Optimization of Direct Drive Induction Motors for Electric Ship Propulsion with High Speed Propellers

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Abstract

Direct drive electric ship propulsion can offer increased flexibility and reduced overall fuel consumption compared to geared mechanical systems [Davis 1987, Doerry 2007]. As a well-established technology, induction motors are a dependable and economical option for electrically controlled ship propulsion, but their size and weight are large due to the relatively low propeller speeds. Increasing the propeller speed allows the design of higher speed motors of comparable efficiency and significantly decreased size and weight. This paper first presents a typical steady-state circuit model of a ship propulsion motor based on published data of an existing 19 megawatt machine. Design variables and constraints specific to this application are discussed before comparing designs adapted to minimize size and weight for driving higher speed propellers. Predicted drive motor total size and weight decrease with increasing full load rotational speed. A basic examination of the motor cooling is also included to verify the feasibility of the new design and investigate possible limiting cases taking advantage of direct water-cooled conductors.

1. INTRODUCTION

Efficient power transfer from the relatively high speed prime mover, the main gas turbine or high-speed diesel engine for example, to the much lower speed propeller remains a challenge of ship propulsion. Two shafts, one rotating at a proportionally reduced speed, can be coupled through gears for one successful solution. However, the fixed ratio mechanical connection between the main engine and propeller requires a low engine speed and consequently low efficiency at lower ship speeds. Alternatively, one or more high speed generators connected directly to the main engine(s) can produce electrical power. The electrical power can then be distributed and converted to supply power to motors driving each propeller as well as all other on-board electrical loads. The electrical connections increase flexibility in the possible locations for the large machinery and provide a variable “gear ratio” between prime mover and propeller. At lower ship speeds, a single engine and generator could operate at a higher load and efficiency point by supplying power to multiple motor drives and ship electrical loads. Electric ship propulsion can be an attractive alternative offering increased flexibility and reduced overall fuel consumption [Davis 1987, Doerry 2007].

Early electric drive ships using both steam turbines and diesel engines together with ac or dc propulsion motors were developed over the first third of the 20th century before improvements in gears made the mechanical coupling superior for most applications [Thau 1937]. The ac motors initially used wound rotor induction machines with variable external resistance for speed control.

Modern electric drive ship propulsion can take advantage of more efficiently operated engines supplying power for both propulsion and electrical loads, removing the large reduction gears between the high speed engine and relatively low speed propeller as well as eliminating the need for secondary generators for ship service power. Variable speed induction motor drives have progressed significantly since the inefficient, variable-resistance, wound rotors. Today, modern power electronic converters control the frequency and voltage applied to the motor terminals at power ratings and efficiencies not practical fifty years ago. Continual development of the semiconductor devices for power conversion and electric motor control manage increasing power levels in shrinking footprints.

Induction motors offer a simple, rugged, and flexible solution for electric drive ship propulsion. There are no potentially damaging currents in the case of internal faults and no risk of demagnetization from a transient temperature or shock. Reliability and robustness can be further increased with multiple phase windings. Efficient cooling strategies allow increasing torque and power densities, but higher speed propellers enable substantial reduction in motor volume and weight for a given load.

Higher speed propellers allow the design of higher speed motors of comparable efficiency and significantly decreased size and weight. The companion paper “OpenProp: An Open-Source Parametric Design and Analysis Tool for Propellers” focuses on the propeller design to achieve increased maximum velocities while keeping cavitation at an acceptable level [Epps et al. 2009]. This paper presents the optimization of the size, weight, and performance of induction motors when driving higher speed propellers. Any reduction in volume, weight, and fuel consumption can then be used to improve total ship layout
and design, as discussed in the companion paper “Toward the Development of an Integrated Electric Ship Evaluation Tool [Chalfant and Chryssostomidis 2009].”

2. INDUCTION MOTORS

Induction motors in general are physically the least complicated and most robust of all electric machines. With no permanent magnets or brushes and only a single set of stator winding input terminals for excitation and control, induction motors require minimum maintenance and offer maximum ruggedness and reliability.

