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Simultaneous Optimization of Propeller-Hull Systems to Minimize Lifetime Fuel Consumption

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Abstract

Traditional propeller-hull matching methodologies focus on a limited number of design points and, hence, may not provide the optimal solution for modern vessels with diverse mission profiles. The objective of this work is to introduce a new probability-based design optimization strategy for propeller-hull systems to minimize the lifetime fuel consumption, LFC. The optimization method considers the variation of the vessel resistance with ship speed and geometry, propeller-hull interaction, dependence on the vessel's mission profile, as well as cavitation considerations. Results are shown for high-speed hull forms and B-series propellers. The proposed method considers the propeller and hull as one integrated system and optimizes the critical geometric parameters of both to minimize the LFC. The proposed design optimization was found to help reduce the fuel consumption and converge on very different propeller geometries than traditional point-based design practices.

Introduction

Historically, the hull and propulsion systems have been considered as two different phases of the preliminary design process. In traditional naval architecture, the hull is chosen first through the use of hull form ratios and coefficients to satisfy the basic requirements of the vessel while minimizing resistance. Once the hull has been chosen, a propeller-hull matching exercise is then performed at selected vessel operating speeds in order to choose the propeller with the best performance, i.e. the highest possible efficiency or maximum cavitation-inception speed at one or a few design speeds.

This method of design has shortcomings that affect the overall performance of the final design. The first critical shortcoming is that the hull resistance and propeller efficiency optimizations are typically based on only a few specific operating conditions without consideration for the mission profile of the vessel. In reality, the vessel will operate over a wide range of speeds and conditions through its lifetime, so an approach that only considers one or a few design points will probably result in a sub-optimal global solution. This is particularly true when the design point is the maximum speed, where naval combatants and patrol craft may operate only a few percent of the time throughout its design life. Secondly, the hull and the propulsor are typically designed as two individual components. However, the propeller-hull relationship is a highly coupled problem. Hence, optimizing the two as separate entities may yield a sub-optimal global design in terms of the system performance. The final issue is that the propeller is matched to the hull in an effort to maximize the efficiency at a specific speed without consideration for the actual fuel consumption characteristics of the prime movers. The probability of operating at the specific design points may be low, so the propeller and the prime movers actually operate at off-design conditions with high fuel consumption rates for the

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majority of its operational life. In order to best match a ship and her propeller, the total lifetime fuel consumption, LFC, should be minimized in order to reduce the total ownership cost of the vessel.

In this work, the entire lifetime operational space is defined using a probabilistic mission profile. This results in a design process where performance metrics such as LFC, lifetime propeller efficiency, or lifetime operational costs can be evaluated.

Over the last few decades, much work has focused on the optimization of B-Series propellers. One recent example is the work of Chen and Shih [2], who used a genetic algorithm (GA) to optimize the hydrodynamic performance of B-series propellers subject to cavitation and strength constraints. The strength constraint was modeled using an algebraic formulation suggested by Oosterveld and van Oossanen [11], and the cavitation constraint was modeled using Keller's formula.

Recent research illustrates the advantages of using a probabilistic design approach as opposed to traditional point design methodologies. Kramer et al. [5] used a probabilistic design approach to optimize the diameter of water-jet propulsors for a surface effect ship (SES). They used a joint probability density function (PDF) of ship speed and sea state to represent the probabilistic operational profile of the vessel. The nozzle diameter of the water-jet was then optimized to maximize the lifetime efficiency of the water-jet propulsors for an SES. Using this methodology, they were able to find the optimal water-jet that yielded a 3-10% increase in lifetime water-jet efficiency and significantly minimized the susceptibility to cavitation compared to a traditional point design approach applied to the same problem. Motley and Young [9] also used a joint PDF to define an operational space in order to investigate the performance advantage of advanced self-adaptive composite propellers over traditional nickel-aluminum-bronze (NAB) propellers. The approach was similar to Kramer et al. [5] in that the propulsor was optimized using the joint PDF of sea state and ship speed to maximize the lifetime efficiency of both propeller types. For the rigid NAB propeller, the pitch tip angle was optimized and the design was found to yield slightly better efficiencies (up to two percent) than the full-scale propellers installed aboard a current naval combatant.

Although the previous work addressed the need for probabilistic design methods in naval architecture, it did not address the need to optimize both the propulsors and the hull simultaneously, nor did it examine the LFC of the chosen designs. Recent research conducted by Motley et al. in [10] has shown the advantage of considering the full probabilistic operational space when searching for propeller designs that will minimize the LFC.

The objective of this research is to develop a probabilistic design methodology to minimize LFC by optimizing the hull and propeller geometry simultaneously to minimize LFC.

A bimodal PDF, similar to those presented in references [5], [9], and [10], is applied to model the mission profile of a high speed combatant craft. The optimization software SNOPT [3] is used to solve the system-level optimization problem. SNOPT is a gradient-based method developed to handle nonlinear constrained problems. To facilitate the interfacing of our performance analysis and the optimization software, PyOpt [12] is used. PyOpt is a Python framework for nonlinear optimization problems that facilitates the description and solution of optimization problems. To demonstrate the new integrated system-based design, results are shown for high-speed hull forms coupled with Wageningen B-series propellers.

Methodology

To demonstrate the new design methodology, a high speed vessel with operational requirements and dimensions similar to a naval combatant is examined. The length and displacement of the ship are fixed to be 76 m and 1,032 metric tons, respectively. The engine room layout is assumed to consist of four medium speed diesel engines, two attached to each shaft. It is assumed that the load on each shaft is distributed evenly across both engines. For proof of concept, the Wageningen B-series propellers were selected owing to the extensive design formula available for these propellers. However, it is acknowledged that they would be a poor choice at the upper end of the vessel's speed range owing to cavitation concerns. The rotational speed range as a function of speed is assumed to always be within the powering limits of the engine. The rotational speeds are also allowed to float as the speed changes throughout the optimization process.

