

The Application of Biomimetics to Maritime Transportation Through Antifouling and Hydrodynamics

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ABSTRACT: Over millions of years of evolution, marine animals have optimized their hydrodynamics and efficiency of movement in water. Elements of marine animals can be replicated to solve real-world design problems. Hydrodynamic features of these animals can be copied, in particular, to help improve the efficiency and emissions of maritime transportation. This paper introduces the growing field of biomimetics and how this engineering tool can be utilized to increase the efficiency of maritime transportation. It is hypothesized that by utilizing biomimetics to replicate aspects of animal biology, the efficiency of maritime transportation can be improved while lowering emissions. The current and future uses of biomimetics in maritime transportation for drag reduction and antifouling are to be compared to current non-biomimetic solutions through a cost-benefit analysis.

KEYWORDS: Engineering, Maritime Transportation, Biomimetics, Sharkskin Denticles, Antifouling.

■ Introduction

Maritime transportation has played a central role in human society for millennia and remains essential to global trade today. While early civilizations such as the ancient Mesopotamians applied hydrodynamic principles for irrigation and water management, modern maritime transportation faces significant challenges.¹ Fuel inefficiency and associated emissions contribute to climate change, disrupting marine ecosystems.² Because maritime transportation cannot be eliminated, improving its efficiency and reducing its environmental impact is critical.

Biomimetics, the application of biological processes and structures to engineering design, offers a promising framework for addressing these challenges.³ Through millions of years of evolution, marine organisms have developed effective solutions to problems directly relevant to maritime systems, including drag reduction and antifouling.^{4,5} Leveraging these biologically optimized strategies provides a pathway toward improving the efficiency and sustainability of maritime transportation.

More broadly, biomimetics is part of a well-established family of nature-inspired design approaches that have been successfully applied across engineering, architecture, and materials science. The existence of related frameworks underscores that drawing inspiration from biological systems is not a speculative idea, but a proven and transferable design paradigm, one that can be meaningfully applied to maritime transportation. Figure 1 provides a visual overview of the broader landscape of nature-inspired design approaches, situating biomimetics within a continuum of strategies that draw on biological systems in different ways. For example, related approaches to biomimetics include biofabrication, which incorporates biological materials into manufacturing; biophilia, which integrates nature into design to support human well-being; and bionics, which applies biological principles to engineering and electronic systems.

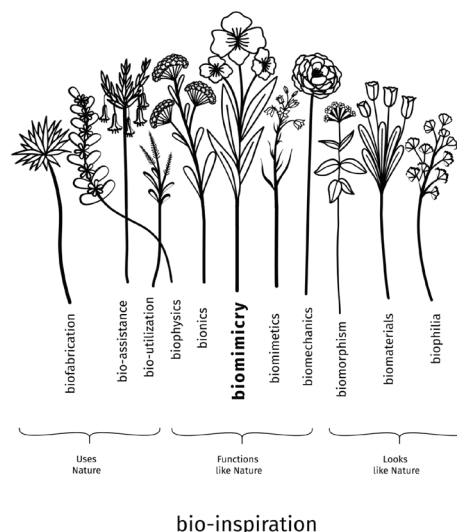


Figure 1: Demonstration of a spectrum of bio-inspired design approaches similar to Biomimetics.⁶

This paper aims to demonstrate the potential of biomimetics in improving the efficiency of maritime transportation. Section 2 focuses on the application of biomimetics in improving the hydrodynamics of maritime transportation vessels to reduce drag, improve efficiency, and reduce emissions. Section 3 provides an overview of historical antifouling strategies and evaluates their performance relative to modern biomimetic antifouling solutions using a cost-benefit framework. Finally, the future of biomimetics itself is discussed briefly in Section 4.

■ Discussion of Improving the Hydrodynamics of Maritime Transportation Through Biomimetics

Reducing hydrodynamic drag is a key pathway to improving efficiency and reducing environmental impact in maritime transportation.⁷ Biomimetics provides valuable insight into

this problem, as aquatic organisms have evolved effective mechanisms for minimizing drag and enhancing locomotion.

