can have devastating effects if poorly carried out. The results of these design consequences drive designers to employ new methods for design and evaluation.

This thesis aims to get experience utilizing multi-objective optimization tools and applying them to real-world industry problems, like propeller design. With a better understanding and experience using these tools, sharing these techniques and ideas will support real case studies.

Multi-objective optimization has been around propeller design for a while, but understanding non-dominated solutions and Pareto fronts have been lacking. The idea of the Pareto front is a set of Pareto optimal solutions. A solution is Pareto optimal when the objectives of the solution (at least two) cannot be improved upon without sacrificing another objective. These are things that good designers consider and are mindful of, but there is a lack of widespread acceptance of the tradeoff between objectives in a formal format. It is typical for the designer to downplay one of the propeller's objectives at the expense of the others with no consideration to the tradeoff cost. With experience, the designer can quickly iterate through this process to find feasible solutions. However, with the complexity and scope of the input parameters, making informed decisions understanding the totality of the effects to the design requires significant effort and time. The solutions for these problems are always nonlinear, and currently, there is no substitute for numerical iteration. These topics make this problem a great example of the application of a multi-objective optimization framework. This thesis will prove that PYMOO, the chosen multi-objective optimization framework, is a viable tool for optimal marine propeller design.

CHAPTER 2 PROPELLER BACKGROUND

Marine propellers have been the mainstay in ship propulsion for the last 150 years. Marine propellers began seeing the start of genuine use in the early 1800s. Many throughout history wrote or designed propellers, but few of them got to put their designs to work aboard actual vessels until 1802 in Gibraltar Bay aboard the HMS DONCASTER. Propeller's had varying effectiveness until coupled with the high efficiencies of the steam piston and steam turbine power plants.

Propeller design in the early days required a substantial amount of building and testing. The builders mainly tinkered with the general concepts of designs as a hobby as opposed to rigorous evaluation. Propeller design's initial difficulty came from the early adopter's belief in the Archimedean screw as a marine propeller. In early development, the idea of the propeller was to screw the vessel through the water like a wood screw. In 1837 Francis Petit Smith was the fortunate one who discovered that this is not the case. While testing his Archimedean screw-style propeller made of wood, half of the propeller broke off. Much to his surprise, he found that his vessel had an increase in speed. He proceeded to patent and continue developing this style of propeller with much success. With their effectiveness now being proven, advanced engineering analysis began after the turn of the century.

Open water analysis began in the early 1900s. This analysis is a simulation of the propeller in open water or non-obstructed flow. Open water analysis is accomplished with a special large apparatus to simulate water flow that a propeller would see in operation. Engineers and designers were then able to review the torque and thrust characteristics and begin monitoring cavitation. With the open water analysis well underway, series propellers were able to be studied and developed. These series propellers were developed with vast configurations to account for all different use cases. These series propellers were non-dimensional designs combining different ratios of the propeller characteristics. The non-dimensional features allowed the series propeller designs to be scaled and fit the vessel. At this point, engineers could size the propeller to the application instead of designing it from scratch. This advancement allowed the engineers and designers to have a known set of performance characteristics to target their design. The series propeller designs drastically drove down the cost of propellers and marine equipment in general. Thus, providing the engineers and designers with a foundation moving forward. Today there are many series propellers, but arguably the most important is the

Wageningen B-Series propellers. These became one of the mainstays of propeller design moving forward.

2.1 PROPELLER THEORY

During the early engineering development, a few prominent theories came out regarding propellers. Momentum theory, where the propeller area is assumed to be a thrust generating disk, accelerates the fluid as it moves through the disk. This idealized mathematical model represented the transition from rotational energy to thrust.

Blade element theory provided a little more detail breaking down the propeller blades into smaller sections or elements. Calculating the individual forces and moments on the individual components and adding them up to find the total effects of the propeller proved a helpful method. To quantify and qualify the performance of the series propellers, engineers developed open water characteristics.

Thrust coefficient, torque coefficient, advance coefficient, and cavitation number are the contemporary propeller characteristics

The thrust coefficient, K_T, is given the equation(1). Torque coefficient, K_Q, is given equation(2). These coefficients and the non-dimensional speed of advance coefficient, J, (3), propeller efficiency,η_0, can be calculated (4).

$$K_T = \frac{T_o}{\rho n_p^2 D^4} \tag{1}$$

$$K_Q = \frac{Q_{p_o}}{\rho n_p^2 D^5} \tag{2}$$

$$J = \frac{V_a}{n_p D} \tag{3}$$

$$\eta_o = \frac{T_o U}{2\pi n_p Q_{p_o}} = \frac{J K_T}{2\pi K_Q} \tag{4}$$

$$\sigma = \frac{p_0 - e}{\frac{1}{2}\rho V^2} \tag{5}$$

With the coefficients and a systematic way to analyze the propeller's performance, designers and engineers began a systematic breakdown of the propeller's performance.

The figure below demonstrates a typical interdependence of the thrust and torque coefficients and the propeller efficiency.

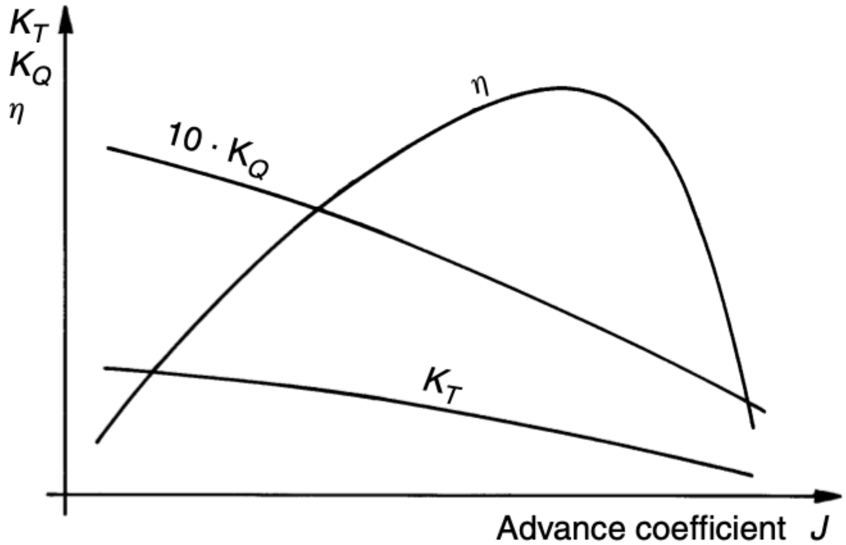

Figure 1 Example KT, KQ, J, and Efficiency Curve (Taken from [4])

2.1.1 GEOMETRY

The shape of a marine propeller requires an unorthodox method of description. The propeller necessitated an unconventional approach to convert a three-dimensional object with complex shapes and distributions to an easily interpretable two-dimensional drawing scheme. Diameter, pitch, chord length, skew, rake, camber, and thickness constitute the primary descriptors of the propeller to this day.

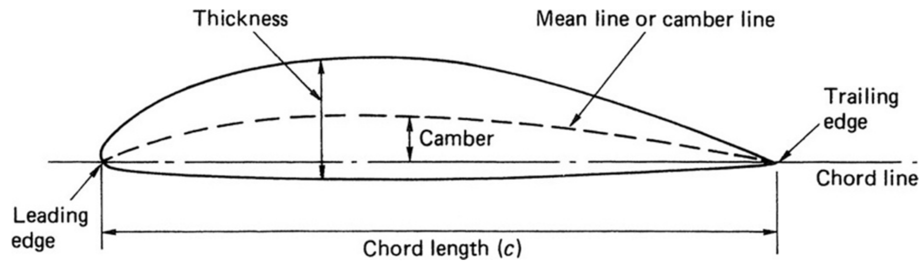

Figure 2 Propeller Blade Section Shape (Taken from [6])

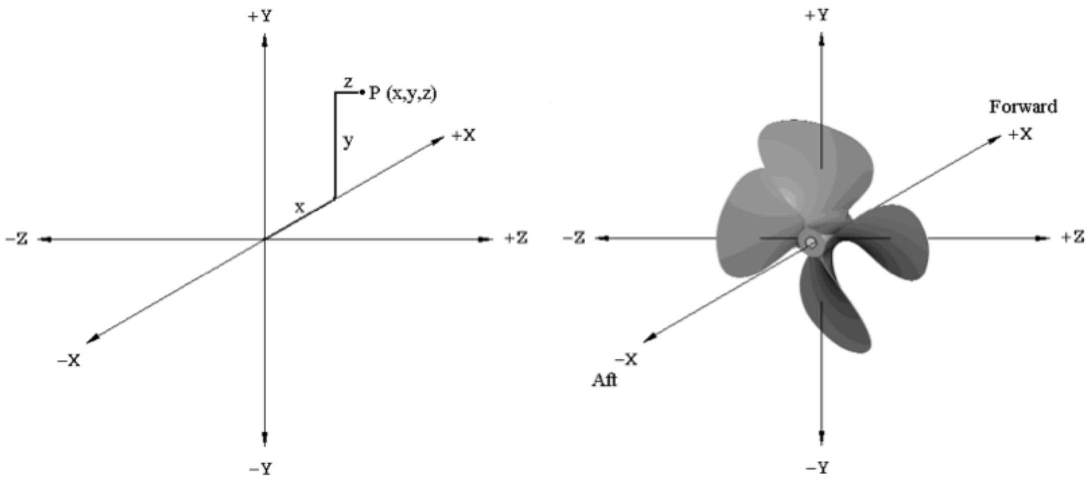

Figure 3 Propeller Coordinates (Taken from [20])

Once propellers required computer numerical controlled machines, cartesian coordinates were required to produce products to the specified detail. The traditional coordinate system has the x-axis in the middle of the propeller hub facing forward toward the incoming water flow. The rest of the coordinates system is the conventional right-hand notation. This methodology is coupled with cylindrical coordinates because the shape is traditionally circular around the shaft axis. The cylindrical coordinates allow for the generation of propeller geometry in the form of blade sections perpendicular to the relative direction of the incoming flow. There are primary geometric features that can be abstracted out to generate the rest of the propeller. The diameter of the propeller is one of the first parameters.

Traditionally this item is specified by the type of vessel the propeller is going on. The design will typically choose the largest size the application will allow with tip clearance and desire draft limiting factors. The tip clearance is the distance from the propeller to the hull. If the propeller is too close to the hull propeller can cause unwanted vibration or noise. The propeller can protrude below the hull, thus adding to the vessel's draft. The draft restriction can be a limit set by the intended use. Fixing the propeller diameter fixes the propeller radius. The remaining propeller characteristics span the propeller radius. The characteristics are typically referred to in their ratio of total radius, like "0.5r/R"

The propeller hub is the central section of the propeller that connects the propeller blades and propeller to the propeller shaft. This feature dictates the available space for the propeller blades along with the minimum section radius. The propeller hub length also sets the lowest radius chord length, more on this characteristic later. These are some of the few propeller characteristics that do not vary with radius.

The remainder of the propeller characteristics varies with radius, also known as propeller distributions. The propeller pitch is the angle of the section of the blade relative to the rotational axis. Pitch is a measure of distance. This measurement is odd in propeller design because pitch corresponds to a blade angle and needs to be converted later for design purposes. The propeller pitch is how far forward a propeller would advance in one full propeller rotation for a simple visual illustration. As the propeller pitch goes out in radius, the pitch angle changes to keep the linear pitch distance the same. For the "constant pitch" propeller, the pitch distances are the same all the way out to the maximum radii. The "constant pitch" design means that the pitch angle changes, but the linear distance pitch is constant. With variable pitch propellers, the pitch distance changes as well. With the higher-end design, the propeller's pitch can vary significantly. This higher-end design configuration leads to a problem classifying and calculating the propeller pitch that is not constant across the blade. One industry standard is to refer to pitch at the 0.7 r/R. Referring to the 0.7r/R pitch is usually a good representation of the design. Chord length is the length of the propeller section.

Cylindrical coordinates are necessary to measure chords. The chord design lengths change going out to the outer radii as a function of r/R. The propeller section is the thought of as how a cylinder cut through the propeller at radius r/R would appear unwrapped in two dimensions. The chord length is measured from the Leading edge (incoming flow side) to the trailing edge(outgoing flow side). This section is in the form of a typical airfoil. The thickness of this airfoil section is also radius based dimension that changes through the span of the radius.

