Determining the Most Feasible Biomimetic Propulsion Mechanism To Reduce Fuel Consumption and Emissions in Maritime Transport

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Abstract

The propulsion of marine animals is the product of millions of years of evolutionary optimization, resulting in extremely efficient movement. Replicating this motion in man-made machines offers the potential to reduce fuel consumption and emissions in ships. This paper examines research on two different promising biomimetic propulsion mechanisms, tubercles and flapping foils, in order to identify the most feasible and effective technology for sustainable shipping. Analysis of experimental and computational studies shows that tubercles upstream of propellors can reduce total resistance by about 6%, directly lowering shaft power requirements and greenhouse gas emissions, while tubercle-modified propellers improve low-speed thrust and wake quality though with tradeoffs at high speeds. Flapping foils demonstrate high propulsive efficiency in controlled tests, but their mechanical complexity, maintenance demands, and scaling challenges limit feasibility for widespread adoption. The findings indicate that tubercle-assisted systems, due to their relative simplicity and proven performance, are the most practical and efficient option for near-term reductions in maritime fuel consumption and emissions.

1 Introduction

The oceans are Earth's highways, with ships carrying over 80% of global trade and contributing nearly 3% of global greenhouse gas emissions [1]. Biomimetics involves the imitation of nature in man-made systems [2]. The propulsion of marine animals is the result of millions of years of evolutionary optimization to develop a very efficient movement, with marine animals like dolphins, tuna, and humpback whales achieving remarkable thrust-to-energy ratios while minimizing drag. In recent decades, engineers have begun translating these biological strategies into propulsion systems, aiming to reduce fuel consumption and emissions of ships.

This paper compares two promising bio-mimetic propulsion mechanisms for marine transportation, tubercles and flapping foils, and argues that tubercles are the more feasible option for improving propulsive efficiency in ships.

This paper reviews research from the past 30 years on these two technologies and fish propulsion. It synthesizes the key findings, examines the obstacles identified in the literature, and analyzes the potential fuel and emission reductions associated with each mechanism. A conclusion is found by holistically comparing this information.

2 Tubercles

Tubercles are sinusoidal, rounded protrusions found along the leading edge of humpback whale flippers, where they enhance hydrodynamic performance by delaying stall, maintaining lift at higher angles of attack, and reducing drag [3]. They contain peaks and troughs that can be defined using amplitude and wavelength as seen in 1 [3].

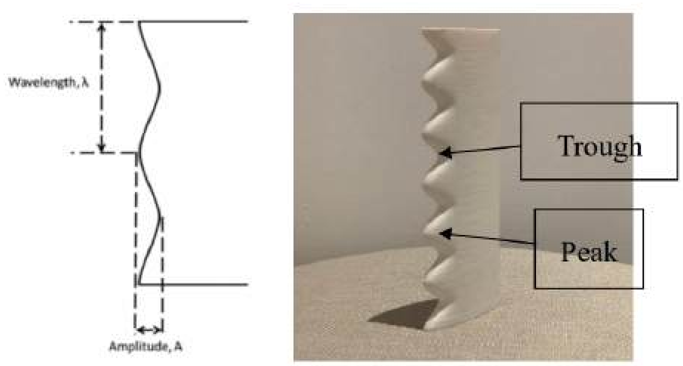

Figure 1: Visual of the troughs and peaks of tubercles and how they can be demonstrated using wavelength and amplitude [3].

These features act as passive flow control devices by manipulating the way water moves over the surface. As air flows over the surface, these features cause the air to swirl in small rotating patterns. These swirls pull fast-moving air from outside the surface layer down toward slower air near the surface. This extra energy helps the airflow stick to the surface instead of peeling away, which improves overall performance [3]. At each tubercle peak, the curvature and geometry cause a pressure difference between the suction side (low pressure) and the pressure side (high pressure) of the foil or blade. This pressure difference drives fluid from the high-pressure region to the low-pressure region in a helical, swirling motion. As a result, each tubercle peak generates a pair of vortices that rotate in opposite directions (one clockwise, one counter-clockwise) as they travel downstream along the flow direction. These vortices continuously mix faster-moving water from outside the boundary layer with the slower-moving water close to the surface. This mixing energizes the boundary layer, making it more resistant to separating from the surface, especially under adverse pressure gradients (where flow would normally slow and peel away). The boundary layer is a thin layer of fluid (in this case, water) right next to the surface of a ship's hull, propeller blade, or any other object in the flow [3–5]. Tubercles can improve ship efficiency by generating vortices and spanwise flows that energize the boundary layer, helping it stay attached longer to reduce drag and flow separation. They also smooth and homogenize the wake into the propeller, reducing load fluctuations and improving propeller performance, and in propeller applications can delay stall to enhance low-speed thrust and acceleration for better manoeuvrability [3–5]. This biomimetic geometry has been adapted for marine applications, including hull-mounted energy-saving devices (ESDs) and propeller modifications [3–5].