Permanent magnet machines offer the potential for increased fields without the losses from the rotor conductors. However, the fixed fields reduce efficiency when running at partial loads. The magnets also add additional cost, manufacturing and repair complexity, and operational issues under short circuit or extreme conditions. As another alternative, super conducting machines hope to nearly eliminate conductor losses at the expense, in terms of cost and maintenance, of the cryogenic cooling system. Both of these topologies may reduce motor size in future applications, but the induction motor is a proven solution for megawatt and larger machines.

2.1. Equivalent Circuit Model Description

A circuit model can be used to quickly estimate and compare the performance of different induction motor designs. The traditional induction machine equivalent circuit, shown below in Figure 1, provides a quick approximation of the motor behavior and losses.

\[ \begin{align*}
\text{R} & \quad \text{X1} \\
\text{X1} & \quad \text{X2} \\
\text{XM} & \quad \text{RC} \\
\text{R2}/s &
\end{align*} \]

Figure 1. Induction motor single phase equivalent circuit

In reality, the values of the simple circuit elements in Figure 1 can change with operating conditions, and additional components can be added to more accurately represent the physical machine [Alger 1970]. The values used for the ship propulsion motors assume a fixed temperature rise and an increased length to accommodate regularly spaced axial cooling air channels. Additional calculations examine the feasibility of the thermal aspects of the design in Section 4.

The resistance values are estimated based on the known conductor geometry and conductivity. Rotor bar impedance values are adjusted for frequency effects using a many-sliced model of each bar [Kirtley et al. 2007]. The reactance values are calculated based on established design equations [Alger 1970]. Laminated core real and reactive power densities are estimated based on manufacturer loss and excitation data together with calculated values of total mass and induction for the motor gap, teeth, and core.

2.2. Baseline Design

A reference motor design has been developed to approximate an existing 19 megawatt, up to 150 revolution per minute induction motor completed around 1997 by ALSTOM for the US Navy [Benatmane et al. 1998, Lewis 2002]. The 12 pole machine operates at line voltages up to 4160 V and frequencies up to 15 Hz. The simplified baseline design represents the main electromagnetic behavior and overall machine performance by estimating essential dimensions and material properties. Non-essential or unavailable specific design details are neglected entirely or roughly estimated. Figure 2 shows an example cross-section of part of the rotor and stator. Bearings, shaft, heat exchanger, and housing and structural reinforcement are included only as a lumped additional weight. The complex cooling system is reduced to additional length for radial air passages. Noise issues are not considered. A basic double layer, 5/6 pitch, three phase winding is assumed in place of the actual 15 phase winding.

Figure 2. Cross-section of part of the motor active region

Traditional design processes often rely on existing test results of similar machines and adapt new machines from previously successful designs. Similarly, calibrating design calculations on this existing machine helps to remove some of the uncertainty from dealing with an unusually large and slow design. Initial values for the equivalent motor circuit are adjusted to match the limited performance data published for the existing 150 rpm, 19 MW motor [Lewis 2002]. This original design is then modified for operation with increased full load rotational speeds.
2.3. Circuit Model Values

Design estimates and calculations based on the equivalent circuit model agree with the limited performance data available in terms of air gap shear stress, rough dimensions, efficiency, and power factor [Benatmane et al. 1998, Lewis 2002]. Total machine weight and overall dimensions are the most difficult parameters to estimate because a significant portion of the 117 metric tonne, 86.4 cubic meter motor is structural reinforcement in order to meet shock requirements. A scaling factor increases the total machine weight and outer dimensions after including approximations for the active material, shaft, rotor spider, and housing.

More detailed, and time consuming electromagnetic finite element simulations could be used to determine more exact values of resistance and reactance for final designs. The goal here is to determine approximate values to quickly compare different design alternatives. The estimated values also provide a useful and more intuitive check on any later finite element calculations.

Table 1. Equivalent circuit values in ohms for 19 MW motors comparing the original 150 rpm to a higher speed up to 250 rpm version at full rated speed and load

<table>
<thead>
<tr>
<th>Parameter</th>
<th>150 rpm</th>
<th>250 rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 [Ω]</td>
<td>0.010</td>
<td>0.008</td>
</tr>
<tr>
<td>R2 [Ω]</td>
<td>0.012</td>
<td>0.009</td>
</tr>
<tr>
<td>RC [Ω]</td>
<td>629</td>
<td>594</td>
</tr>
<tr>
<td>X1 [Ω]</td>
<td>0.137</td>
<td>0.097</td>
</tr>
<tr>
<td>X2 [Ω]</td>
<td>0.102</td>
<td>0.105</td>
</tr>
<tr>
<td>XM [Ω]</td>
<td>2.91</td>
<td>3.12</td>
</tr>
</tbody>
</table>