Rake is a linear measurement parallel to the x-axis. A propeller blade with zero rake will be perfectly perpendicular to the x and y planes. Looking at the propeller blades from the -y-direction, it is the amount the propeller blade sweeps aft or away from incoming flow. This dimension again is represented as a function of blade radius. The skew is a measurement of angle sweep around the x-axis. This dimension changes with radius as well. Two features utilize 2-dimensional variation in the characteristic, the local thickness, and camber. Local thickness is variable at each radius at each position along the chord length. This attribute is a function of the propeller's maximum thickness and provides the location along with the pressure and suction faces of the propeller. Camber is also a function of radius and the x position along the chord length. Camber is distance off the chord length. Camber is applied to apply local pitch angle variation. This variation allows for decreased angle of attack at the blade tip and increases effective pitch through the rest of the blade section. The decrease in the tip angle of attack helps stave off cavitation inception.

These are the primary characteristics of the propeller blades. A few other features can be easily applied to a radius distribution for the ease of application but are specific details not relevant for optimization, like trailing-edge thickness, leading-edge thickness, etc.

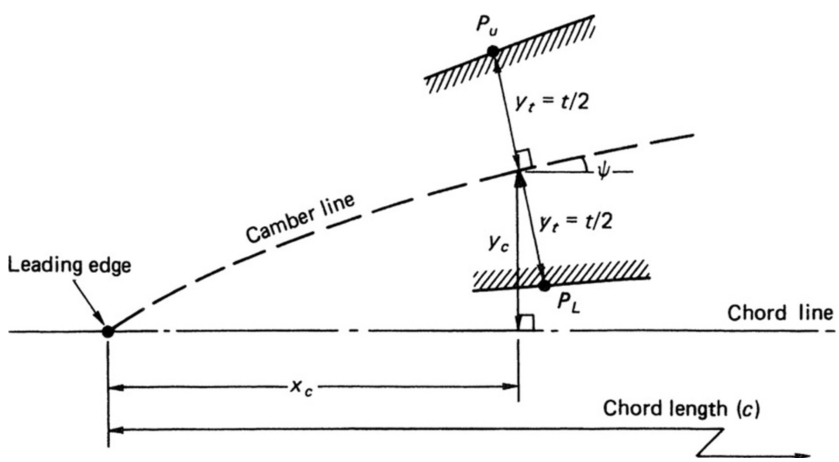

Figure 4 Example of Camber Line and Local Thickness (Taken from [6])

In order to reference positions on the propeller blades, a system of ratios has been developed. When referring to the span-wise dimensions, a fraction of the radius is used, r/R. The denominator is the overall radius, and the numerator is the particular radius dimension at this specific station.

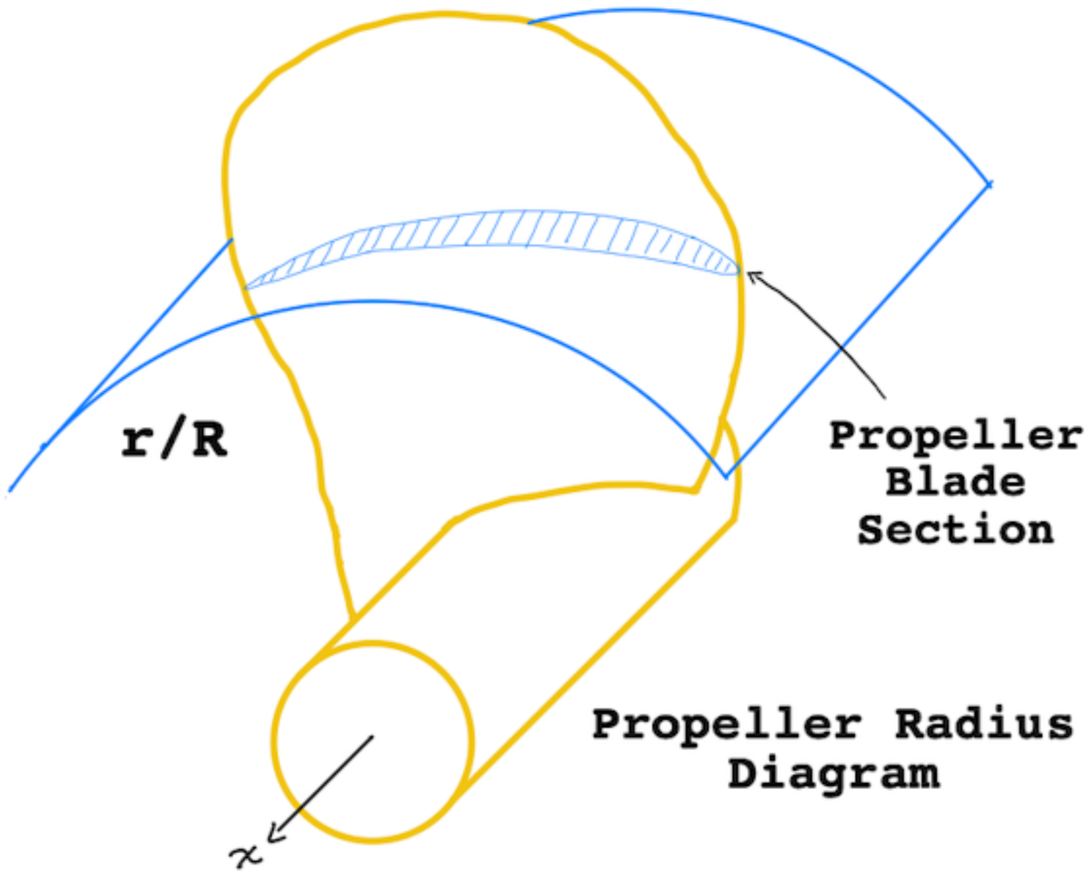

Figure 5 Propeller Radius Diagram (Displaying r/R)

The other ratio used is the chordwise position. This ratio, x/C, is used to represent the position on the propeller section. The denominator, C, is the chord length for the particular section, and the numerator, x, is the distance down the chord length, see figure below. This dimension is usually provided to the calculation as a percentage of the total chord length.

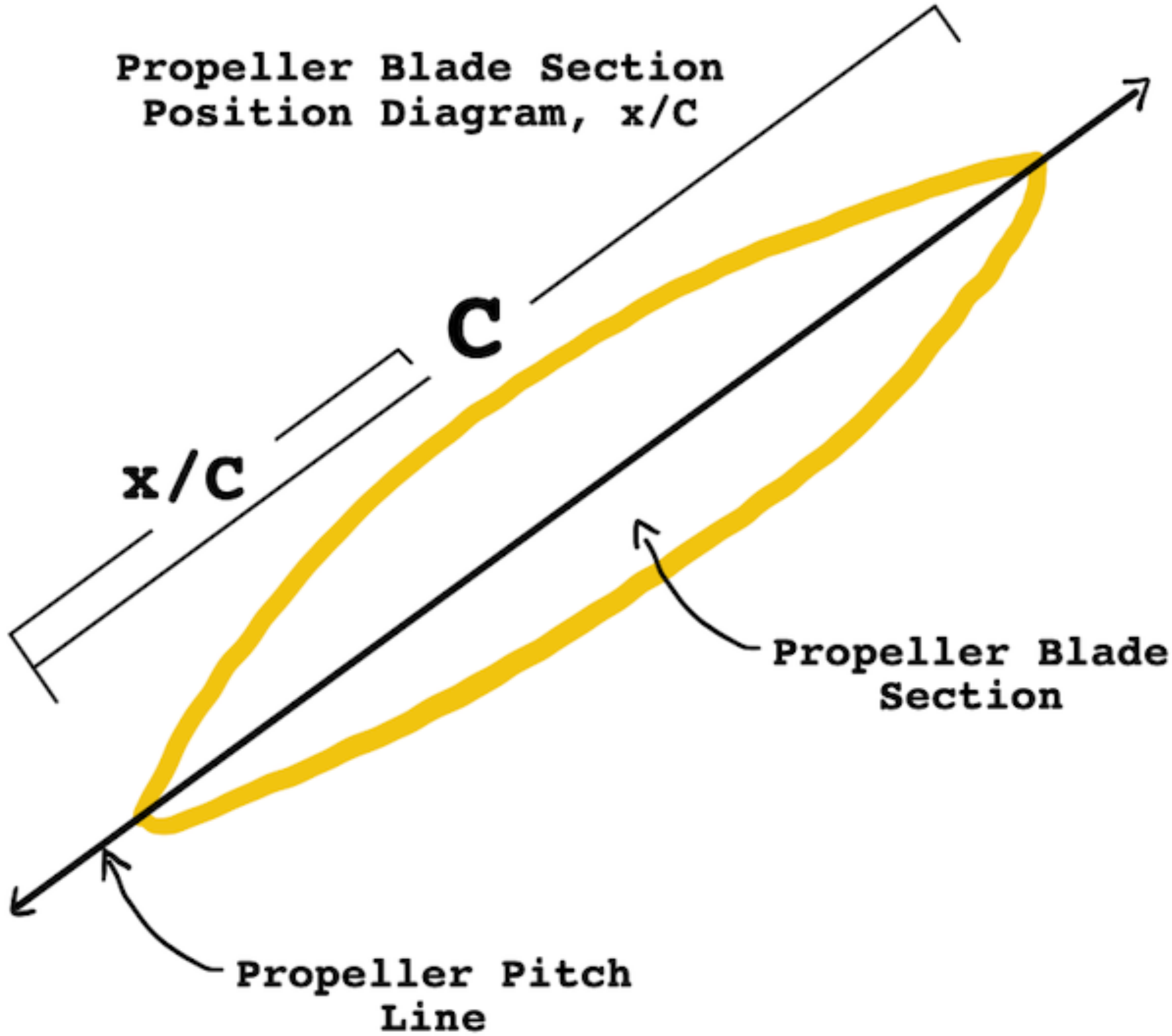

Figure 6 Propeller Blade Section Diagram (With x/C description)

CHAPTER 3 EVOLUTIONARY ALGORITHM BACKGROUND

A basic review of evolutionary and genetic algorithms is necessary to explain their application to this specific problem. Evolutionary algorithms are a subset of the optimization algorithms used to sort through functions to find solutions. These algorithms operate on modeling natural evolution and genetics. This modeling technique simulating evolution has proven itself as computational efficient in finding a near-optimal solution. In evolutionary optimization methods, a population of solutions are evaluated for objectives and constraints of the problem and are compared against each other. The algorithm selects the best solutions for the next generation determined from the objectives and constraints from the evaluator outputs.

This operation continues until the desired number of generations (or iterations) has been reached, or some other criteria are satisfied. If performed correctly in a multi-objective problem, the results are non-dominated solutions close to the Pareto solutions.

Popular genetic algorithms for multi-objective optimization are NSGA-II [9] and NSGA-III [8]. These algorithms have a proven track record of success and have proved efficient in applications similar to marine propeller design. These genetic algorithms have demonstrated the ability to provide diversity in solutions to multi-objective problems. Point-based optimization methods tend to struggle to find the global optimum by getting stuck in locally optimal solutions. Evolutionary algorithms have the ability to find and go beyond local optimal solutions by utilizing population diversity in unique ways. This means that a widely distributed set of results or options can be found all along the Pareto optimal front.

Most evolutionary algorithms have a similar setup and follow very similar steps. First, the algorithm generates an initial population. An initial population is a number of solutions generated by the algorithm to test. Then, the evaluation is administered based on the specific algorithm. The selection process is conducted by ranking results(based on non-domination and a diversity metric called crowding distance[9]) from the generated population; the specifics of the selection process are again dependent on the algorithm. Based on the ranking results from the previous step, the algorithm generates a new population.

The latest population then replaces the preceding population and is evaluated for objectives and constraints. This operation completes one generation. This loop repeats until the specified termination condition is satisfied. Termination conditions can be based on a specified maximum number of generations or criteria-based, satisfying a certain specified limit on the objectives. Different algorithms vary in the way they conduct each step to achieve satisfactory results.