Biological Inspiration: Sharkskin Denticles:

One organism that depends heavily on efficient underwater movement is the shark, for which sharkskin denticles play a key role in enhancing hydrodynamic efficiency. Denticles are small tooth-like structures embedded in sharkskin to reduce drag during swimming. Figure 2 provides a close-up image of these denticles. This has inspired researchers to mimic denticle designs to improve the hydrodynamics of various underwater surfaces.⁴

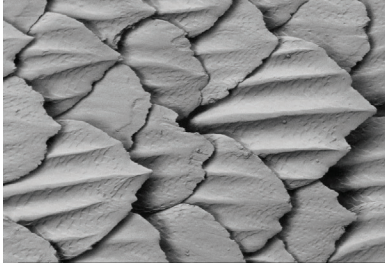


Figure 2: Image of sharkskin denticles.⁸

While sharkskin denticles demonstrate highly effective drag-reduction strategies in biological systems, their performance in engineered applications depends strongly on surface properties that may not be as easily replicated in large maritime structures; yet, the following research studies show great promise for implementing them for the future of maritime transportation.

Role of Surface Flexibility:

Surface flexibility is a critical factor in determining whether biomimetic denticles can effectively reduce hydrodynamic drag. Flexibility influences not only where denticles may be applied on a surface, but also whether their interaction with the surrounding flow can produce performance benefits.

In 2012, Oeffner and Lauder conducted experiments on artificial shark skin, real shark skin, and a flexible Speedo foil material.⁴ As part of their testing setup, some denticles were sanded down to form small surface nubs. When applied to rigid surfaces, these denticles showed no consistent improvement in swimming performance. Although a systematic explanation for the lack of performance change was not provided, the surface nub results suggest that denticle surface roughness alone is less important than the interaction between the surface and the flow. In particular, the ability of the shark skin to deform underwater, in addition to the denticles on the surface of the shark skin, provides the performance-enhancing benefits underwater.⁴

In contrast, when surface nub denticles were applied to a flexible surface to create artificial shark skin, swimming speed increased by 12.3%.⁴ The testing in this model closely replicated the hydrodynamics of real shark skin underwater. These denticles experienced an average strike number, St between .28 and .38, which is within the range of Strouhal's number of swimming sharks: 0.21 to 0.41.⁹ This is defined as $St = fL/U$, where f is the frequency of the foil, L is the charac-

teristic length, and U is the flow speed. Strouhal's number is a dimensionless parameter that expresses the ratio of vibrational-to-flow velocities.¹⁰

One potential cause behind the improved performance of the denticles on flexible surfaces is due to how a flexible surface might mimic the flesh of a shark. The denticle's improved performance on flexible materials leads towards the potential future use of sharkskin-inspired denticles on athletic swimwear and flexible underwater robots.

To further assess when a surface is flexible enough to benefit from denticles, a scaling analysis can be used. The degree to which a material deforms under fluid loading is characterized by its bending stiffness, B given by:¹¹

$$B = \frac{Et^3}{12}(1 - \nu^2) \quad (1)$$

where E is Young's modulus, t is the thickness, and ν is Poisson's ratio.^{12,13} The force exerted by the fluid can be estimated using the dynamic pressure, q :¹⁴

$$q = 1/2 \rho U^2 \quad (2)$$

Suppose the pressure acts across a length L , the surface area exposed to the flow scales as L^2 , where the total bending moment acting on the material is $M=qL^3$. The ratio of the fluid force to the resistance force is then given by $\underline{B}$:

$$\underline{B} = \frac{6(1-\nu^2)\rho U^2 L^3}{Et^3} \quad (3)$$

Equation (3) can be used to predict if a material would benefit from the addition of denticles under certain flow conditions. When $\underline{B} < 1$, the elastic resistance dominates, and the structure does not bend under flow, making it rigid and unlikely to benefit from the addition of denticles. When $\underline{B} > 1$, the fluid forces dominate, and the structure deforms greatly under fluid forces. Under this regime, the structure would benefit most from the addition of denticles.

Several trends can be inferred from equation (3), plots of which are shown in Figure 3 for the case when $\underline{B} > 1$. First, thinner structures benefit more from the addition of denticles. Second, the flow regime is especially important. Below in Figure 3, equation (3) is graphed with $\underline{B}$ as our dependent variable and U as our independent variable. The velocity U ranges from 0 to 15m/s; this ranges from 0 to 29 knots. Figure 3 shows 3 cases at thicknesses of 5 and 25mm. Additionally, a length of 1 meter, a Poisson's ratio of .3 and a Young's modulus of $(5)10^{10}$ is utilized. Water density at approximately 3.98 C is assumed.