2.1 Summary of Results from Recent Studies

2.1.1 Hull-mounted ESDs

ESDs are one of the most inexpensive and convenient technologies to enhance ship efficiency [3]. Full-scale computational fluid dynamics (CFD) tests of a novel tubercled ESD located upstream (Zone 1, see figure 2) of the propeller on the cargo ship Regal showed an average 6% reduction in total resistance, primarily due to viscous drag reduction from improved boundary layer mixing. 3 demonstrates this reduction in the difference of resistance between the ship hull without the ESD and with the device.

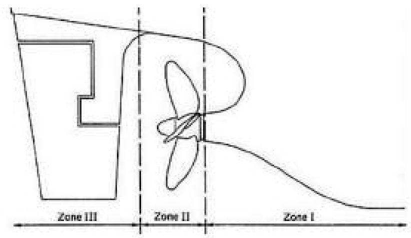

Figure 2: The different zones surrounding a propellor. Hull mounted Tubercles are mounted in Zone 1, upstream of the propellor [3].

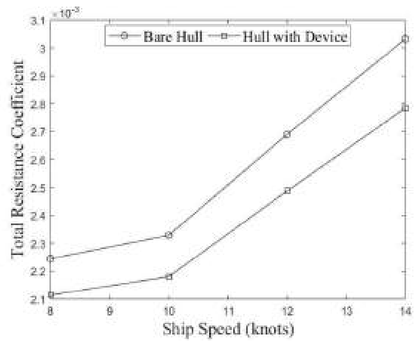

Figure 3: Shows the 6% reduction in resistance using Hull mounted tubercles [3].

The wake behind the ship became smoother and more even, with axial velocity in some areas increasing by about 44%, which can reduce propeller vibration and help it operate more efficiently [3].

2.1.2 Propeller Leading Edge Modifications

Testing of tubercle-modified propellers shows consistent trends in hydrodynamic influence but mixed outcomes for overall performance [4]. In model tests (Figure 4, tubercle-like leading edges lowered surface pressures across most of the face and back, simplified gradation patterns, and reduced trailing-edge pressures, effects that can decrease drag.

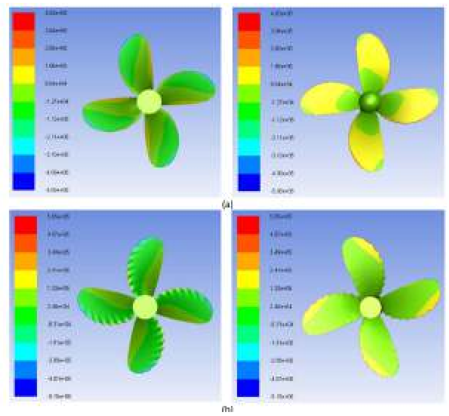

Figure 4: Uses CFD simulations to show the reduction in surface pressure on propellors equipped with leading edge tubercles [4].

They also increased surface Reynolds number velocities, indicating localized turbulence from flow separation at tubercle peaks, and lowered power surface acoustic levels, suggesting a noise-reduction benefit 5[4].

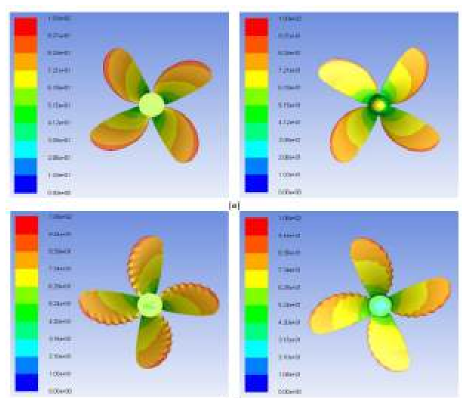

Figure 5: Uses CFD simulations to demonstrate the reduction in power surface acoustics with tubercles on the leading edge compared to without them [4].