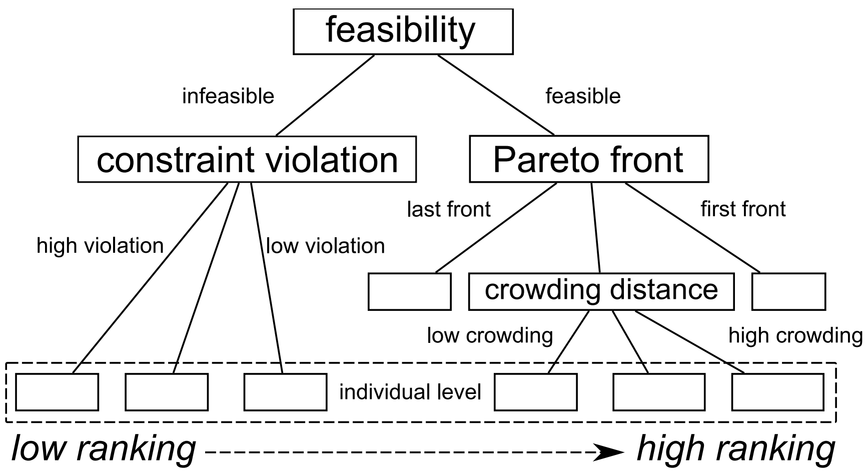

Figure 7 Example Evolutionary Algorithm workflow (Taken from [19])

3.1 NSGA-II

Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) [9] is the second version of this popular algorithm series. NSGA-II handles multiple objectives in terms of creating a non-dominated sorting of population members in its niching-based selection operation and generating a new population from the best sorted members. Comparing the algorithm's populations to each other, NSGA-II uses tournament selection to generate a new population.

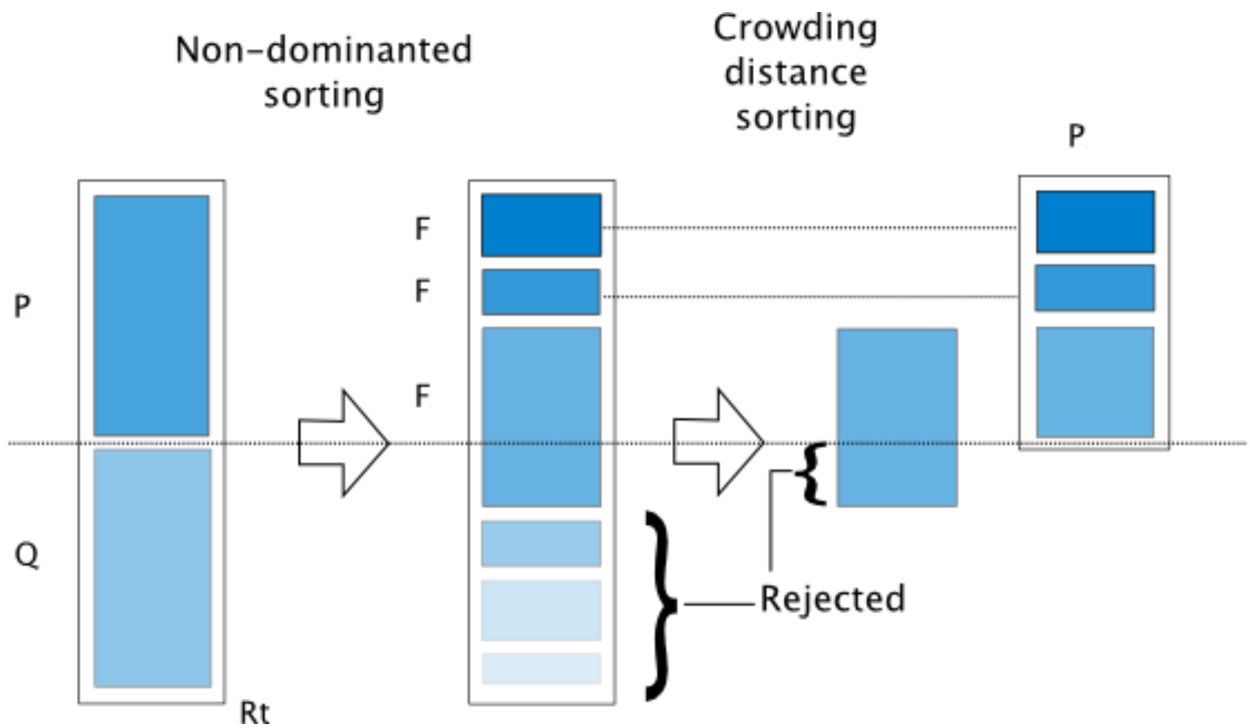

Figure 8 Diagram of NSGA-II Sorting (Taken from [5])

3.2 NSGA-III

The proposed analysis required optimization of more than two objectives. NSGA-II is not the ideal tool for this many objectives, which led to the investigation of other algorithms. NSGA-III [8] is very similar to NSGA-II, except for the additional reference vectors. The framework needs additional information for the algorithm to find the Pareto front on higher dimensional (usually applied to three or more objectives) problems. NSGA-III requires a set of reference vectors supplied at the start of a run. By comparing the closeness of each population member's normalized objective values close to each reference line, a distributed and non-dominated population is maintained in each generation. The creation of a new population and termination condition is identical to that in NSGA-II. The supply of a set of well-distributed reference vectors in the entire positive sector of the high-dimensional objective space and ensuring that population members approach the Pareto front by covering as many such reference vectors as possible, NSGA-III achieves a well-distributed and well-converged set of near Pareto solutions. The reason for both NSGA-II and NSGA-III's popularity comes from the fact that they are parameter-less, making them easier to apply to new problems.

CHAPTER 4 REVIEW OF LITERATURE

Once multi-objective evolutionary algorithms were made available, with proven success solving complex engineering problems, the marine community began proposing their use for propeller development. Benni [1] was the first to apply these algorithms to propeller design in 2003. He demonstrated a method to optimize B-series propellers for efficiency and thrust coefficients using cavitation as a constraint. It was one of the first applications to demonstrate the potential of these algorithms to help the design find solutions that the older propeller design methods could not. Takekoshi 2005 [22] was successfully able to apply the optimization algorithms directly to the blade sections. The propellers were evaluated with Vortex lattice methods and coupled to multi-objective optimization algorithms to adjust the blade sections to achieve optimal results. In 2006[7], Chen[7] demonstrated that multi-objective optimization methods could solve various optimization problems in the marine space. This method showed that efficiency could be optimized against vibration and provide an optimal front with genetic algorithms.

Gassama 2016 demonstrated that multi-objective optimization techniques could help determine the optimal propeller and ship combination. These methods optimize for fuel consumption and a specific function evaluating the propeller characteristics. Optimizing for propeller and ship characteristics allowed the ship parameters to be adjusted as well. In 2016 [23], Vesting provided an overview of a propeller design optimization scheme with population-based algorithms utilizing a meta-model of the propeller. This method demonstrated the feasibility of NSGA-II as a suitable optimization tool for the marine propeller by altering the control input variables. Jiang in 2016 [15] optimized the propeller design for efficiency unsteady force and mass. This method incorporates the fluid-structure interaction coupled with the panel method and a finite element analysis for the strength. The proposed method used Gaggero 2017 proposal [13] as a model. The unique characteristics of this method are the parameterized propeller characteristics using panel methods as evaluators. Once the solutions converged, the method called for the optimal solutions assessed with more sophisticated CFD software to verify the results. This method proves a unique method for optimizing efficiency, cavitation characteristics, and ship speed. Traditionally propeller design and optimization use a fixed speed. This method uniquely allowed speed to be optimized.

CHAPTER 5 PROPOSED DESIGN METHOD

5.1 GEOMETRY

The proposed and current design method used was designed by Maritime Research Associates and Michigan Wheel Marine. The propeller orientation framework is arranged by "A Rational Approach to Propeller Geometry" [17]. The design method utilizes spline interpolation for extracting the radial distributions. These calculations are all done inside a Microsoft Excel Workbook extend with Visual Basic macros. The excel book generates all the read-in files for the evaluators, PropCav, MPUF, LLSR, and Pdesign. The excel work uses the primary variables and the prearranged spline routines to map the propeller parameters out on the radius distributions. The primary variables are the beginning of the propeller design. These items include Propeller Diameter, Hub Diameter, Engine Horsepower, Gear ratio, and Engine RPM. These begin the distributions. Previously successful propeller designs are also beneficial in this stage. A proven successful propeller provides the designer the foundation of the propeller design.

The spline workbook generates propeller blade geometry for evaluation in the form of text files. The workbooks polynomial functions that go through a set of desired points. These functions are called splines. The splines are means to keep the propeller shapes fair and free of drastic shape changes. There are different methods to find polynomial functions to represent the points; this workbook splines through the points, and the desire is able to review the derivatives for the functions.

When the spline routines generate the propeller blade shape, it is only for one blade. The final propeller generation software copies and rotates the blade for a complete design. The evaluation codes used can read the text file information printed by the spline workbook. With the blade number provided, the evaluation codes perform the calculations on the whole propeller. This information is read back into the excel workbook and compared to the primary variables. The designer repeats this process until satisfactory results are archived. These evaluators will be reviewed in more detail later. All the designs work on only one propeller blade because each blade is the same regardless of the blade count. The blade pitch is described by a non-dimensional Pitch over the Diameter ratio. This ratio is a function of blade radius. The other options are using the x/C, the x-location on the chord line over the chord line length, and then using both r/R and x/C to create surrogate surfaces. Surrogate surfaces can calculate thickness and camber distribution as two-variable functions. The P/D points and the r/R points generate a spline function. These splines keep the blade fair with limited abrupt changes in shape or form, which can have severe detrimental effects on cavitation performance. The current method adjusts the spline with points at a radius distribution. The adjustments are fixed on the radii and can only move up and down in P/D value. This method is similar to the calculated chord length over diameter (C/D) vs. r/R and the maximum blade thickness vs. r/R.

The propeller skew and rake calculated splined with functions of r/R, but these values are not adjusted unless the design is for an unusual or specific operation.

There are characteristics not listed here that are used to detail the propeller, including leading and trailing edge adjustments. These features are essential to performance but are not a focus on this method.

The geometry is then calculated for a single blade. With the characteristic distributions defined, the proposed design method can calculate the propeller blades. The design can be broken down into a few primary data sets that are necessary for the evaluators.

5.2 EVALUATORS

The evaluation software used was proprietary software developed by the Consortium on Cavitation Performance and High-Speed Propulsors. This group consisted of industry, government, and academics to advance the marine propulsion community. Michigan Wheel and Maritime Research Associates were a part of this consortium and provided access to these evaluation computer codes. The two primary evaluation codes that were used were PropCav 2A and MPUF 2A. PropCav uses the boundary element method for evaluation, and MPUF uses the vortex lattice method. PropCav is used to determine low-speed Kt and KQ coefficients and propeller cavitation information, including cavitation volume and pressure coefficients.

MPUF is used for the faster speed Kt and KQ information. These are both acceptable methods for middle-level analysis. More advanced evaluation methods using Unsteady Reynolds Averaged Navier Stokes (URANS) equations are used for more in-depth evaluation, but this is at the cost of much more computational complexity. Utilizing URANS data is possible for optimization, but it does require more computational resources. The boundary element method and vortex lattice methods are inviscid computation models assuming there is no viscosity in the water, making the models fast and accurate enough for mid-level analysis. URANS simulations include the viscosity of the water. Thus, it provides the user with a much more complete evaluation.

Table 1 Primary inputs for Marine Propeller Design

Primary Inputs
Allowable Diameter
Engine Horsepower
Reduction Gear Ratio
Number of blades
Gear and Shafting Reductions
Targeted Vessel Speed
Number of Blades
Shaft Angle
Hub dimensions

5.3 REVIEWING THE DESIGN

Once the evaluators have run the current framework, the same workbook reads back the KT and KQ values output from MPUF and PropCav. The KT and KQ values are then compared to the available, delivered horsepower to the propeller. If the design requires too much or too little power, the propeller blade design is adjusted and reevaluated. The error in this calculation was minimized one at a time. The traditional method requires the designer to load or unload the propeller by altering the pitch and chord. The spline adjustment method is proven to be very useful during this process because it facilitates multiple quick adjustments to specific regions of the propeller. Pitch and chord are adjusted first because these are the primary drivers when dealing with propeller loads. The greater the pitch, the larger the pitch angle, meaning greater attack angles and more load. The larger the propeller's chord is, the more area on the blades to impart the engine load onto the propeller, which in turn imparts into the water. Once the engine loads are reviewed as acceptable, the cavitation performance is reviewed. The framework allows for vorticity and cavitation pressure to be evaluated in a Tecplot window. This application reads the propeller geometry and data output from the Prop Cav and MPUF for visual evaluation. The designer analyzes the design for satisfactory conditions. If the propeller is showing too much cavitation, the design can be adjusted to elevate the cavitation. The stress in the propeller blades is also reviewable within this framework. Figure 7 demonstrates the results from the stress analysis. These values all must be reviewed and iterated over until a feasible solution is found.