Mission profile

In order to calculate the LFC of the vessel, a probability density function, PDF, was used to model the lifetime mission profile of the ship. A bimodal PDF was assumed for the variation of vessel speed over its lifetime. The profile, which is shown in Figure 1, has two peaks: one at 20 knots representing the endurance speed and another at 40 knots representing the mission speed. The maximum speed assumed is 50 knots. The fuel consumption of the vessel is directly related to the required power

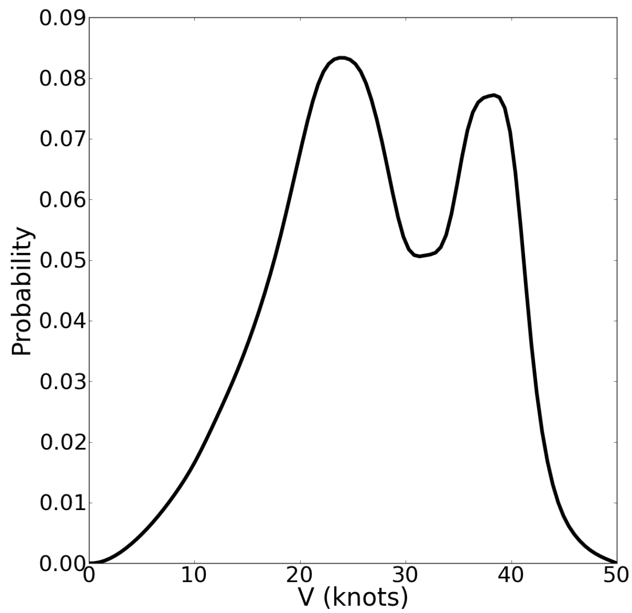

Figure 1: Vessel operational speed profile. The modes of this distribution represent an endurance speed of 20 kts, and a mission speed of 40 kts

of the propulsors at each speed, and the probability of operating at a given speed as defined by the mission profile shown in Figure 1.

Hull resistance calculation

In order to calculate the resistance-speed curve for a given hull form, data is taken from model tests performed at Hyundai Laboratories on high speed hull forms [8]. These model tests were performed on hulls with varying block coefficients, C_b, length to beam ratios, L/B, and beam to draft ratios, B/T. In the test results presented in Min et al. [8], the Froude number, F_n, varied between 0.3 to 1.3, while L/B varied between 10 and 30. In order to represent a realistic upper bound for a slender monohull, L/B is assumed to be fixed at 10 in this paper. Hull forms were tested at block coefficients of 0.4, 0.5, 0.6, and 0.7 and B/T values of 1.2, 2.4, and 3.6 [8]. Polynomial interpolation was used between the tested points to generate resistance curves for the analysis. For each of the tested hull forms, the coefficient of residual resistance, C_R, and coefficient of dynamic wetted surface area, C_{DS} was found [8]. Curves were produced to describe both coefficients as functions of Froude number for each hull form.

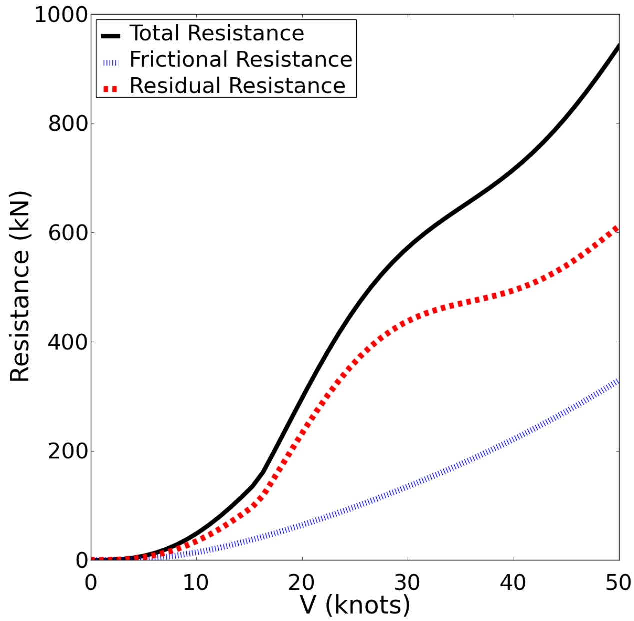

Figure 2: Example of a resistance curve generated by interpolating between the model hull forms tested at Hyundai Labs

The data found in these model tests is used to estimate resistance curves for hull forms within the bounds described above. A Lagrange polynomial was used to interpolate each of the parameters altered in the experiments, yielding a coefficient of residual resistance, C_R, and a coefficient of dynamic wetted surface area, C_{DS}, for the resistance calculations.

The coefficient of frictional resistance, C_f, was calculated from the ITTC frictional line:

$$C_f = \frac{0.075}{((\log R_n) - 2)^2} \tag{1}$$

where R_n is the Reynolds number based on the vessel's overall length. The total wetted surface area, S, the coefficient of total resistance, C_T, and total resistance, R_T, can be calculated using the following equations:

$$S = 2LTC_{DS} \tag{2}$$

$$C_T = C_f + C_R \tag{3}$$

$$R_T = \frac{1}{2}\rho V^2 S C_T \tag{4}$$

This yields the total resistance for the vessel across a range of speeds based on any beam to draft ratio and block coefficient within the bounds of the tested hull forms. An example of one of the generated resistance curves using this process can be seen in Figure 2.