However, torque reductions were observed, pointing to possible losses in delivered power. Full-scale CFD simulations of Tubercle Assisted Propellers. Tacar et al. similarly found that tubercles can enhance performance in specific regimes, producing greater thrust and faster acceleration at low speeds [5]. Yet at higher speeds, the conventional propeller reached and maintained a higher equilibrium velocity, indicating that poorly tuned tubercle designs can limit efficiency at high speeds. Together, the results indicate that while tubercles can improve low-speed thrust, wake quality, and acoustic performance, they may impose efficiency penalties at higher speeds unless geometry and operating profile are perfectly tuned [5].

2.2 Obstacles to Implementation

Most early tubercle studies examined laminar or transitional flows, but ship stern and propeller flows are predominantly turbulent, making flow regime sensitivity an important consideration [3]. Optimizing design parameters, such as amplitude, wavelength, and integration with hull or duct geometry, has a significant impact on performance outcomes [3, 5]. However, these designs involve trade-offs, as increased turbulence can introduce vibration or torque loss in propellers [4]. Additionally, tubercle-assisted propellers (TAPs) may underperform at high speeds compared to conventional propellers, limiting their operational range [5]. To fully validate performance predictions from computational fluid dynamics (CFD), more full-scale sea trials and long-term operational data are needed [3].

2.3 Evaluation of Potential for Fuel and Emission Reduction

Hull-mounted tubercled ESDs demonstrate clear potential for reducing fuel consumption and greenhouse gas emissions, with the 6% resistance drop translating to power requirements in ships, reducing fuel consumptions [3]. This makes them good candidates for upgrades that meet International Maritime Organization climate rules. For propellers, benefits are speed-dependent: TAPs improve low-speed thrust and maneuverability, which is valuable for service and offshore vessels, but the potential torque losses and reduced high-speed performance observed in both Arifin et al. and Tacar Ilter et al. demonstrate the need for carefulness in the system [4, 5].

3 Flapping Foils

Flapping foil propulsion draws inspiration from the oscillatory motion of fish fins and cetacean tails, which generate thrust through coordinated heaving (vertical translation) and pitching (rotation) motions - that shed vortices in their wake, here alternating vortices direct momentum downstream, increasing net thrust and propulsive efficiency [6, 7]. Unlike conventional screw propellers, flapping foils produce thrust by accelerating discrete packets of fluid rearwards, enabling both high propulsive efficiency and enhanced maneuverability [7, 8]. This process can be tuned to recover energy from upstream flows or to improve efficiency under a wide range of operating conditions. An oscillating foil can function as a primary propulsor or as an energy-harvesting and flow-conditioning device mounted ahead of a propeller.

3.1 Summary of Results from Recent Studies

Experimental and numerical studies consistently report higher propulsive efficiencies for flapping foils compared to traditional propellers, especially at moderate speeds. In some ship trials, oscillating foil propulsion demonstrated efficiency gains of up to 50%, with fuel consumption reductions ranging from 33% to 50% relative to screw propellers [8]. Analyses of swimming fish and foil tests show that maximum propulsive performance occurs when the Strouhal number, which describes the oscillations of a flapping foil, lies between about 0.25 and 0.35. This effect is visualized in Figure 6. When the foils in the M.I.T. tanks were tuned to this range, measured efficiencies exceeded 86%, showing a stark difference to small underwater vehicle propellers, which show efficiencies of 40% under comparable conditions [6].

Figure 6: Demonstrates the vortex's created when the Strouhal number lies between 0.25 and 0.35 [8].

Wake–foil interactions can lift performance above what isolated foils achieve: a two-dimensional inviscid analysis showed conventionally defined propulsive efficiency can exceed 100% because the foil recovers energy from the oncoming vortices in sheets of water [9]. Flapping foils could operate as either the main propulsion system or as auxiliary thrusters to recover wave energy, reducing ship resistance and motion. Flexible foils in particular can increase thrust by 1–2× and double propulsion efficiency compared to rigid foils under similar kinematic conditions [8].