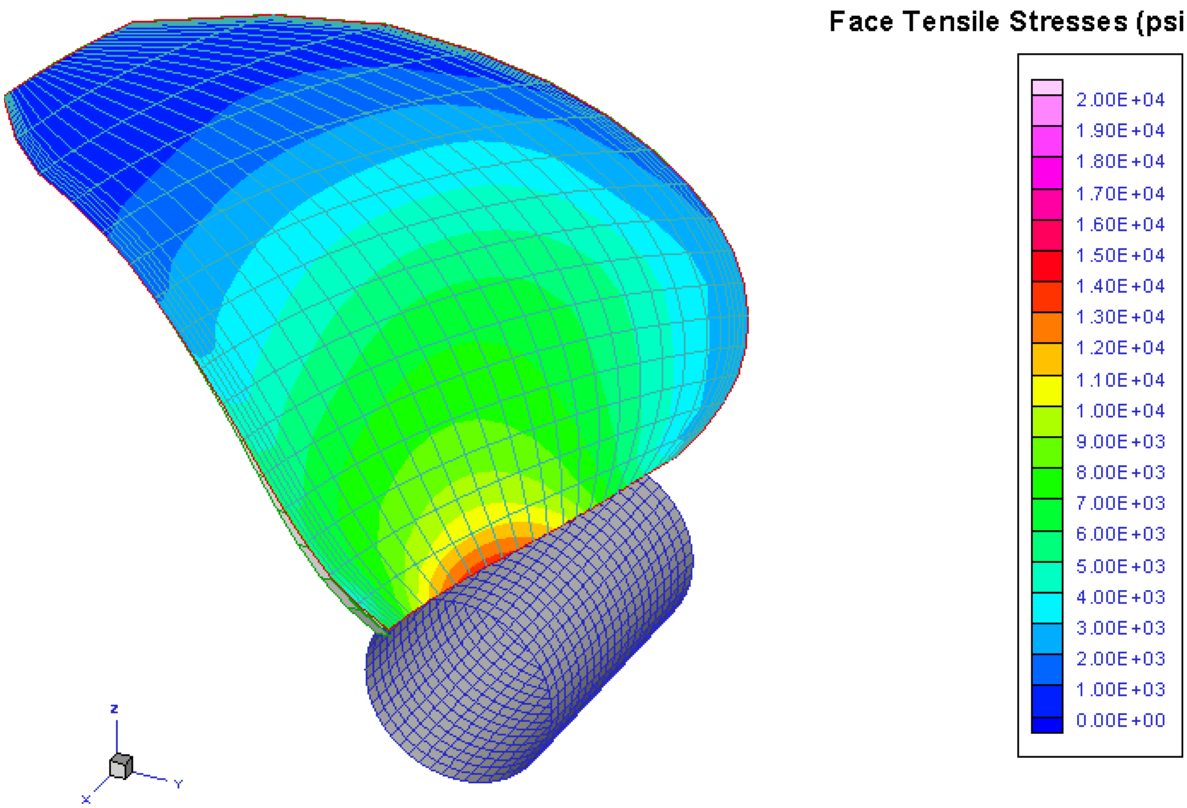

Figure 9 Example Stress from FEA (Showing maximum stress at the root of the blade)

This process is very time-consuming and requires weighing multiple design considerations at the same time to evaluate. The tradeoffs are a significant factor as well. Maximizing efficiency while minimizing cavitation is at the very heart of propeller design. The complexity of the problem requires a multi-objective design approach.

The main target of the propeller design is the efficiency described above. Propeller efficiency is specific to the propeller. This does not account for hull efficiency or engine efficiency. The propeller efficiency is based on the thrust for the given rpm. To limit the scope, so we don't dive into the whole vessel design, the analysis concerns just the propeller. In practical applications, propeller efficiency is usually considered when referring to vessel efficiency and engine efficiency. It is best to have the propeller efficiency peaking at the engine's rated horsepower. The engine-rated horsepower usually corresponds to the engine's desired operating condition. Most marine engines may not be at the top of the fuel efficiency, but it is where the engine manufacturer would prefer to have the engine consistently operate for any number of reasons, whether it be maintenance requirements or overheating issues. This is the target speed. During the design, the goal is to maximize propeller efficiency at the rated engine speed.

Maximizing the efficiency ends up putting a significant load on the propeller blades themselves. If done correctly, most of the engine's power will be transferred to the water as thrust. This thrust is transmitted through the propeller blades. Part of increasing efficiency is making these blades as thin as necessary. Thinning down the propeller blades also puts significant stress on the propeller blades. During the design process, considerable attention needs to be paid to the propeller blade stress. This stress cannot exceed the yield stress of the material. For this design scenario and this evaluation, the assumption was that the propeller would be made from the American Bureau of Shipping Nickel Aluminum Bronze Type IV, which has a minimum yield stress of 35,000. The design calls for the blade stress not to exceed 15,000 psi, which provides a safety factor of 2.3.

The subsequent primary consideration when designing and evaluating propellers is cavitation. As described briefly above, cavitation is the vaporization or boiling of the water around the propeller caused by the pressure dropping below the head pressure of the water around it. This drop in pressure causes the water to boil and form bubbles. The bubbles themselves are not harmful except for some loss in efficiency, but when the bubbles collapse, they can cause significant erosion. This erosion can be major enough to condemn the propeller or even cause the propeller to lose a blade while operating. The potential damage caused by cavitation is something to consider while reviewing propeller performance. Figure 8 below provides an example of the cavitation cavity that can be seen from the design evaluator.

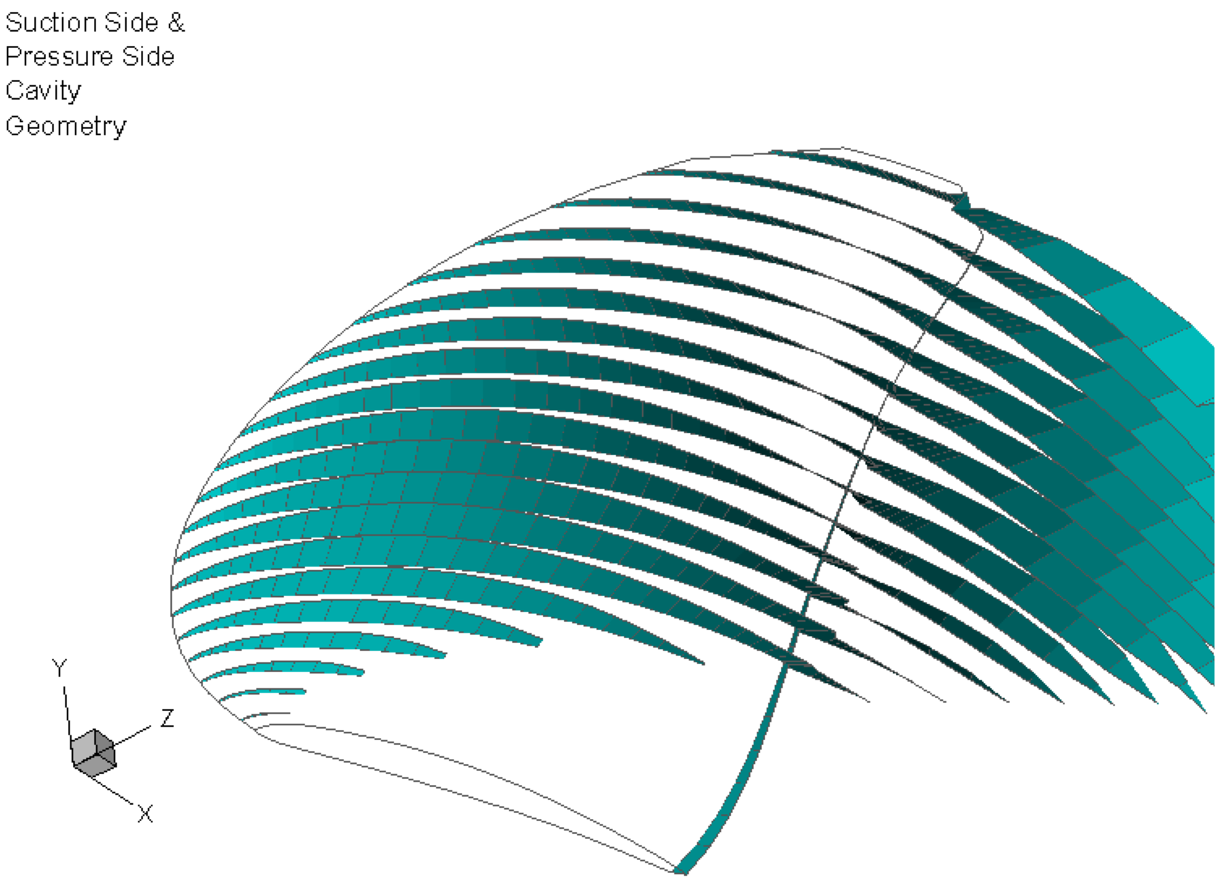

Figure 10 Example large Cavitation Cavity (From Propcav)

Loading the engine is also an essential factor in propeller design. For typical propeller design scenarios for the type that is considered, the vessel's engines are selected in advance cannot be changed along with the gearbox. These high-speed diesel engines typically are turning around 2,000 rpm and have gearboxes that step the RPMs down by 2:1. When we study loading the vessel's engine, we must consider a few other considerations. The engine power is being lost to gearing and shafting efficiencies losses. Calculating the delivered horsepower is essential because this is the target engine horsepower that the propeller design needs to match. If the propeller is designed for the Brake horsepower of the engine by the time the power gets to the propeller and into the water, this will cause the vessel's engine to be overloaded. Overloading the vessel's engine is bad for performance in multiple ways, including fuel economy, maintenance items, and overheating. The propeller design is trying to maximize the amount of power that goes into the water, so designing the propeller so that it uses too little horsepower is also not desired.

CHAPTER 6 PROPOSED OPTIMAL DESIGN METHOD

The method proposed here is based on the framework that is currently in place and uses the same evaluators. The changes to the technique begin with software for development. To avoid any license, issue the blade creation, and optimization was chosen to be complete in open-source python. Using the same programming language as the targeted optimization framework, pymoo [5], allowed the optimization software to communicate back and forth easily. In addition, the python standard libraries are extensive, user-friendly, and accessible.

6.1 PARAMETERIZED SPLINES

A similar approach for propeller characteristic distributions was used as the current method. For reference, the present process is splined through specific points to generate the distributions. The proposed framework is splined with control points. These control points are then adjusted by the inputs from the optimization code. Pymoo sends a NumPy vector to the blade generator. The blade generator uses these control point variables to spline the distributions and generate the required propeller characteristics. Spline through the control points has multiple advantages. Two-dimensional adjustment to the control points allows for more adjustability to the splines with fewer variables. Controlling the spline control points allows the splines to maintain fairness even at non-typical configurations. The range of these spline controls points needs to be set for each design.

The two-dimensional distribution, thickness, and camber required another tool to be used. These distributions are variable by the radii and by the position on the chord. Surrogate surfaces were used to calculate the values that changed in two dimensions. This method is like that proposed in Gaggero et al. in 2017[13]. The values calculated with the surrogate surface set the points on the surface of the blade. These surfaces were splined through control points once again. The surrogate distribution surfaces and distribution splines allowed the characteristics to be recalculated frequently by providing a list to the spline object. This list stored all the radii and would recalculate each spline as necessary. An additional benefit is the controlled edges, and smooth splines that work with these. Michigan Wheel's methodology to control the trailing edge thickness is to use a method called truncation. This method pre-maturely truncates the propeller section at specific radii. This operation is completed so the design can have control over the trailing edge thickness. The trailing edge thickness is critical because of the releasing effect of the shape edge and its ability to help minimize propeller vibrations. The surface method uses the trailing edge thickness radius distribution splines and uses them to generate the splines points for the thickness surfaces. This thickness surface provides smooth spline surfaces without changing the airfoil section shape. Any change that would be done to the section shape would be reflected in the surrogate surface. Simple logic with if/then statements not letting the thickness go below a certain point leaves the generated surface with edges. These edges are less than the ideal representation of the propeller and are hydrodynamically very problematic. The specified edges cause distribution in the flow path. The generated surrogate surfaces allow this to be a smooth continuous representation to the edge of the propeller. An example representation of the splines and surfaces is available in Figure 9.