Propeller performance

Much of the operational performance of a marine propeller is governed by the advance coefficient, J, which, according to equation 5, relates the mean axial advance velocity of the fluid through the propeller plane, V_a, to the rotational speed of the propeller, n, and the diameter of the propeller, D. V_a is related to the ship velocity, V, by the wake fraction, w, as shown in equation 7,

$$J = \frac{V_a}{nD} \tag{5}$$

$$V_a = V(1 - w) \tag{6}$$

The wake fraction is estimated based on block coefficient, C_B, using the following equation as found in [6]:

$$w = 1.7643C_B^2 - 1.4745C_B + .2574 \tag{7}$$

Research conducted by Bernitsas et. al [1] on the B-series propeller has produced regression equations that can be used to calculate the thrust coefficient, K_T, and torque coefficients, K_Q, for a given propeller. The thrust and torque coefficients for the B-Series propellers are expressed as polynomial functions of the pitch to diameter ratio, P/D, advance coefficient, J, expanded blade area ratio, A_e/A_o, and number of propeller blades, z.

$$K_T = \Sigma C^T_{s,t,u,v} \left(J\right)^s \left(\frac{P}{D}\right)^t \left(\frac{A_e}{A_o}\right)^u \left(z\right)^v \tag{8}$$

$$K_Q = \Sigma C^Q_{s,t,u,v} \left(J\right)^s \left(\frac{P}{D}\right)^t \left(\frac{A_e}{A_o}\right)^u \left(z\right)^v \tag{9}$$

$C^Q_{s,t,u,v}$ and $C^T_{s,t,u,v}$ are regression coefficients and s, t, u, and v are power coefficients [1]. The open water efficiency of the propeller can then be calculated as follows:

$$\eta_{ow} = \left(\frac{J}{2\pi}\right)\left(\frac{K_T}{K_Q}\right) \tag{10}$$

Once the open water propeller characteristics have been determined, the required thrust coefficient, K_T/J^2, for the vessel can be determined as a function of thrust, T, diameter, D, water density, ρ, and the advance speed, V_a according to equation 11. As shown in equation 12 the required thrust, T, is related to the total resistance, R_T, via the thrust deduction factor, t, which is related to the wake fraction as given in [6] and in equation 13.

$$\frac{K_T}{J^2} = \frac{T}{D^2 \rho V_a^2} \tag{11}$$

$$T = \frac{R_t}{(1 - t)} \tag{12}$$

$$t = .25w + .114 \tag{13}$$

The thrust requirements of the vessel can be matched with the thrust characteristics of the propeller, to find the operating J value (and, hence, propeller rotational speed, n) and corresponding η_{OW} at each speed, as shown in Figure 3. These values determine the powering characteristics of the propeller. The propeller hull matching process is performed for each point in the probabilistic operational space for each hull-form generated, allowing the optimizer to determine the propeller-hull system with the best lifetime operational characteristics.

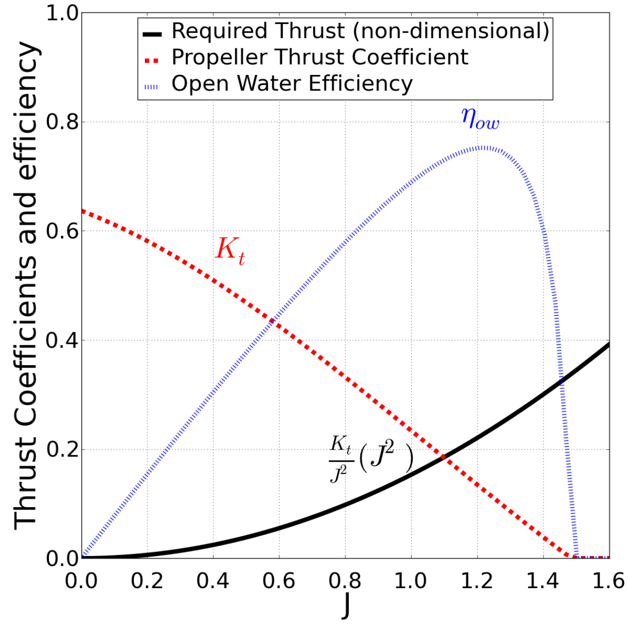

Figure 3: An example of a propeller-hull matching exercise showing the required thrust at the endurance speed of V = 20 kts, the open water thrust coefficient, and efficiency curves.

Cavitation constraint

The expanded blade area ratio of a propeller is found using Keller's formula, similar to Chen and Shih [2]. As shown in equation 15, the minimum blade area ratio needed to avoid cavitation is calculated as a function of thrust, number of blades, hydrostatic pressure at the propeller shaft axis (P_o as defined in equation 14), saturated vapor pressure of water ($P_v = 1.646\ kPa$), propeller diameter, and a correction coefficient, K:

$$P_o = P_{atm} + (\rho g h) \tag{14}$$

$$\frac{A_e}{A_o} = \frac{(1.3 + 0.3 \cdot z)\,(T)}{(P_o - P_v)\,(D^2)} + K \tag{15}$$

In Equation 14, h is assumed to be the depth of the propeller shaft axis from the free surface and P_{atm} is the atmospheric pressure, 101.3 kPa. For this work, the cavitation constraint is applied at a ship speed of 30 knots. The correction coefficient, K, is based on ship type. For high speed twin screw hull forms, $K = 0$.