The quadratic relationship between $\underline{B}$ and U is evident in all 3 cases; additionally, the thickness of the material significantly impacts the value of $\underline{B}$. At the lowest thicknesses of 5mm, $\underline{B} > 1$ at the majority of speeds; however, a thicker material requires greater speeds for $\underline{B} > 1$. For example, with a thickness of 25 mm, U must exceed 12 m/s for $\underline{B} > 1$. Consequently, at thinner values the use of denticles is almost always beneficial; however, as the thickness increases, the velocity of the ship must exceed greater and greater values for denticles to become beneficial.

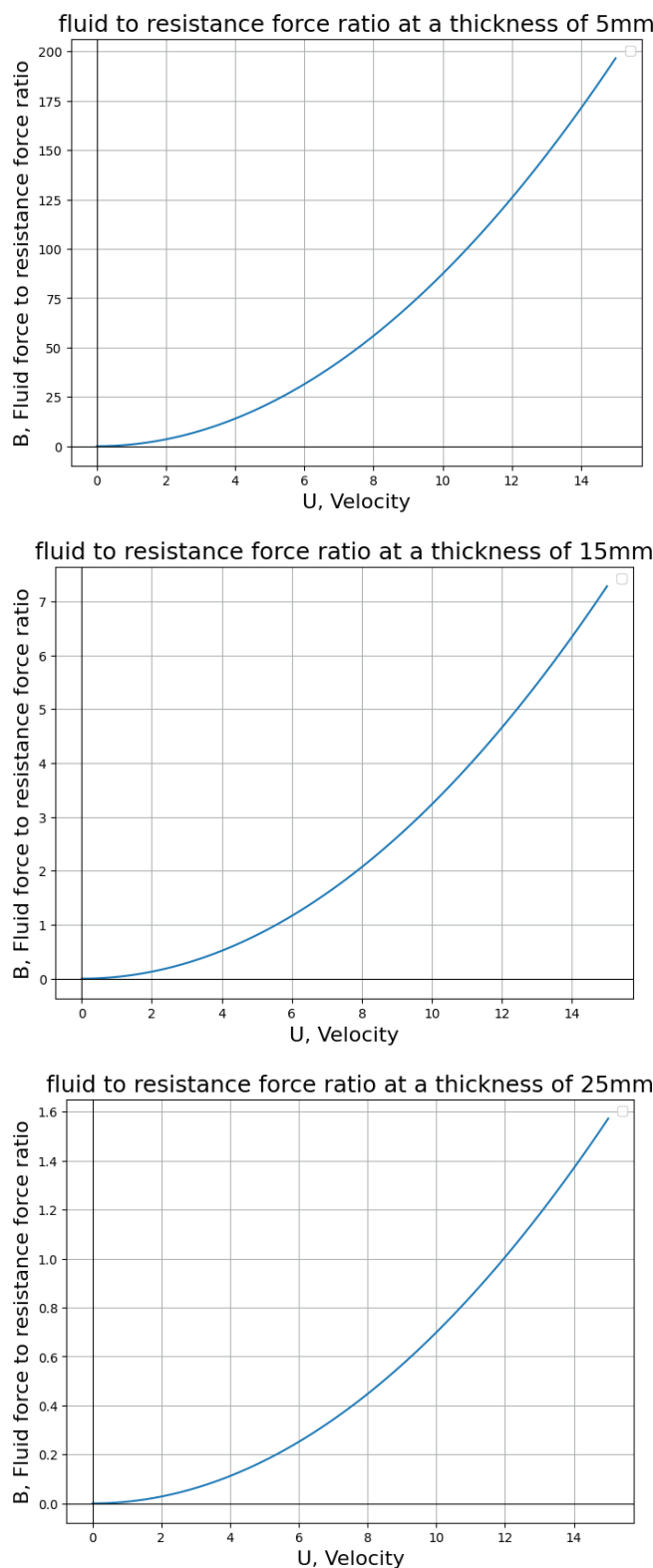


Figure 3: Graphs of equation 3 plotted with thicknesses of 5, 15, and 25 mm. A quadratic relationship exists between the velocity and force ratios. Additionally, the thickness of the material impacts the curve; thicker materials require greater velocities for the denticles to be beneficial. Plots generated by the author.