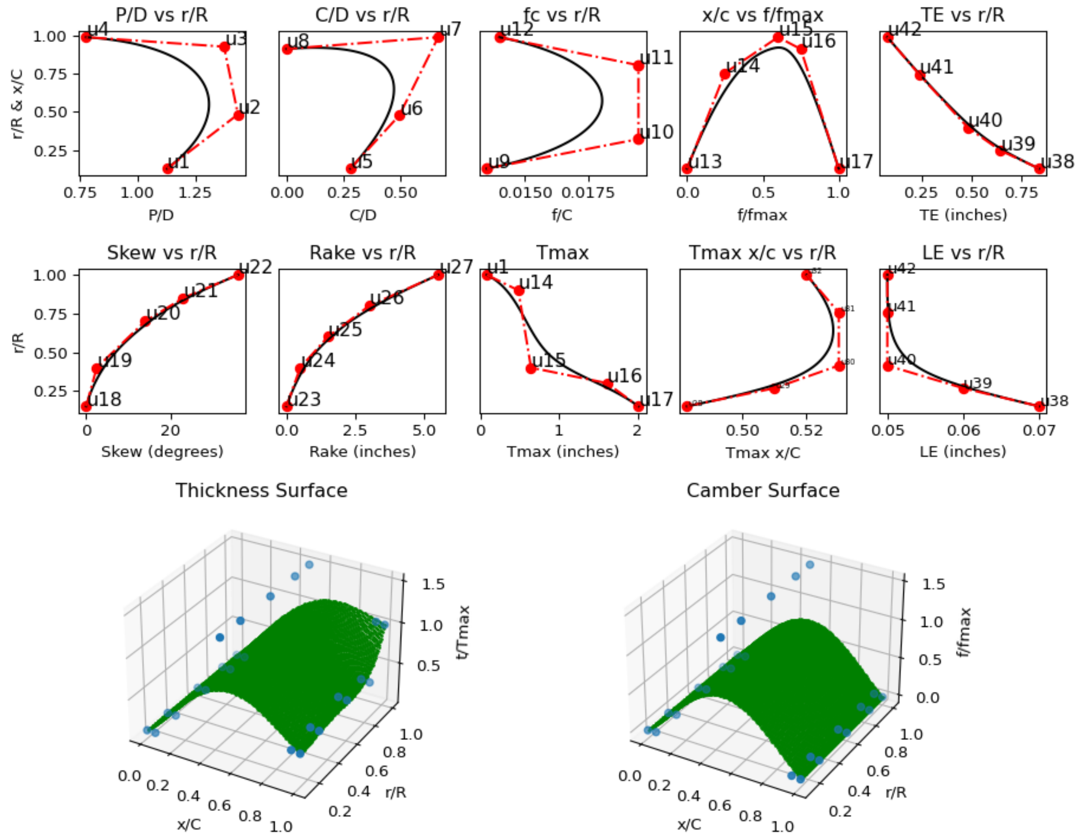

Figure 11 Example Spline Arrangement (Control points are used as variables to the optimization process. All parameters that are not labeled are dimensionless ratios.)

6.2 PYMOO SOFTWARE

The optimization software that was chosen for the optimization part of this problem was pymoo [5]. This code is written in python3 at Michigan State University's Computational Optimization and Innovation (COIN) Lab. The analysis began attempting to modify the Michigan Wheel's blade generator, but this could not be done to allow python to input the data necessary, so the rest of the generator software needed to be rewritten to accommodate the various evaluator software. Michigan Wheel's propeller generator tool had several specialty scripts that needed to be rewritten to call the evaluators from python. Many of them were specific read-in files detailing how the evaluator code needs to be arranged to run the current design. Some files required specific propeller characteristic distributions. This task was handled by simply calling the spline objects and providing the object with a list.

NSGA-II was the primary algorithm used in this operation. The study primarily looked at two objectives at a time. This algorithm was designed to handle such a problem. Most of the primary default operations are left as they were.

6.2.1 INTEGER-BASED EVALUATION

During the optimization schedule, the observation was made that the program was getting hung up on a few feasible solutions with very similar outputs resulting in a slight variability in population size. This was to be expected, but the algorithm is supposed to continue to explore the design space and find other positions for the input variables where the values are significantly different enough. This was later abandoned because other programming errors were found, allowing for better distributions.

Arranging pymoo to provide the correct information when each population member is called requires continuous adjustment. As the code was run, it began exposing other issues with the evaluators and spline generation code. The entire blade generator was stored in a python class outside of the pymoo script. Pymoo initialized and called an instance of the blade generator, and the blade generator returned the objective and constraints as float objects. The blades optimizer was run with the following objectives and constraints.

6.2.2 MAXIMIZE PROPELLER EFFICIENCY

This is a traditional propeller evaluation procedure described above. The values were provided from MPUF 2A in K_T and K_Q format. The vessel's speed is above the recommended velocity for the Kt and KQ values from Propcav 2A. This objective is to be maximized for a good design. Pymoo can only deal with minimizing objectives and constraints. A negative operator was necessary to get the correct functionality.

6.2.3 MINIMIZE CAVITATION VOLUME

These values were taken from one of the many outputs from PropCav. PropCav provides cavitation values at many different positions and types. The value chosen for this minimization is overall cavitation volume. The volume is the overall size of the cavitation bubble and is an acceptable cavitation performance metric regarding the extension of the cavitation. Cavitation performance has traditionally been a competing objective to efficiency. The higher the propeller efficiency, the more cavitation is present. The cavitation usually isn't a direct hinder to propeller efficiency until the stall angles are reached. Cavitation is a competing objective with efficiency because of the other detrimental effects cavitation has on the propeller, including erosion and vibration. This objective is to be minimized for a good design.

6.2.4 MINIMIZE BLADE VOLUME(WEIGHT)

The blade volume is calculated as part of the finite element analysis compiling the blade's stress. This value also corresponds to the weight of the propeller. The material being constant solid density, the larger the volume, the heavier the propeller. Heavier propellers have several detrimental effects, including the additional cost for more material, harder to handle, and the more mass the propeller has, the less material the vessel can move. This objective is to be minimized for a good design.

6.2.5 NOT TO EXCEED STRESS

The stress limit was chosen as a constraint for the propeller design. Traditionally, the thinner the propeller, the better is the performance; however, this understanding has a limit because the propeller blades experience a significant load. The stress constraint is necessary to prevent the material from yielding while under the applied load. The design utilizes standard material Nickel Aluminum Bronze ABS Type IV. This copper alloy is the typical marine propeller material chosen for its mechanical properties and corrosion resistance. With a yield strength of 35,000 psi, Nickel Aluminum Bronze provides good strength with superb corrosion resistance and workability. The stress calculations are provided for the constraints in two theories: Blade beam theory and Michigan Wheel's Finite Element Analysis. The blade beam theory is the typical calculation used by the regulatory bodies. The finite element analysis provides greater detail to the designer as to where the loads are centralized.

6.2.6 DELIVERED HORSEPOWER

Keeping the propellers' absorbing horsepower below the available horsepower is one of the primary constraints. This was chosen as a constraint because it is part of the primary propeller design criteria. The goal of any propeller is to get as much of the vessel's engine horsepower into the functional, forward thrust as possible. The engine horsepower is then stepped down through different gearing efficiency losses and wake fraction losses. The losses are intended to represent the amount of power that goes into the propeller from the engine. The wake fraction losses represent vessel wake loss. As the vessel or anybody moves through the water, it carries with it water referred to as a wake. This wake fraction is there to account for this loss in efficiency of the propeller turning the vessel's wake.

The corresponding constraint for this optimization run is above 99% of the available horsepower. To ensure that the propellers are correctly sized, the minimum horsepower is considered. If the propeller is overloaded, the engine will fail to reach the desired rpm, and if the minimum amount of engine horse is not converted by the propeller, the engine will be underloaded, which is also not ideal. The ideal propeller design is appropriately sized for the engine and speed.

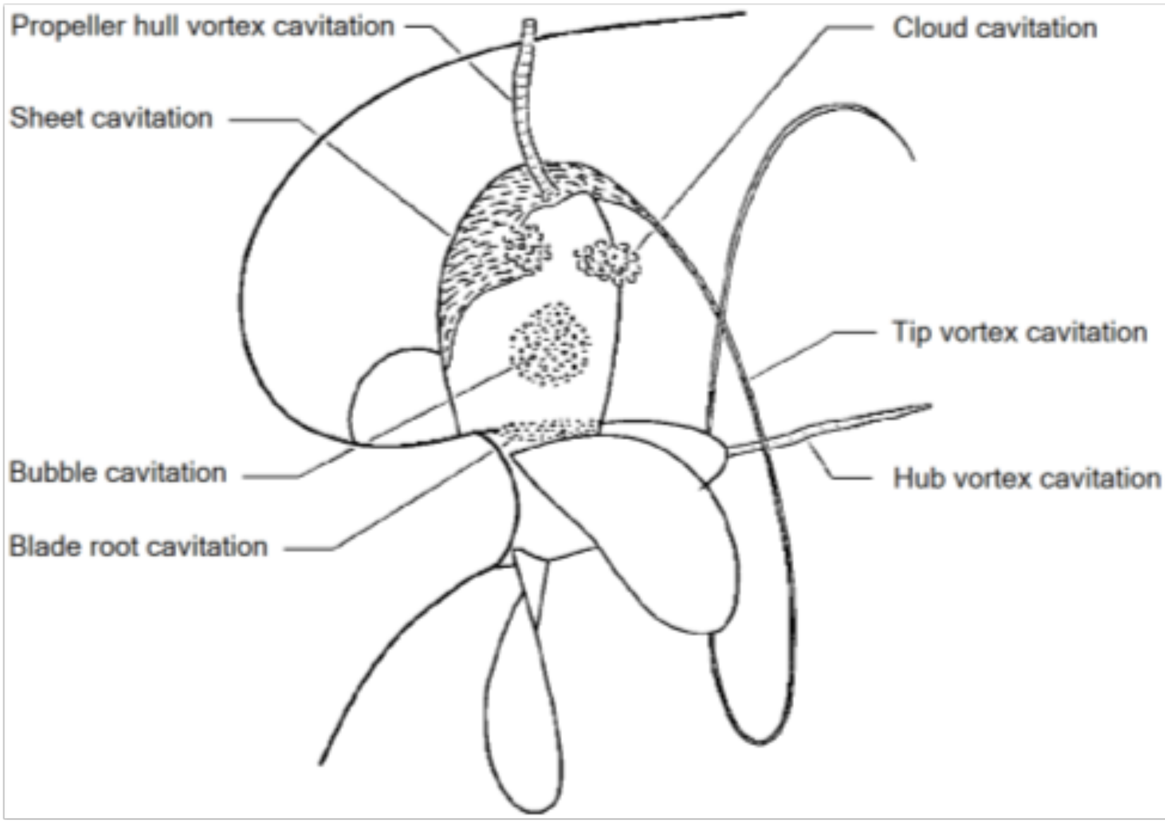

Figure 12 Different types of Propeller Cavitation (Taken from [6])

6.2.7 CAVITATION

Cavitation constraints were necessary despite using cavitation volume as the minimizing objective. The positive cavitation volume constraint was required because, during the initial testing of the code, the optimizing code found designs with negative cavitation volume, which corresponds to cavitation on the pressure face or after side of the propeller. Cavitation on the pressure side is usually worse than cavitation on the suction side because the pressure forcing the cavitation to close has the potential to damage the blade quicker. Limiting Cp pressure was also chosen as a necessary constraint because it prevented any abrupt changes or pressure spikes. These quick changes in pressure cause cavitation to initiate. Figure 12 represents a typical pressure coefficient diagram. CP is a coefficient to represent the pressure on either side of the propeller blade.