Lifetime fuel consumption

The specific fuel consumption, SFOC, is provided by engine manufacturers as a function of load. In order to determine the fraction of engine load, the power requirements must be known. The effective power of the vessel relates the vessel resistance and speed by

$$P_E = R_T V \tag{16}$$

The resulting delivered powers required of the propellers can be calculated using equation 17:

$$P_D = \frac{P_E}{\text{QPC}} \tag{17}$$

where QPC is the quasi-propulsive-coefficient given by the product of three efficiencies affecting the hull and the propeller:

$$\text{QPC} = (\eta_H)\,(\eta_{RR})\,(\eta_{OW}) \tag{18}$$

where η_H is the hull efficiency as shown in equation 19, $\eta_{RR} = 1.0$ is the relative rotative efficiency, and η_{OW} is the open water efficiency as calculated in equation 10.

$$\eta_H = \frac{1-t}{1-w} \tag{19}$$

In this work, the losses due to shaft and bearing efficiencies are assumed to be negligible.

Once the power is calculated, the specific fuel oil consumption (SFOC) at each speed can be found based on the percentage of load. Since power is a function of the ship velocity, and the PDF of the vessel speed is known, fuel consumption can be calculated. The SFOC for the L51/60DF engine as a function of engine load taken from the MAN B&W catalog [13] and shown in Figure 4, is used in the current work.

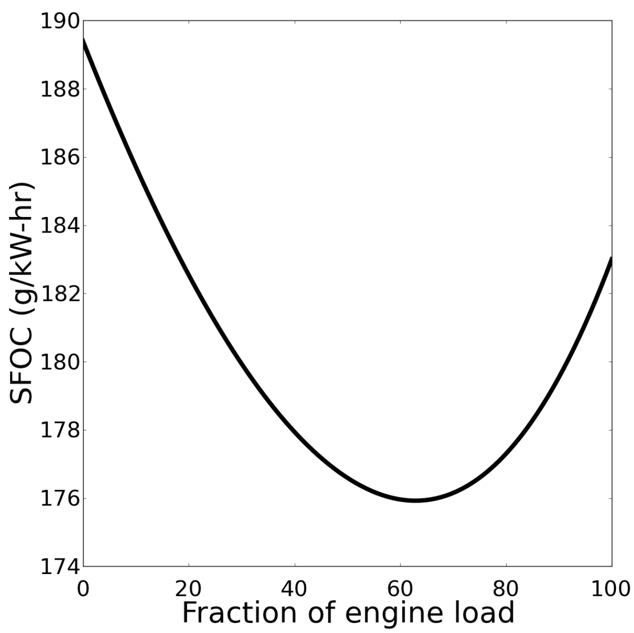

Figure 4: Specific fuel consumption as a function of percentage of load for the L51/60DF engine.

Assuming that the vessel operates for 120,000 hours over a 50-year lifetime, the LFC can be calculated by

$$LFC = \left(\int_V p(V) SFOC(V) P_D(V) dV \right) \times 120,000 \tag{20}$$

This corresponds to the integral of the fuel flow rate (g/hr) of the engines weighted by the operational PDF, and multiplied by the total number of operational hours.

Optimization

The objective of the optimization problem is to minimize the LFC with respect to beam-to-draft ratio, B/T, pitch-to-diameter ratio, P/D, and diameter-to-draft ratio, D/T. The beam-to-draft and pitch-to-diameter ratios are given upper and lower bounds based on the range of data available, and the diameter-to-draft ratio is bounded based on geometric constraints. The length-to-beam ratio is fixed at 10, as this is the smallest ratio tested by Hyundai Labratories, and any value greater than this is unrealistic for monohull vessels. Displacement is fixed as a specified parameter, which allows for the calculation of C_B given L/B and B/T. The number of blades is assumed to be four.

The nonlinear optimization constraints consist of upper and lower limits on the block coefficient, again due to limits on the data available, and a cavitation constraint based on Keller's formula (15) and the upper expanded area ratio of the B-series of 1.05. The optimization problem can be summarized as follows:

$$\begin{aligned} \text{minimize} \quad & LFC \\ \text{with respect to} \quad & 1.2 \leq B/T \leq 3.6 \\ & 0.5 \leq P/D \leq 1.4 \\ & 0.5 \leq D/T \leq 1.2 \\ \text{subject to} \quad & 0.4 - C_b \leq 0 \\ & C_b - 0.7 \leq 0 \\ & \frac{A_e}{A_0} - 1.05 \leq 0 \end{aligned} \tag{21}$$

Optimizer

Since the objective and constraint functions are continuous and smooth, a gradient-based optimizer, SNOPT [3], is used. SNOPT is a Sequential Quadratic Programming (SQP) algorithm that solves the Quadratic Programming (QP) subproblems using a reduced-Hessian active-set method. A brief description of the SQP and QP algorithms used in SNOPT is presented below.

Consider a nonlinear optimization problem with objective function, f, design variables, x_k, equality constraints, c_i, and inequality constraints, $\tilde{c}_j$, required to be less than or equal to zero. The Lagrangian, with Lagrange multipliers, λ_i and $\tilde{\lambda}_j$, and slack variables, s_j, is defined as

$$\mathcal{L}(x_k, \lambda_i, \tilde{\lambda}_j, s_j) = f(x_k) + \lambda_i c_i(x_k) + \tilde{\lambda}_j(\tilde{c}_j(x_k) + s_j)$$

The SQP major iterations of SNOPT attempt to satisfy the Karush–Kuhn–Tucker necessary conditions by finding the stationary points of the Lagrangian with respect to x_k, λ_i, $\tilde{\lambda}_j$, and s_j. The quadratic subproblem generated by each major iteration approximates the Lagrangian as a quadratic and linearizes the constraints. For the approximate Hessian of the Lagrangian, the identity matrix is used initially and subsequent major iterations apply the Broyden–Fletcher–Goldfarb–Shanno (BFGS) update to successively increase the accuracy of the approximation as the optimizer approaches the convex region surrounding the optimum.