Manufacturing Constraints and Feasibility:

Although shark skin denticles have the potential to improve the drag of maritime transportation and robotics, they

suffer from being hard to manufacture. Due to the tiny size of these denticles and the harsh conditions they endure, the manufacturing and design of these denticles becomes a significant roadblock. In 2024, Graybill and Xu analyzed different manufacturing techniques, including bioreplication, molding, 3D printing, and metal CNC machining for the creation of biomimetic denticles.⁷ These denticles mimicked those of the Shortfin Mako Shark.⁷

Molding:

Molded silicone denticles were the closest in size to real shark skin denticles, which were also the smallest of all manufacturing techniques. The molded denticles experienced a drag reduction of 9.7% at 0.9 m/s to 18.6% at 0.45 m/s.⁷ Compared to a flat PU sheet, molded denticles experienced 31% more drag reduction, and replicated denticles a 36.7% reduction with MSN texturing, which is close to the nearly 39% of sharkskin.⁷

CNC Machining:

CNC machining these denticles from Aluminum is a complex and traditional process. Denticles were machined with spacings from 0.150 to 1.001 mm and tested with flow velocities ranging from .55 to 4.52 m/s.⁷ The smallest design at 0.150mm experienced the greatest average drag reduction at 13.05%, peaking with 27.7% at 2.36 m/s.⁷ Along with producing the worst results, CNC-machined denticles struggle with feasibility, as traditional CNC manufacturing could be more expensive than molding or 3D printing.

3D Printing:

Another primary manufacturing method analyzed is 3D printing with thermoplastics. These were tested in flow speeds between .1 to .5 m/s with widths ranging from .15 mm to 3 mm in width.⁷ Although 3D printing technology is more time-efficient in outputting the desired product, there are limitations in the context of denticle production, where achieving smaller-sized denticles under 2 mm is much harder. Bigger denticles (~2 mm) experienced reduced drag reduction benefits as the form drag of a larger denticle overcomes its hydrodynamic benefits.⁷ A drag reduction of 31% was experienced with the smallest denticle of width 1.53 mm.⁷

One of the potential benefits of 3D printing compared to molding is that they are easier to produce on smaller scales; however, on large scales, molding is a much more scalable option.⁷ In 2018, Domel *et al.* further tested 3D printed denticles and found that the smallest denticle with a chordwise length of 2.1 mm reduced the most drag.¹⁵ The denticles were 3D printed out of a thermoplastic with a rubber-like membrane designed to simulate the actual materials of sharks.¹⁵ Static water-tank testing was conducted to measure drag forces, with denticles tested at three different sizes under the hypothesis that smaller denticles would reduce drag relative to larger ones.¹⁵ Additionally, all denticles experienced increased drag at faster flow speeds and similar Reynolds numbers below 2000, suggesting the overall flow is similar between each.¹⁵

Overall, all machining methods found that smaller denticles under 2 mm in width most consistently reduced drag.¹⁶

Implications for Future Maritime Technologies:

The use of sharkskin denticles to reduce hydrodynamic drag and improve efficiency is incredibly promising.¹⁵ Optimizing for reduced drag, smaller denticles of length 1 to 2 mm on flexible surfaces produce the best results. Currently, biomimetics research indicates that denticle-based designs are most easily transferable for applications involving flexible or deformable surfaces, such as competitive swimwear and underwater robotic systems. In underwater robotics, where compliant outer structures are often used to enhance maneuverability and efficiency, the integration of denticle-inspired surface textures may offer tangible performance improvements.

In contrast, the application of denticles to large maritime vessels faces challenges that require more in-lab investigations. Ships and larger vessels suffer from not being able to have more flexible hulls without sacrificing other important components. Additionally, larger aquatic vessels would require more denticles, which could increase the cost of manufacturing, assembling, and maintaining so many small structures on the ship's hull.¹⁷ Drag reduction through denticle-inspired designs does have the potential to lower fuel consumption and associated emissions, but the economic and environmental costs of producing and maintaining such surfaces must be carefully weighed against these benefits.