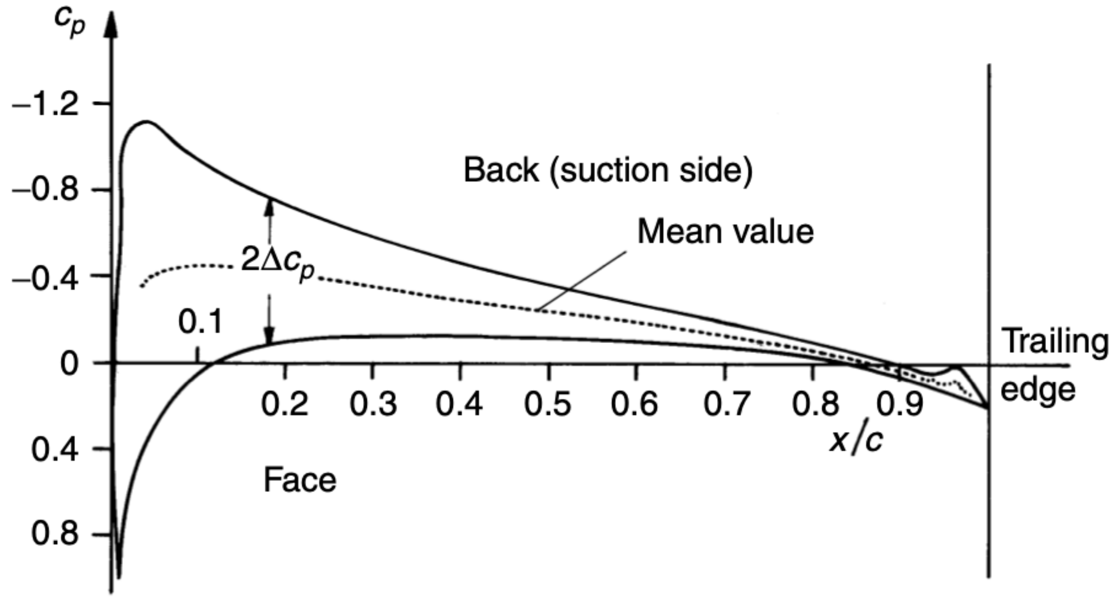

Figure 13 Pressure Coefficient Distribution (Taken from [4])

6.2.8 VARIABLES

The evaluator began by varying the pitch and cord length. Then the evaluator incorporated blade thickness. The pitch and cord variables have two degrees of freedom, while the thickness splines can be scaled as the algorithms go on. The thickness addition was required because the first trial sets were failing due to the stress-induced on the propeller design as the optimizer loaded up the propeller blade.

6.2.9 SECTION SHAPES

The used section shapes are elementary. They are simple ogival section shapes. The more advanced propeller section shapes use more sophisticated airfoil design principles. These advanced section shapes are dictated by the camber and thickness surfaces. These surfaces have control points that an optimizer can adjust. However, due to the scope of this analysis, the surface control points are not examined in full detail for the thesis.

CHAPTER 7 RESULTS

Testing the proposed multi-objective propeller design framework is necessary to attempt to prove several things. The first beginning that the algorithms can indeed evaluate and work toward feasible solutions providing a Pareto front. The first several test cases for this framework were conducted on a propeller with extreme operating conditions. This design had extreme cavitation, and the algorithms were unable to find feasible solutions. When the variables were restricted, the framework was able to work toward acceptable solutions. The application of the three cases below uses the primary variables in this table.

Table 2 Primary inputs for Test Case

Diameter	59	in
Hub Diameter	8.75-8	in
Hub Length	13	in
Vessel Speed	24.62	knots
Number of blades	5	
Horsepower	2600	HP
Engine RPM	2450	RPM
Gear Ratio	4.033	

7.1 CASE 1: NSGA-II FOR OPTIMIZING FOR EFFICIENCY AND CAVITATION VOLUME

The design is attempting to maximize the propeller efficiency while minimizing the issue causing cavitation. These are the classic design objectives for marine propellers. The non-dominated results were found to maximize efficiency and minimizing cavitation volume. Through 50 generations, only nine non-dominated solutions were found. This result is less than ideal because the algorithm has not found a distributed population along the Pareto front with such few solutions. With enough generations, this algorithm could ideally continue to find better solutions. The plot detailing the objective spaces demonstrates the beginning of a high tradeoff point which is useful in decision making.

Table 3 NSGA-II's performance by generations: Case 1

Generation	NDS	Evaluations
25	1	750
30	1	900
35	6	1050
40	5	1200
45	3	1350
50	9	1500

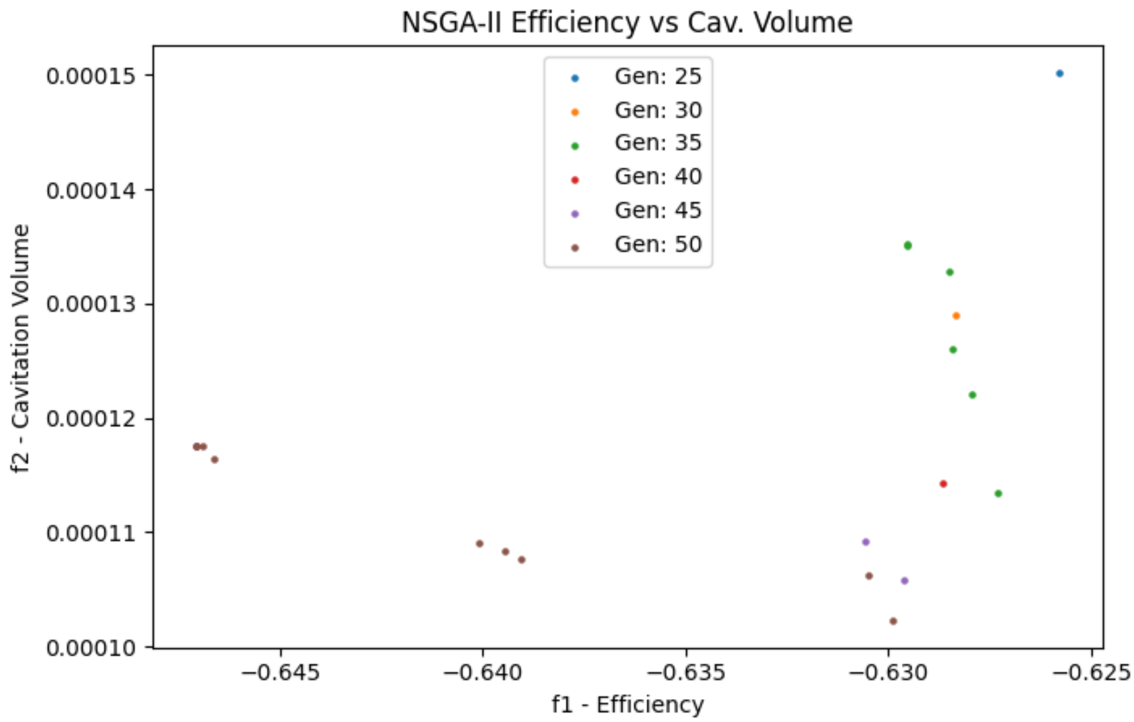

Figure 14 NSGA-II Objective Plot of Efficiency and Cavitation Volume

Table 4 NSGA-II's performance on Case 1: Objective values at Generation 50

Objective Values at 50th Generation	
F1: Efficiency (max)	F2: Cavitation Volume (min)
0.647071	1.1761E-4
0.647069	1.1757E-4
0.646897	1.1749E-4
0.646634	1.1641E-4
0.640093	1.0911E-4
0.639453	1.0830E-4
0.639041	1.0773E-4
0.630488	1.0622E-4
0.629886	1.0232E-4

The results showed that non-dominated solutions could be found. The solutions provided a range of 1.5 percent for propeller efficiency and around 9.7 percent improvement in cavitation volume. When plugging the non-dominated solutions back into the optimizer to begin visually inspecting the solutions, the results showed that the chord length at the very tip of the propeller had what is believed to be an excessive length. This issue is believed to have escaped the optimizer because of the stress finite element analysis constraint not detecting issues at the outer radius. The result is expected because the main methodology in iterative design to minimize cavitation is to increase the chord length. These results led to the next set of evaluations.

7.2 CASE 2: NSGA-II OPTIMIZING FOR EFFICIENCY AND BLADE VOLUME

In this case, NSGA-II runs in response to case one generating blade shapes with a significant cord length at the out tips. This optimization required that the cavitation volume be switched from a minimizing objective to a less than constraint. A cavitation volume limit was set as the constraint from previously run evaluations. These two optimization runs have completely different meanings in the evolutionary computing space. The difference resulted in infeasible designs that had cavitation volumes that were just inside the minimum constraint. NSGA-II was able to achieve feasible solutions with better distributions along the Pareto front using this method.

The plot of the objective spaces shows the solutions closer to the Pareto front in similar time frames. The distribution is also along the front with a range of 36.48 lbs. and a 3 percent difference in propeller efficiency.

Table 5 NSGA-II's performance by generations: Case 2

Generation	NDS	Evaluations
15	1	450
20	7	600
25	9	750
30	5	900
35	2	1050
40	6	1200
45	6	1350
50	8	1500

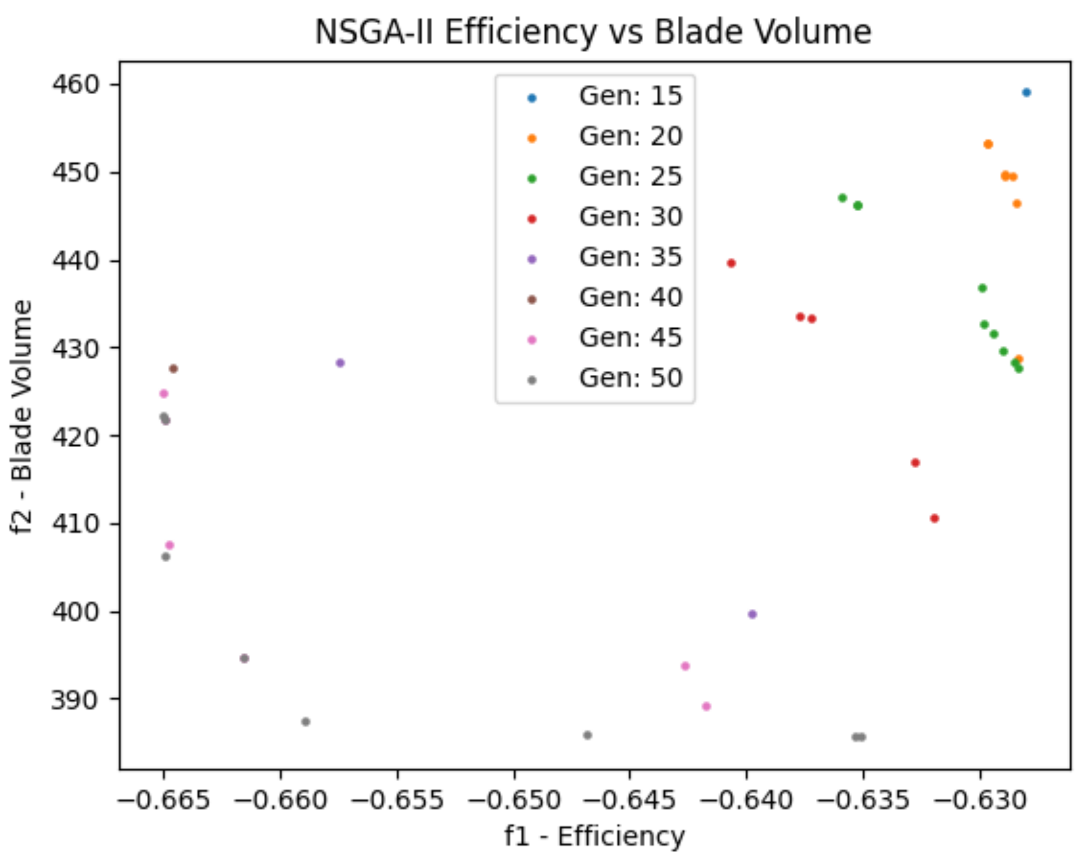

Figure 15 NSGA-II Objective Plot of Efficiency and Blade Volume

Table 6 NSGA-II's performance on Case 2: Objective values at Generation 50

Objective Values at 50th Generation	
F1: Efficiency (max)	F2: Blade Volume (min)
0.66505	422.1
0.66494	421.7
0.66492	406.3
0.66156	394.6
0.65897	387.4
0.64684	385.8
0.63535	385.6
0.63509	385.6

7.3 NSGA-III OPTIMIZING FOR EFFICIENCY, CAVITATION VOLUME, AND BLADE VOLUME

The evaluation was continued with the NSGA-III because NSGA-II could not handle more than two objectives. Utilizing NSGA-III requires the additional vector distribution to get the ability to handle three objectives. The results showed that the algorithm worked towards the Pareto front, like the first two optimization runs. From the performance tables of the algorithm, it does appear that NSGA-III takes a longer time to work its way to the front.