The QP solver computes the optimal step from the subproblem generated in each major iteration. The linearized constraints are expressed in a form that separates the set of basic, superbasic, and nonbasic variables, where the basic variables are those used to satisfy the constraints, nonbasic variables are fixed at their bounds, and superbasic variables represent the true degrees of freedom that can be varied to minimize the objective. After a step direction is computed from the reduced

Hessian and gradient in terms of the superbasic variables, a line search is used to find a step size that yields a sufficient decrease in the augmented Lagrangian, which is the Lagrangian with an additional quadratic penalty term for each constraint. More details can be found in [3].

Implementation

The flowchart in Figure 5 illustrates how optimization is used to perform simultaneous hull-propeller optimization over a range of operating conditions. The elements on the diagonal represent distinct processes, the thick, gray lines indicate data dependency, the thin black lines indicate process flow, and the numbers indicate order of execution. A variable on the upper triangular indicates data flow from the process with which it shares a row to the process with which it shares a column, and a variable on the lower triangular indicates data flow from the process in the same row to the process in the same column, which is indicative of feedback present in the system.

The hull and propeller analyses are evaluated in sequence as the hull resistance, R_t, has no dependence on propeller performance. The propeller analysis computes the operating advance coefficient based on the value of R_t it receives, yielding the required propeller rotational speed which is then used in computing the SFOC and the cavitation criterion. To consider the full mission profile, the hull-propeller analysis sequence is run for a range of speeds during each function call and weighted based on the PDF.

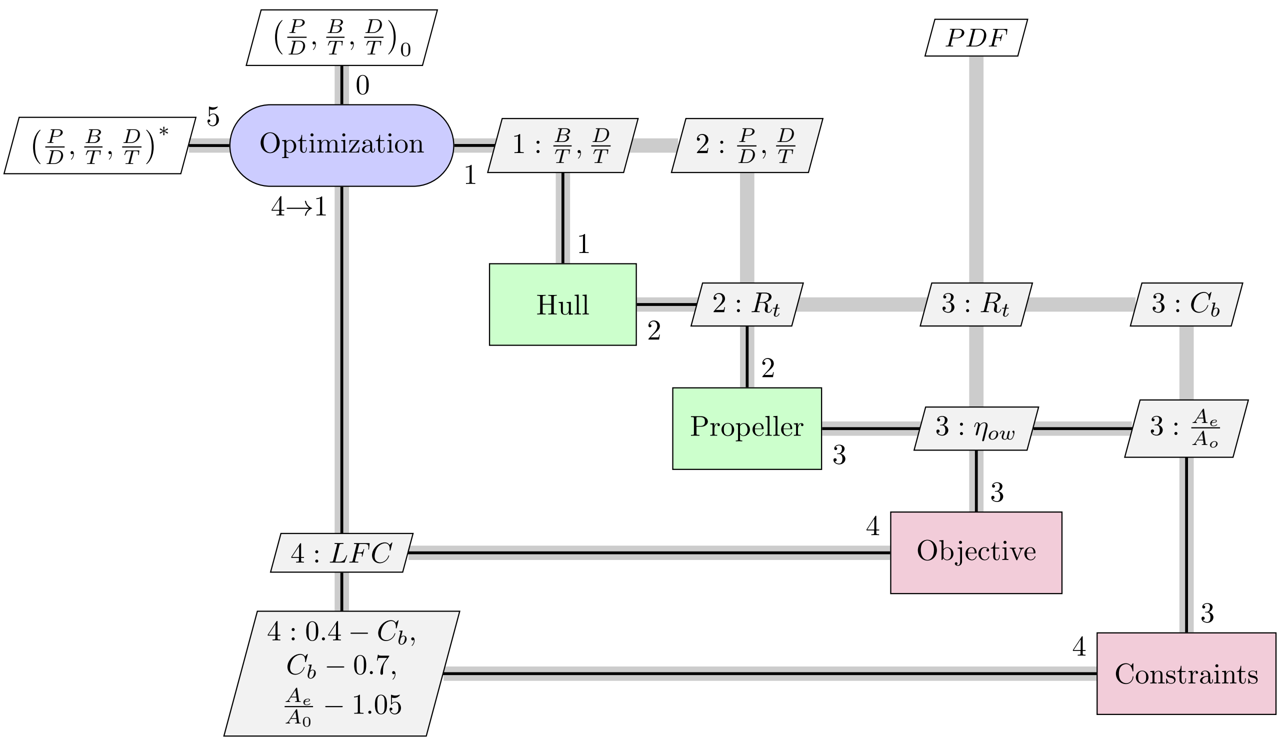

Figure 5: Data and process flow diagram for the hull-propeller design optimization process.

Figure 5 also explains the sequence in which the hull and propeller analyses are executed within the context of optimization. We begin at the initial set of design variables, $(P/D, B/T, D/T)_0$, execute the hull and propeller analyses in order, and return the value of the objective and constraint functions to the optimizer. Based on this information, the optimizer internally computes the next iterate — the new set of design variables — and executes the hull-propeller sequence again to obtain the new values of the objective and constraints. This process is repeated until the optimizer determines that the design variables have converged, at which point it exits the loop and returns the optimum, $(P/D, B/T, D/T)^*$.

The objective function gradient and constraint Jacobian are evaluated using the forward-difference method with a step size determined internally by SNOPT based on the scaling of the problem. Finite-difference methods such as the one used here often suffer from significant truncation error because the amount we can reduce the step size is limited by subtractive cancellation error, which typically begins to dominate at relative step sizes smaller than 10^{-6} [7]. When necessary, the complex-step method and automatic differentiation are two options for circumventing this limitation. However, the low curvature in this design space reduces the impact of truncation error in the problem considered, as Figure 6 shows efficient convergence to a gradient norm of nearly 10^{-9}.