The equations used to calculate the circuit parameters in Table 1 generally agree with those given by Alger.[Alger 1970] The stator leakage reactance, X1, is a combination of stator winding slot and end winding terms but also includes the total reactance for the 5th, 7th, ns/p-1, and ns/p+1 belt and slot space harmonic circuits, about 0.062 Ω in these cases, where ns is the number of stator slots and p the fundamental pole pairs. These undesirable higher order field fluctuations arise from the lumped, non-perfectly-sinusoidal distribution of conductors, currents, and fields around the motor air gap. The rotor leakage reactance, X2, is a combination of slot and zigzag (or differential) reactance terms. The stator and rotor resistance values R1 and R2 are calculated from the copper conductivity at an assumed 80 degree C operating temperature divided by the effective conductor length and area. The core resistance RC is set to give the calculated core loss at no load, when the core elements see nearly the full terminal voltage. The reactance XM is the parallel combination of the calculated air gap magnetizing reactance and the core reactance calculated from the reactive power required by the laminations at no load.

3. DESIGN GOALS AND CONSTRAINTS

Similar to the main engines, the drive motors also benefit from higher speed operation. The combination of field strength and relative motion produces the desired output power and torque. Apart from relatively small improvements possible by minimizing losses or maximizing electromagnetic coupling, significant increase in general motor power density can be accomplished by increasing the field strength through higher current densities (or stronger permanent magnets in some motors) or by increasing the motor rotational speed.

This section examines the design process to reduce the motor size with increased rotational speed. The goal is to supply the required output torque while minimizing the motor size and weight and maintaining a power factor of at least 85%. The calculated power factor is sensitive to design adjustments on these large propulsion motors, so maintaining a consistent and relatively high power factor ensures a fair comparison between machines designed for different full load speeds. Maximizing efficiency remains another important design consideration but only of secondary importance for the initial designs because of the comparatively small range of variation in the initial calculations. A number of potential constraints and design considerations, some general to all electric machines and others more specific to this nautical application, should be considered during the modification process of the drive motor.

3.1. General Design Limitations

A number of mechanical, thermal, and electromagnetic limits impose realistic boundaries for practical motor designs. Mechanical constraints from the peripheral speed and forces around the rotor rim of the drive motors are roughly proportional to the rotor radius and the square of the speed. The significant increase in size of these drive motors over conventional machines is more than accounted for by the similar decrease in speed. Design of these large, slow motors will not be limited by mechanical constraints until speeds significantly higher than the few hundred revolutions per minute presently considered become achievable.

The electrical steel used to conduct the magnetic fields limits the magnetic flux density in traditional induction machines. The machine geometry determines relative magnitudes between the average fields in the air gap, teeth, and core. However, saturation limits around 2 T set an upper
bound on the magnitude of the magnetic flux density anywhere in the laminations before the permeability of the iron laminations abruptly declines and motor core losses rapidly increase. Maximum power transfer requires flux densities approaching the upper limits, and motor performance declines dramatically with departures in either direction.

Both the magnetic field as well as thermal considerations determine the electrical limits on maximum practical current densities in the stator slots and rotor bars. The majority of the motor losses in these large, low speed propulsion motors are generated by the currents in the copper stator and rotor conductors. Despite the high conductivity of copper, there are still substantial resistive losses in the conductors. The total resistance is also temperature dependent, with the conductivity falling roughly linearly for the moderate temperature rise around 60 to 100 deg C expected in most motors. Effectively removing the developed heat from the conductors enclosed within the iron laminations and, for the stator, surrounded by layers of electrical insulation is a significant challenge [Kirtley et al. 2009]. For the large ship propulsion motors, recirculated air is forced over the motor surfaces and through radial passages in the laminations before returning to coolers to remove the generated heat. Alternatively, tubes placed within the conductors themselves could also carry water or gas to directly cool the conductors.