Table 7 NSGA-III's performance by generations: Case 3

Generation	NDS	Evaluations
24	4	720
27	3	810
32	6	960
38	8	1140
40	6	1200
44	5	1320
47	2	1410
50	6	1500

Table 8 NSGA-III's performance on Case 3: Objective values at Generation 50

Objective Values at 50th Generation		
F1: Efficiency (max)	F2: Cav. Volume (min)	F3: Bld. Volume (min)
0.63748	1.186E-4	416.7
0.63633	1.122E-4	427.5
0.63032	1.035E-4	414.5
0.63031	1.133E-4	411.1
0.63028	1.079E-4	411.0
0.62936	1.205E-4	410.4

The set of three-dimensional scatter plots show the non-dominated solutions. It is difficult to visualize the front with such few solutions. The population scatters plot was added to demonstrate how the entire population migrates close to the ideal point.

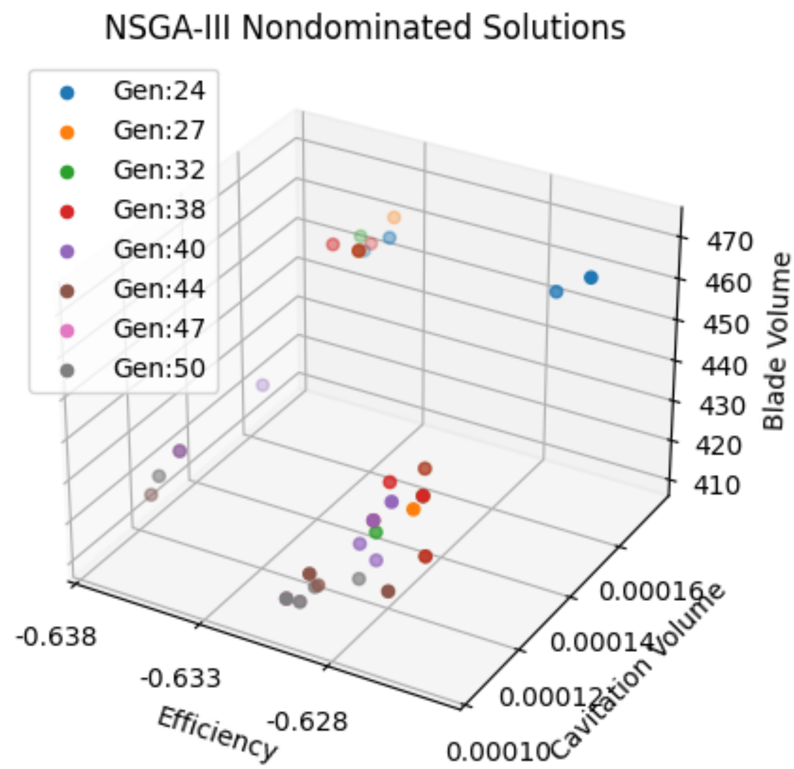

Figure 16 NSGA-III Objective 3D plot: Eff., Cav. Vol. and Bld Vol. - 1 of 3

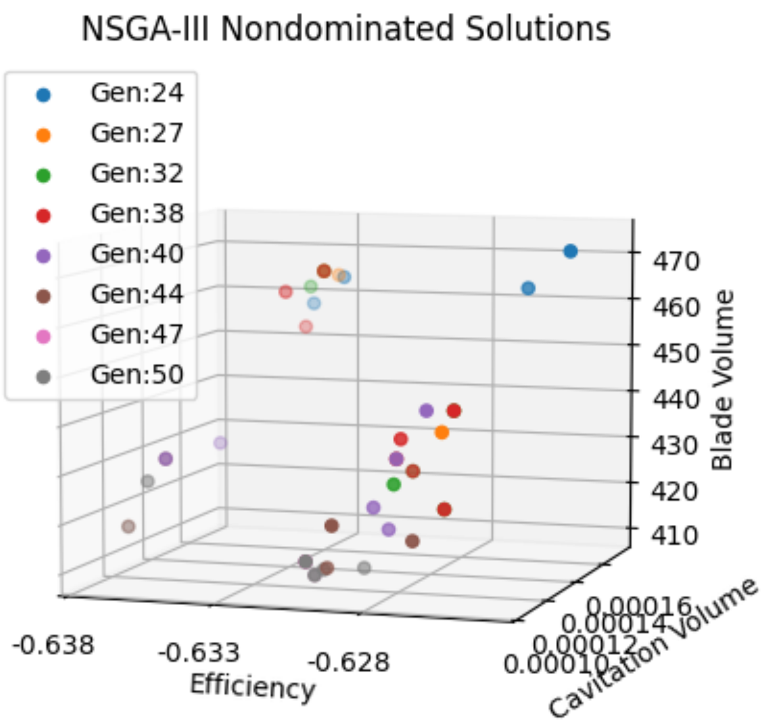

Figure 17 NSGA-III Objective 3D plot: Eff., Cav. Vol. and Bld Vol. - 2 of 3

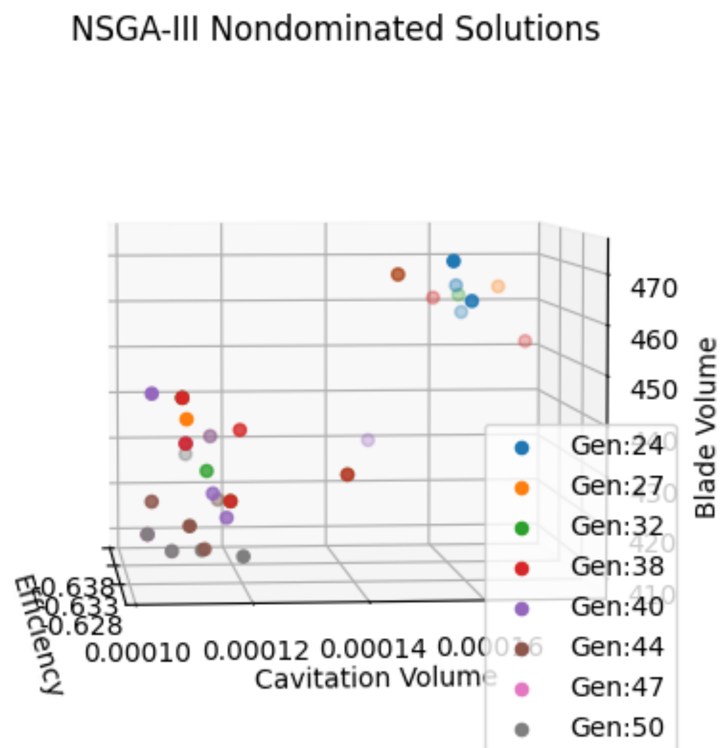

Figure 18 NSGA-III Objective 3D plot: Eff., Cav. Vol. and Bld Vol. - 3 of 3

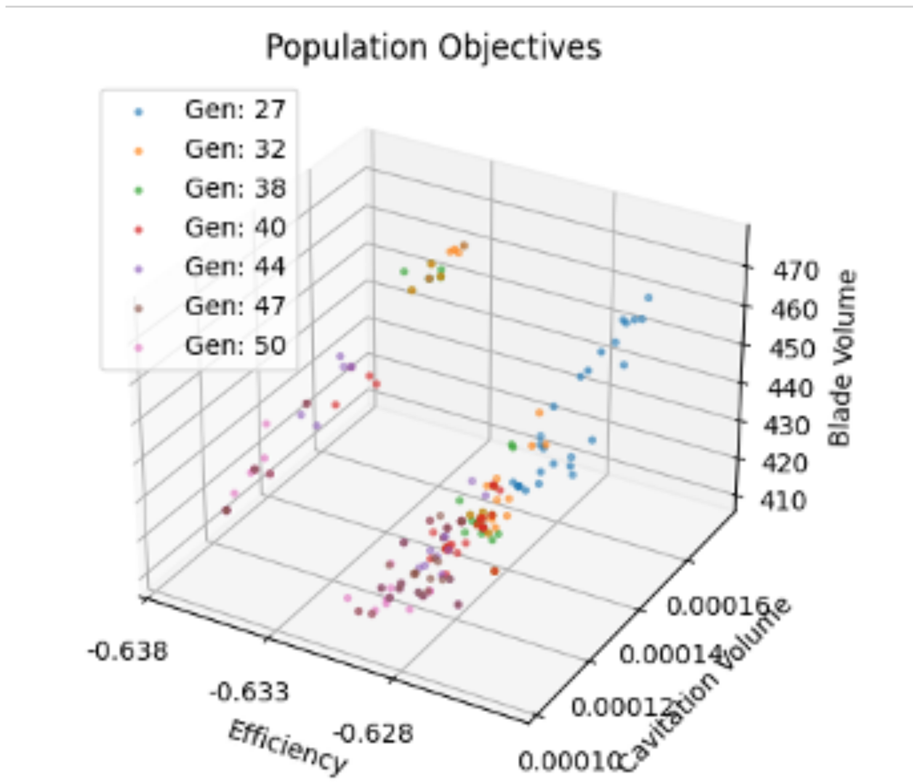

Figure 19 NGSA-III Case 3 Population Plot - 1 of 3

Figure 19 is an example of the propeller sections from one of the non-dominated solutions. As the figure shows, the blades sections are very wide at the top of the propeller blade. This extra blade area is expected when optimizing for minimal cavitation. The extra chord length helps to minimize the cavitation volume.