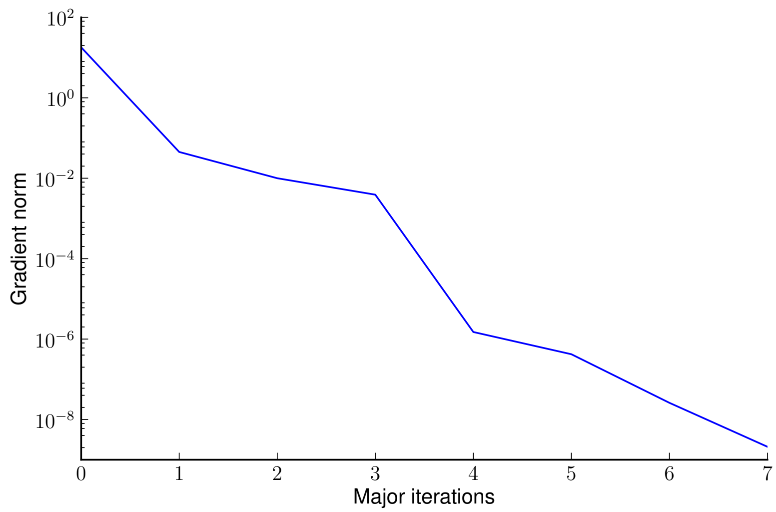

Figure 6: Convergence history of the gradient of the Lagrangian plotted against major iteration count.

Results

The optimal design vector found through the optimizer is shown in table 1.

Table 1: Optimized design vector

B/T	D/T	P/D
3.05	1.2	1.1

The value of D/T converged to the upper bound, 1.2. Figure 7 shows that, within the feasible domain, higher D/T values yield a lower LFC because they allow the propeller diameter to increase, which reduces the required rotational speed and, hence, decreases the powering requirements. It can also be seen from the same figure that the feasible domain only includes D/T values higher than 1.0 because of the constraint imposed by Keller's formula. The P/D converged to a value of 1.1 and is driven by the open water efficiency as calculated in Equation 10. Figure 8 shows the trend for LFC

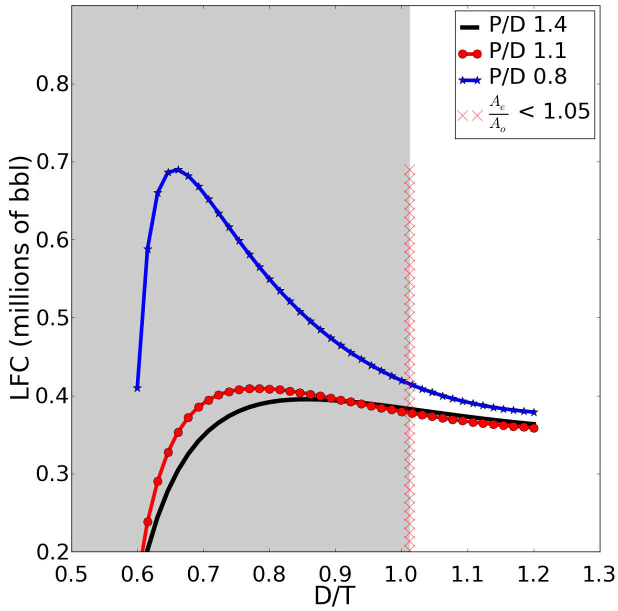

Figure 7: Variation of LFC with D/T at the optimum B/T of 3.05. The shaded region is infeasible because it violates A_e/A_o requirements imposed by Keller's formula.

and P/D. Figure 9 shows the trend of the overall efficiency, averaged over the entire operational profile, as a function of P/D. As shown in the figures, $P/D = 1.1$ leads to the lowest LFC, or best overall fuel efficiency.

For the hull forms being investigated, the fuel flow rate averaged over the entirety of the probabilistic design space steadily decreases as B/T increases as shown in Figure 10. Consequently, the LFC also decreases with increasing B/T, as shown in Figure 11.

The final convergence point is driven not only by the P/D, B/T, and D/T values, but, also, by the block coefficient, C_B, constraint. Due to the model test data used to define this problem the upper limit on C_B is 0.7, which constrains the LFC as shown in Figure 11. The maximum B/T value that the optimizer can converge on and not violate the C_B constraints is 3.05.

In order to evaluate the effectiveness of the simultaneous design technique, traditional point-based design methodologies were used to find alternate designs to compare the performance with a probabilistic integrated design approach described above. Traditional techniques involve preliminary design of the hull first with an emphasis on minimizing the resistance encountered by the bare hull form. Once this process is completed, the optimal propeller is then found which, based on the corresponding hull form, has the greatest efficiency at the selected speed. In this work, the traditional method was applied at a speed of 20 knots and at a speed of 40 knots.

The B/T value that yielded the lowest resistance at these points is first found by using the propeller characteristics ($P/D = 1.1$, $D/T = 1.2$) that resulted in the maximum efficiency, i.e. the best scenario for point-based optimization. As shown in figure 12, the B/T values found for 20 knots and 40 knots respectively were approximately 3.05 and 2.95. As expected, if the optimal characteristics are used, the optimal B/T value corresponds to the point-based optimal for the endurance speed because it has a higher probability of operation than the mission speed as shown in Figure 1.