3.2. Application Specific Characteristics

There are a number of unique features and requirements for these unusually large and slow machines. Many of the finer details specific to this application are largely omitted from the simplified designs. The structural and winding arrangements to help ensure low noise and high shock resistance are not included beyond a basic stator winding and physical scaling to increase overall size and weight. A fixed winding temperature rise replaces the complicated air paths and dedicated air circulation and cooling system required to cool the motor.

The length of the air gap between stationary and rotating sections is a fundamental design parameter for electric machines and is particularly important in induction machines. Generally, the smaller the air gap length the better the machine performance from improved field coupling, but mechanical considerations impose lower limits to ensure reliable operation. An increased air gap length is used in this case for enduring adverse sea conditions and meeting shock requirements for military vessels. The Lewis paper describes an 8 millimeter gap for the 19 MW drive motor in order to meet naval requirements for impact survivability [Lewis 2002]. Despite this relatively large air gap, the existing design demonstrates that high efficiency and power factor are still possible with careful design.

The density of electric current in the rotor and stator conductors and the power factor are the three fixed constraints for the motor designs at every speed. Limiting the stator and rotor current densities helps ensure the motor can be adequately cooled. The current densities depend on the geometry of the stator slots and rotor bars but also increase with reduced efficiency and power factor. The minimum power factor balances machine size and performance. Reduced power factor would increase the size and required current for the power converter and would also require additional external capacitance. The motor power factor depends on the reactance values in the equivalent circuit of Figure 1, and (with a fixed air gap) decreases if the laminations are overworked by excessive magnetic fields or as the slot and bar height increase. A good design must balance the space allotted for the current carrying conductors in the stator slots and rotor bars against room for the magnetic field paths in the iron lamination teeth.

In reducing the motor size, decreasing the active length can have less of an impact than decreasing the radius. A decreased radius decreases both slot and tooth widths and requires either a shorter slot height, with higher current density, or shortened lamination cross section in the back iron. The number of series connected stator winding turns must also be adjusted to maintain an adequate air gap flux density with changing speed and dimensions. This value can only be altered in discrete steps, depending on the winding arrangement. Any change reducing the machine size while maintaining power output has the potential to create a design that is impractical to cool. The next section examines approximate cooling requirements between different designs.

4. THERMAL ANALYSIS

Motor thermal limitations are a critical and difficult to determine design constraint. Conductor resistivity values increase with temperature and insulation materials fail above specific temperature limits. The size and power density of theoretical designs require adequate cooling of the machine to be practical. A detailed analyses of the motor loss and temperature distributions may be necessary before constructing any large machine. However, a simpler approach can help to provide quick initial design verification and comparison, limiting the required number of full, complicated analyses.

4.1. Total Machine Coefficient of Heat Transfer

A common equation for heat flow rate from convection is given below where \( P_D \) is the total power loss in watts, \( \theta \) is the temperature rise of the fluid, \( A \) is the surface area in m\(^2\), and \( h \) is the coefficient of heat transfer in W/(m\(^2\)K) .

\[
P_D = h \theta A
\] (1)
The goal is to use this simple equation together with motor loss calculations, surface area estimates, a maximum allowable temperature rise, and published typical coefficients of heat transfer in order to get an idea of the required cooling for the original and the reduced size machines. The original machine, already constructed and tested, is assumed to have sufficient cooling and can be used for comparison to other machines of higher speed and reduced size. Surface area estimates of components like the stator end windings are approximate but consistent between designs. Finite element calculations, along with more time and effort, could more accurately examine temperature distributions within the motor, but only a quick check of the feasibility of cooling different designs is required at this point.

The overall coefficient of heat transfer for these approximations averages out variations in materials, geometries, temperatures, and air flow. Levi lists some typical ranges of heat transfer coefficients ranging from 20 to 50 W/(m$^2$K) for traditional induction motors with cast rotor fans. He gives around 90 W/(m$^2$K) for motors with forced air cooling and 70 to 130 W/(m$^2$K) as a possible range with liquid cooled conductors [Levi 1984]. These values vary with the machine size and design but offer a starting point for comparison to calculations.

Based on the given values, a heat transfer coefficient of at least around 100 W/(m$^2$K) seems reasonable in this case for the large, low speed, closed circuit air cooled motors. The large cooling surfaces and low electrical frequency are advantages over smaller, 60 Hz machines. The low frequency reduces the hysteresis and eddy current losses developed in the laminations while the increased surface area aids in heat removal. The fans from the dedicated air circulation and cooling system ensure sufficient air velocity independent of the rotational speed.