3.2 Obstacles to Implementation

Despite their promise, flapping foil systems face several engineering and operational barriers. Unlike the simplicity of a rotating propellor, they require robust systems to synchronize heave and pitch motions, which increases mechanical complexity, wear, and maintenance demands [8]. Their efficiency is also highly sensitive to precise kinematic tuning, meaning that even small changes in phase angle, frequency, or amplitude can significantly reduce thrust or increase drag [9]. In addition, integration with hull forms must be carefully managed, as hull–foil interactions can generate unsteady inflow patterns that, if well-aligned, can enhance efficiency through energy recovery but, if misaligned, can diminish performance [7, 9]. Finally, scaling these systems from laboratory or small-vessel applications to large commercial ships presents challenges, as structural loads, foil-span limitations, and hydrodynamic behavior may not translate directly without significant adaptation [8].

3.3 Evaluation of Potential for Fuel and Emission Reduction

Flapping foils seem promising as they reduce the energy demands for propulsion, by improving fuel efficiency. As a result, they indirectly reduce greenhouse gas emissions from marine transport. Flapping foils work well in rough conditions by recovering otherwise wasted energy from ship motions, including ocean waves, which again enhances the net energy efficiency. Flapping foils also improve maneuverability in difficult conditions such as congested ports, by letting ships turn more tightly and maintain better control even at low speeds.

However, for flapping foils to have realizable benefits at scale requires modern ships to be nearly completely redesigned. Otherwise, the actuation mechanisms and structural supports that are needed would compromise hull integrity or cargo capacity. The mechanical complexity of flapping foils also cause higher maintenance demands. Furthermore, it's possible hydrodynamic performance may be more difficult to sustain under the variable conditions encountered by large commercial vessels.

4 Discussion

Both tubercle-assisted and flapping foil propulsion systems draw inspiration from marine life to improve hydrodynamic efficiency, but their performance characteristics and operational limitations differ substantially.

Hull-mounted Energy Saving Tubercles, they have been shown to smooth the nominal wake, creating a more uniform inflow and reducing the risk of blade load fluctuations. This can improve propeller efficiency and lower fuel consumption, particularly at steady, low-to-moderate speeds. However, flapping foil propulsion systems operate on a different principle, generating thrust through oscillating motions that mimic the swimming of fish and marine mammals. When tuned to optimal motion parameters, flapping foils can achieve very high efficiencies and even recover energy from upstream flows. On propeller blades themselves, tubercle-like leading edges can reduce surface pressures and noise while improving low-speed thrust. However, similar to flapping foils, these benefits are not uniform across all speeds. Indeed, full-scale tests show that conventional propellers can perform better than designs inspired by tubercles at high speeds. Therefore, there may be a trade-off between the possible maneuverability gains and maximal efficiency. Additionally, flapping foil systems utilize complex actuation mechanisms, precise motion control, and they require a lot of work for their integration into the hull, which increases both costs and maintenance requirements.

5 Future Works

To progress systems leveraging tubercles towards broader adoption, additional sea trials at full-scale are needed in order to validate and test CFD and model-scale findings. It also would be helpful to further test a broader range of amplitudes, wavelengths, and placements, particularly in identifying configurations that are optimal for various vessel types. We recommend future research should focus on scaling the technology to larger ships; advanced simulations should be combined with pilot projects to investigate performance and durability at scale.

6 Conclusion

We find tubercle-assisted devices could be a more feasible choice to reduce near-term fuel emissions compared to flapping foils. Tubercle-assisted devices improve wake quality, reduce flow separation, and enhance low-speed thrust, and they do not require major modifications to the hull nor complex other complex integrations. Therefore, tubercle-assisted devices are easier to modify and reduce operational risk.

Even though the higher peak efficiencies are possible with flapping foils, their implementation is hindered by inordinate costs, related to their mechanical complexity, control requirements, and structural integration needs. These barriers limit their immediate viability to specialized vessels where performance gains justify the expense.

In summary, we believe tubercle-assisted ESDs and propellers present the most feasible path forward for scalable, affordable solutions in the maritime industry. They offer a balance of proven hydrodynamic benefits and low adoption costs, making them an effective step toward more sustainable ship propulsion. In the future even more advanced biomimetic technologies may be implemented.

7 Acknowledgments

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