Using the hull forms found above, the open water efficiencies for the propeller at each speed were

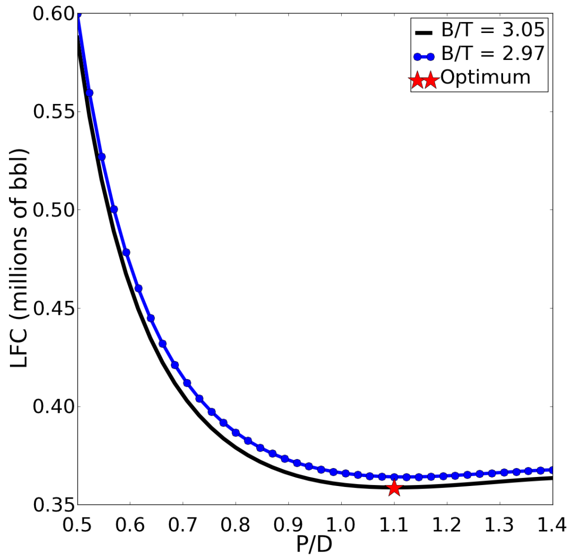

Figure 8: Variation of the LFC as a function of P/D at $D/T = 1.2$ and for three different B/T values.

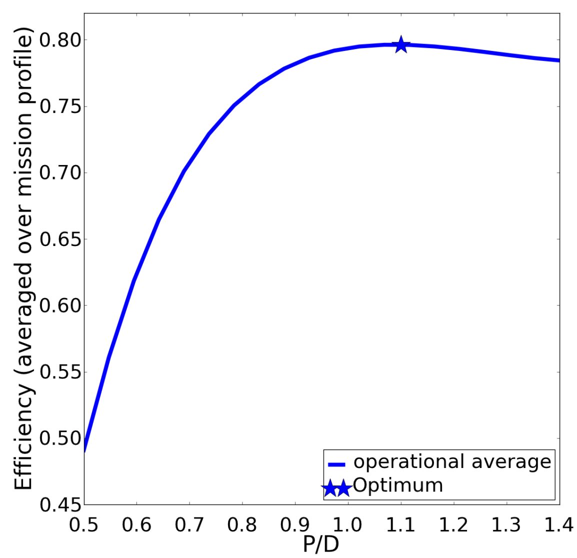

Figure 9: Variation of the overall efficiency averaged over the entire operational profile as a function of P/D. D/T and B/T are both at the optimum values of 1.2 and 3.05, respectively.

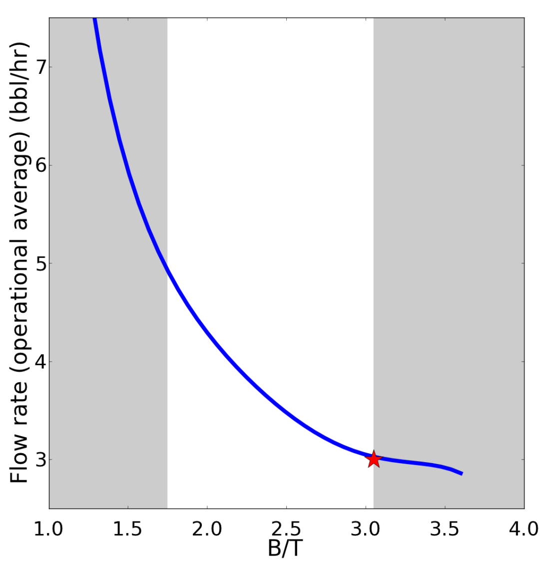

Figure 10: Variation of the flow rate as a function of B/T, confirming the idea that lifetime consumption should decrease as the beam to draft ratio increases.

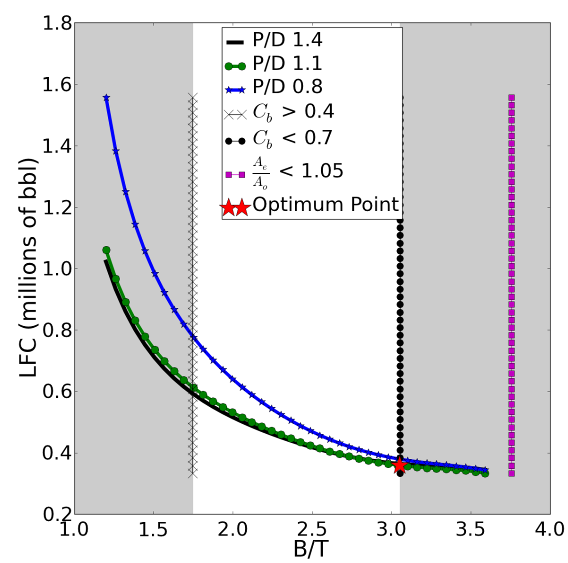

Figure 11: Variation of the LFC as a function of B/T. This figure shows the trend of decreasing consumption with increasing B/T. The shaded region is the infeasible domain and it can be seen that the upper limit on C_B is constraining the problem.