For the drive motor designs, the copper conductors generate the bulk of the motor losses but also have much less exposed surface area compared to the iron laminations. For efficient cooling, a significant portion of the heat from the conductor losses must be transferred to and dissipated from the surrounding laminations. The calculated motor losses and approximate surface areas for different areas of the motor can be combined with a maximum allowable temperature rise in order to estimate overall coefficients of heat transfer for each motor. These numbers can then be compared between different designs and against published reference values.

The total surface area is dominated by the laminations including the inner and outer air gap surfaces, stator exterior, rotor interior, and substantial area due to the cooling channels along the rotor length. Calculations for the initial 150 rpm and higher speed 250 rpm motors resulted in the values displayed in Table 2.

<table>
<thead>
<tr>
<th>Table 2. Calculation of approximate overall coefficient of heat transfer for baseline and high speed motors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Motor</strong></td>
</tr>
<tr>
<td>Total Area [m$^2$]</td>
</tr>
<tr>
<td>Total Loss [kW]</td>
</tr>
<tr>
<td>Overall h [W/m$^2$K]</td>
</tr>
</tbody>
</table>

These values neglect any heat transfer through the motor shaft, rotor spider, frame, and structural supports. The higher speed machine may require a few degree higher temperature rise or an increased number of cooling channels in order to ensure cooling similar to the baseline design, but the smaller design does not appear unrealistic.

4.2. Fan Power Loss

Cooling systems themselves also require increasing power as more heat must be forcibly removed from the motor. An approximate volume of fluid required to remove a given power loss, assuming a uniform increase in temperature over the entire volume, can be calculated using Equation (2).

$$Q = P_d / (c_f \rho \theta)$$  \hspace{1cm} (2)

In Equation (2), $Q$ is the required volume flow rate in m$^3$/s, $P_d$ is the total dissipated loss in watts, $c_f$ is the specific heat of the fluid in J/(kg K), $\rho$ is the density of the fluid in kg/m$^3$, and $\theta$ is the uniform increase in circulating fluid temperature. For the air cooled machines, the fan power loss to provide this cooling air flow can be calculated from the volume flow rate and total pressure drop.

$$P_f = \sigma Q / \eta$$  \hspace{1cm} (3)

Equation (3) calculates the fan power, $P_f$, in watts, where $Q$ is still the volume air flow in m$^3$/s, $\sigma$ is the total pressure drop in N/m$^2$, and $\eta$ is the per unit fan efficiency. J.H. Walker gives typical values of temperature rise and pressure drop based on experience with large hydro generators [Walker 1981]. Using Walker's recommended 18 degrees C temperature rise, the approximately 600 kW of loss requires an air flow of about 30 m$^3$/sec. Alger similarly suggests limiting the total increase in cooling air to only one quarter or less of the total change in temperature, so 18 degrees seems reasonable for a worst case 80 degree winding temperature rise [Alger 1970]. Walker also suggests a range of values of total pressure drop across both the motor and cooler ranging from 100 to 175 N/m$^2$ as representative of large hydro generators [Walker 1981]. Using the upper limit of suggested total pressure drop of 175 N/m$^2$ together with the 30 m$^3$/sec calculated volume air flow and an arbitrary 50 percent fan efficiency gives an estimated fan loss of about 10.5 kW. These values are based on estimates for large hydro generators, but give at least an
initial idea of the quantities required, and specific values can be checked against manufacturer data for specific cases. Additional loss from the heat exchanger can also be included. Only in extreme cases should the total cooling system losses significantly decrease the total motor efficiency.

4.3. Water Cooling

This section describes an attempt to estimate minimum possible motor size and weight when directly water cooled conductors allow arbitrarily increased current densities. The conductors are adjusted to include small, 4 mm diameter pipes for carrying water. The designs are again minimized in size. A small increase in the number of turns maintains the air gap flux density, and the minimum power factor is still fixed at 0.85, but now the rotor and stator current densities are unconstrained. These cases give approximate lower limits to the size and weight of this type of machine for each given maximum speed, assuming that the water cooling can sufficiently remove all of the internally generated heat. Table 3 in Section 5.3 compares the designs of air and water cooled motors at the original and an increased full load rotational speed. The water-cooled lower boundaries on the design size and weight still account for substantial foundational and structural reinforcements for shock requirements, scaled to the reduced dimensions.