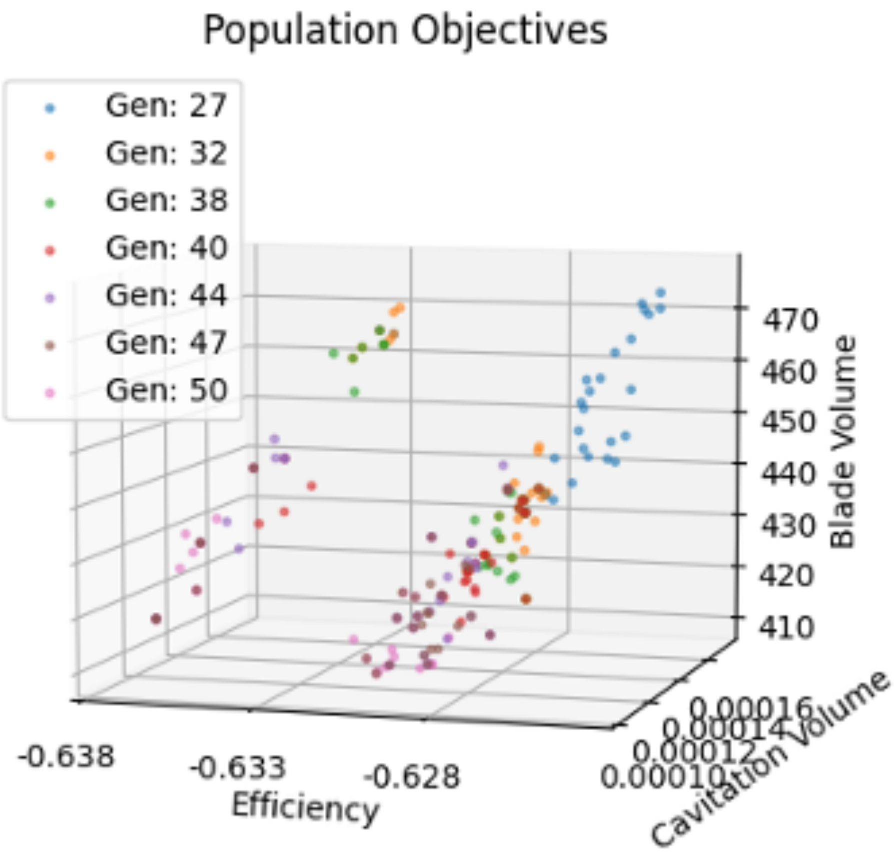

Figure 20 NGSA-III Case 3 Population Plot - 2 of 3

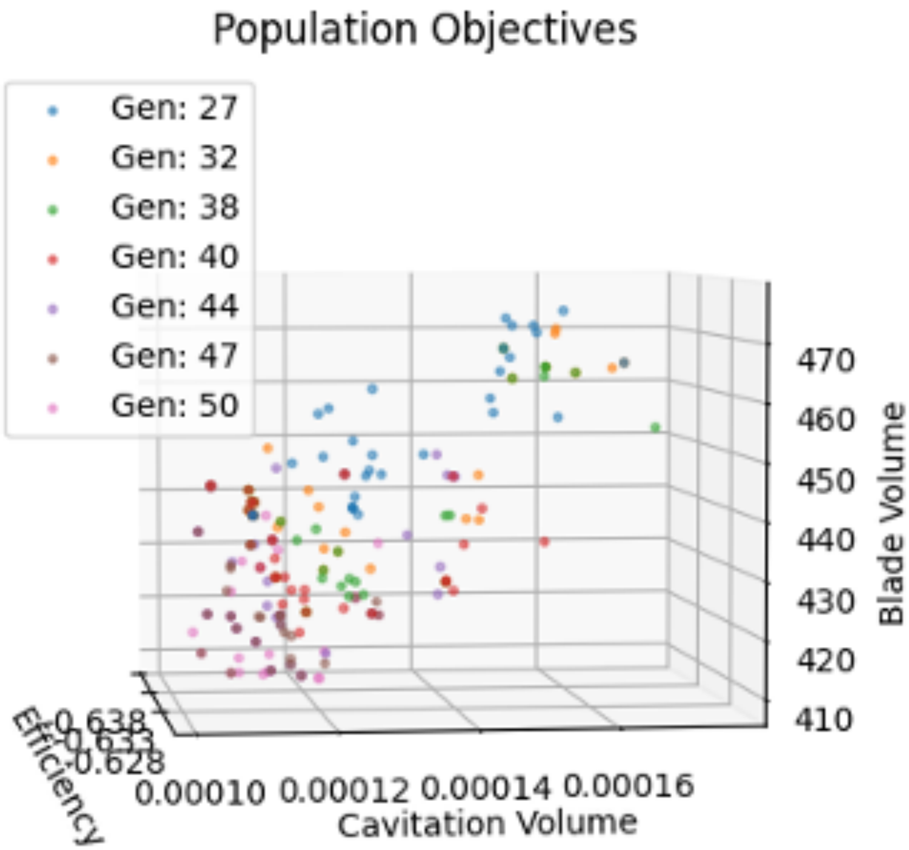

Figure 21 NGSA-III Case 3 Population Plot - 3 of 3

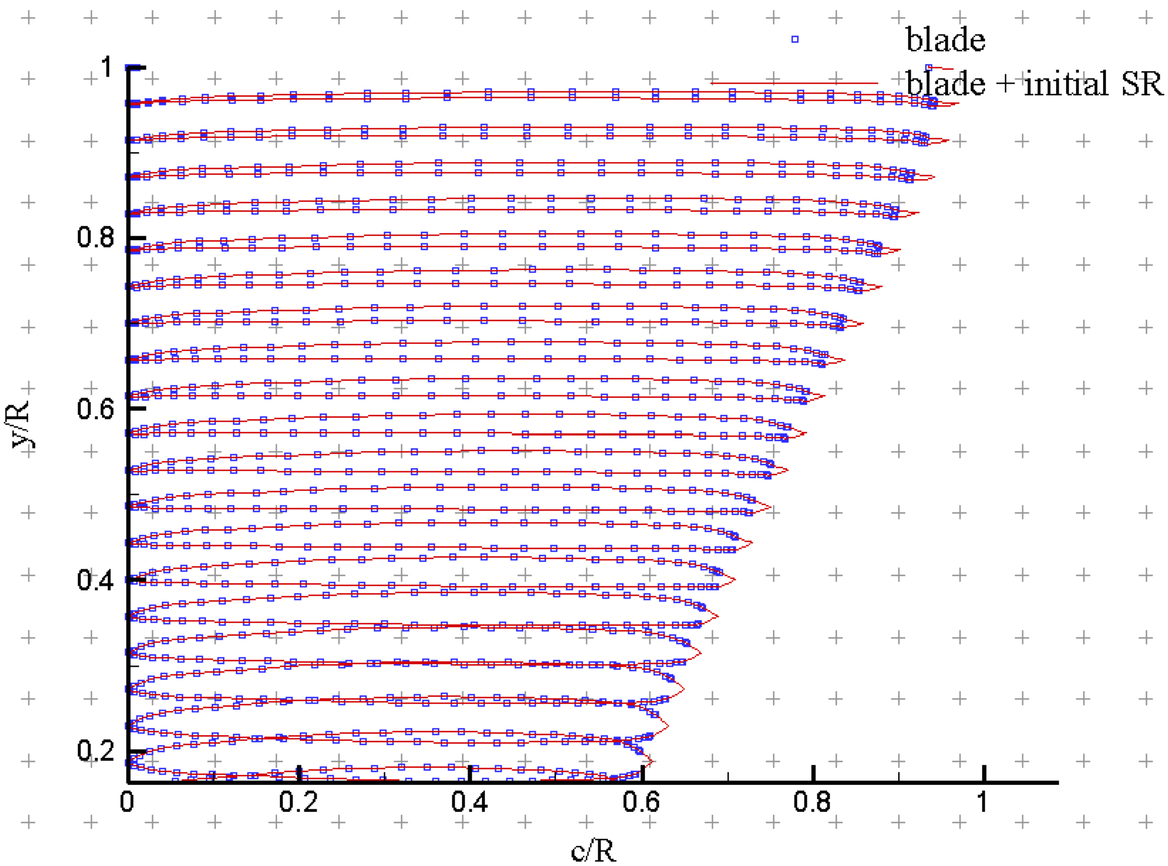

Figure 22 Case 3 Example NDS

Figure 23 shows the cavitation pattern output from PropCav for the same solution. Notice the very minimal amount of cavitation of the trailing edge; this is the desired outcome.

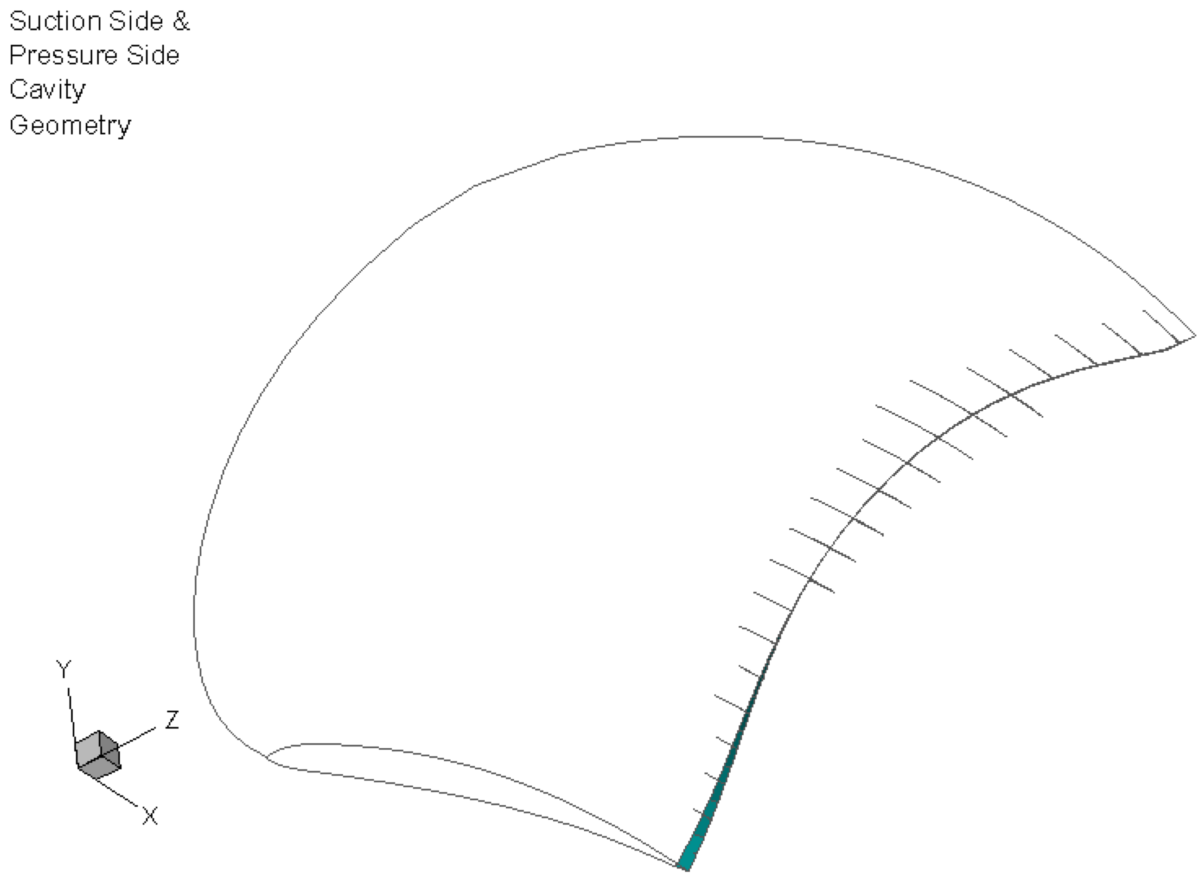

Figure 23 Case 3 Example NDS Cavitation Pattern

CHAPTER 8 CONCLUSIONS AND FUTURE EXTENSIONS

8.1 CONCLUSIONS

This thesis has formulated and optimized the propeller blade design for two and three conflicting objectives. Two evolutionary multi and many-objective optimization methods – NSGA-II and NSGA-III – are used for this purpose. The main reasons for their use are their popularity in solving similar other engineering design problems and the availability of a python-based software environment. Existing evaluation codes (in Fortran) have been integrated with python-based NSGA-II and NSGA-III algorithms from the pymoo distribution. Two and three-dimensional non-dominated solutions have been obtained and analyzed in this thesis. The solutions satisfy all specified constraints, making the whole computational process worthy for practical applications.

8.2 AREA FOR FUTURE DEVELOPMENT

The current evaluator of the propeller geometry, PROPCAV, and MPUF, took a significant time to run. Future development would have to include parallelism in the evaluators. The optimization frame has this capability, but computational resources hindered this method for this review. If this method is to be put into production, this item would need to be solved. Paralleling the computation would allow for faster evaluations and more generations, which would continue to find additional solutions that were Pareto optimal. One future development area would be the possibility of mesh sensitivity adjustment for propeller design. This method works in more advanced URANS software packages. This method could evaluate the propeller with a cost function in the meshed state and adjust the original design by morphing the mesh. This technique has been shown successfully in other airfoil experiments. The suggested method would result in a polygonal mesh surface which is less than ideal for manufacturing. This issue could be solved with the current advancement of mesh to surface technology. The benefits of this potential method are that the designer does not need to be present during the optimization. The design is not limited to the dimensional space that they have traditionally seen.

Further constraints, the 2D cavity plots could have a constraint that restricts the propeller designs with cavitation inception on the blade leading edge. The additional constraint would be a relatively simple addition, limiting the design space and cause evaluators to take longer for designs. Another area that could be beneficial is the addition of more variables. Optimization utilizing more or all the control point variables could have promising results because of additional flexibility in the models. The extra range would allow for the algorithms to process a completely flexible spline configuration. Using this method would only have a population size of 60, but the design will have much more flexibility. From studies, the additional population size, when solving a large number of variable problems, is only beneficial to a population of around 60. Runs using the blade generator were complete using a population size of 30-40 with only 20 variables.

Designs can be evaluated and iterated using this method; however, they come at high computation costs. The Pareto front is critical to multi-objective design because of the ability to review high tradeoff points. The ability to analyze the different configurations and know which propeller designs have advantages over others is helpful to the designer because the current method relies a lot on the designer's experience of propeller design to assist and guide the design phase. Restricting the additional control points limited the ability of pymoo to assign characteristics in certain distributions. With this method, the designer can compensate to some extent for the lack of local knowledge.

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BIBLIOGRAPHY

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