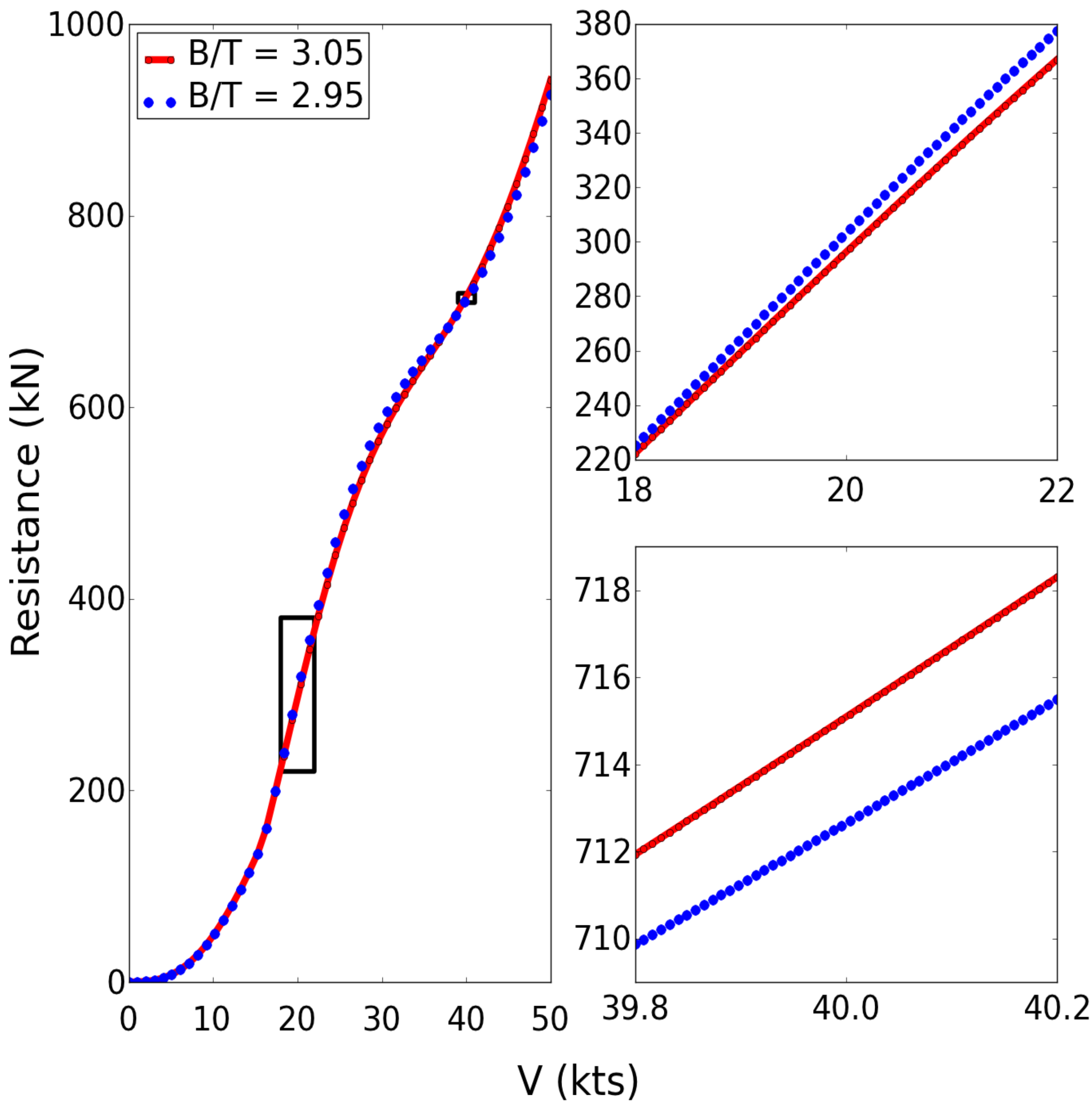

Figure 12: Resistance curves for the different optimization methods. The hull forms are all similar; so the curves are magnified to show the differences near each design speed.

maximized subject to the cavitation constraint. The results for these optimizations are slightly different from the design found using the simultaneous optimization technique. Both designs converged to a D/T value of 1.2; however, the 20 knot hull form propeller design condition converged on a P/D value of 1.01, whereas the 40 knot design converged to a P/D of 1.20. It should be noted that the single point-based design at 20 knots leads to a different optimal P/D value because the design objective was to maximize the propeller efficiency at 20 knots only, and not over the full operational space (as in the probabilistic integrated design approach).

Table **??** outlines the different design methods used and the corresponding results. The three optimization methods converged to very different P/D ratios. The lifetime profile design did lead to the minimum LFC. The relatively small difference in LFC is because the optimal P/D and D/T values are limited by the cavition constraint (Eq. 15) due to the use of the B-series propellers, which were chosen simply due to availability of data and is not actually appropriate for high-speed vessels. By expanding the feasible design space based on high fidelity simulation tools for both the hull and the propulsor, or via a more extensive collection of data, the benefit of the proposed probabilistic system based design method is expected to increase compared to traditional point-based design approaches. The advantage of the lifetime profile optimization criteria is that it removes the inherent uncertainty and ambiguity in selecting the proper design point.

Optimization Criteria	**B/T**	**D/T**	**P/D**	**LFC (millions of bbl)**
Lifetime Profile	3.05	1.2	1.1	1.434
Design Speed (20 kts)	3.05	1.2	1.01	1.438
Mission Speed (40 kts)	2.95	1.2	1.2	1.462

Table 2: Comparisons of the different optimization methods and their computed LFC values.

Conclusion

A new probability-based design method to minimize LFC by simultaneously optimizing the hull and propeller geometry has been presented in this work. This new approach has shown improvements in fuel consumption, and converged to a propeller geometry significantly different from that obtained using a more traditional design approach.

The process presented here is in no way a high-fidelity model of the propulsor-hull system. It is also limited by simplicity of the cavitiation constraint to which it is subjected and the accuracy and scope of the model test data. It is also based on the accuracy of the mission profile used to describe the probabilistic design space of the vessel. Higher fidelity calculations for the loading and cavitation of the propeller could help capture the complexity of the design problem.

With further additions of these high fidelity constraints, and with the optimization of modern hull forms and propulsion types, this process could be extended to a wide range of propulsor types, such as controllable pitch propellers for high speed vessels. The methodology could be easily extended to optimize all-electric propulsion plants or hybrid plants for the next generation of naval vessels. These modern propulsion plants combined with a probabilistic optimization method could yield even further reductions in LFC, as well as minimize lifetime carbon emissions.

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