5. CALCULATION RESULTS

In general, calculated total propulsion motor size and weight decreased almost proportionally to increased full load propeller speed. Figure 3 plots the estimated total size and weight of 19 MW motors designed for full load speeds ranging from the original 150 rpm version increasing up to 300 rpm. The larger decrease in weight compared to volume arises from uncertainty in scaling the extra material added to reinforce the motor housing. The results assume a decrease in scaling factors for both size and weight proportional to the reduction in weight of the active material in the rotor and stator.

Figure 3. Estimated decrease in total size and weight with increased motor rotational speed

Ship speeds vary below the maximum rating or designed full load operating point, and the drive motor must operate efficiently over a wide range of speed and load. Lower speed operation can potentially offer the greatest efficiency savings from electric propulsion if a single engine can be run at a higher speed and efficiency, providing power to multiple drive motors at reduced load, as well as any other on-board electrical loads. Figure 4 shows the voltage and frequency input to the motor as a function of the power output. Figure 5 plots the corresponding motor efficiency with changing speed and load, operating at the voltage and frequency levels from Figure 4.

Figure 4. Calculated voltage and frequency values as a function of the motor load or shaft speed
5.3. Design Comparison

A comparison of the calculated dimensions, weight, and full load operating efficiency and power factor are displayed in Table 3 for both air and water cooled versions of the baseline, up to 150 rpm, motor and the higher speed, up to 250 rpm, version. The given water cooled values represent roughly the lower limit in total size and weight at the given speed for this type of machine, including the structural reinforcements and an 8 mm air gap. Further reduction in total size and the available iron magnetic field paths results in excessively high magnetic field densities. The minimum 0.85 power factor will not be achievable for designs much smaller, regardless of the cooling strategy.

Table 3. Comparison of the motor designs with different maximum speed and air or water cooling

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Air Cooled</th>
<th>Water Cooled</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>150 rpm</td>
<td>250 rpm</td>
</tr>
<tr>
<td>radius [m]</td>
<td>1.45</td>
<td>1.34</td>
</tr>
<tr>
<td>stack length [m]</td>
<td>1.205</td>
<td>0.82</td>
</tr>
<tr>
<td>total width [m]</td>
<td>4.5</td>
<td>4.25</td>
</tr>
<tr>
<td>total height [m]</td>
<td>4.0</td>
<td>3.75</td>
</tr>
<tr>
<td>total length [m]</td>
<td>4.8</td>
<td>3.68</td>
</tr>
<tr>
<td>volume [m³]</td>
<td>86.4</td>
<td>58.6</td>
</tr>
<tr>
<td>active weight [t]</td>
<td>51</td>
<td>33.5</td>
</tr>
<tr>
<td>total weight [t]</td>
<td>117</td>
<td>76.4</td>
</tr>
<tr>
<td>power factor [%]</td>
<td>85.7</td>
<td>85.0</td>
</tr>
<tr>
<td>efficiency [%]</td>
<td>96.5</td>
<td>97.1</td>
</tr>
</tbody>
</table>

6. SUMMARY AND CONCLUSION

Induction motors are a dependable and economical option for electrically controlled, direct drive ship propulsion, but their size and weight can be large because of the relatively low propeller speed. Increasing the propeller speed is an effective strategy to reduce the large size and weight of propulsion motors on electric drive ships.

The total volume and weight of the baseline propulsion induction motor is predicted to decrease almost proportional to any increase in propeller speed. For example, nearly a 66 percent reduction in total motor volume and weight is expected for a corresponding 66 percent increase in rated full load rotational speed.

Increased power density through directly water cooling conductors is another option for even further decreasing motor size. The minimum motor size with ideal water cooling does not provide as much of a size and weight reduction as the increase in rotational speed, but the smallest and lightest possible design includes both the water cooling and the higher speed operation. Contra-rotating propellers are another possible strategy under investigation to capitalize on the reduction in motor size, with increased relative motor speed and higher propeller efficiency while avoiding increased propeller speed together with the risk of increased cavitation.

References


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