Despite these challenges, sharkskin denticles illustrate biomimetics' capacity to inspire novel solutions to modern maritime challenges, with recent studies examining denticle geometry, surface compliance, and hydrodynamic performance to evaluate their potential translation from biological systems to engineered marine surfaces, including ship hulls.¹⁷

■ Discussion Of Applying Antifouling to Biomimetics

Biofouling as an Efficiency and Environmental Problem:

Biofouling, the accumulation of marine life, has always been a problem in the maritime transportation sector. The accumulation of marine life on the hull of a ship results in an increase in weight and friction, causing an approximate 40% increase in fuel consumption or 72 million tonnes each year.¹⁸ Additionally, the overall cost associated with hull biofouling in the Navy alone is estimated to be \$56 million per year.¹⁹ Although biofouling can impact fuel emissions and costs, biofouling also contributes to the spread of invasive organisms. This can occur when a biofouled ship travels long distances. In the state of Hawai'i, nearly 80% of non native aquatic species have been introduced through biofouling.²⁰ This section explains biofouling, a brief history of antifouling solutions, and their pros and cons. Furthermore, current antifouling methods are compared to biomimetic alternatives.

Biofouling begins with the formation of a biofilm on a submerged surface, initiated by the colonization of microorganisms such as diatoms and protozoa. These early-stage, single-celled organisms create a conditioning layer that facilitates the subsequent settlement of algae spores and larger

marine organisms. Figure 4 illustrates this biofouling progression over the course of one year.

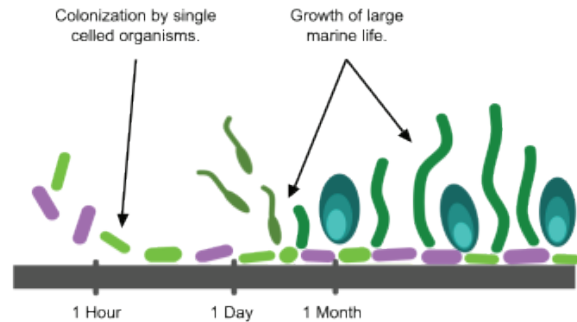


Figure 4: Model of the biofouling process over time. Image created by the author.

With biofouling's impact on overall efficiency and movement, antifouling techniques were guaranteed to arise. Antifouling is a design technique to prevent biofouling or the accumulation of marine life on the hull of ships. One early example of antifouling is the plating of a ship's hull with copper and lead to remove marine organisms.²¹ Figure 5 is an example of biofouling on the hull of a ship.



Figure 5: Biofouling on a workboat.²²

Conventional Antifouling Methods and Their Limitations:

Several modern antifouling solutions include regular cleaning of surfaces and applied coatings or paints. In the 1960's, antifouling paints with Zinc, Mercury, and other toxic compounds were used that had a considerable impact on the marine environment.²³ One of the most common antifouling paint solutions, known as TBT, is a compound that lasts up to 4-5 years.¹⁸ The toxic effects of TBT are well researched and have extreme impacts on marine biology. For example, in 1982, France banned the use of TBT on vessels less than 25 meters in length.¹⁸ Additionally, TBT has been found in human blood and liver.²⁴ Compared to traditional non-biomimetic antifouling solutions, biomimetic solutions are a lot more promising when it comes to environmental impact.

Biomimetic Antifouling Approaches:

One emerging biomimetic antifouling solution includes the use of algae-inspired biomimetic haloperoxidases.⁵ This solution is based on haloperoxidases that algae naturally secrete to prevent the attachment of microorganisms. Different haloperoxidases are still being tested for use, as a perfect solution has not yet been found, but this remains a promising antifouling solution. Additionally, naturally produced enzymes struggle with long-term stability and cost compared to their artificially produced alternatives. Another emerging biomimetic solution

to antifouling is the use of capsaicin films for their antifouling and antibacterial uses.²⁵ Multiple films composed of capsaicin-filled nanocapsules were tested for their antifouling capabilities and ability to release capsaicin in a gradual and controlled manner. The films maintained over 90% antibacterial properties after 60 days of performance.²⁵ Furthermore, as time goes on, biomimetic antifouling solutions will become cheaper and more effective. Environmentally friendly antifouling solutions have gained significant interest over the past couple of years as traditional coatings are banned.²⁶ As scientific development and research around antifouling progresses, biomimetics will emerge as a promising solution.

Comparative Cost-Benefit Analysis:

Section 3.4. presents a comparison between a conventional antifouling agent, TBT, and a biomimetic alternative based on haloperoxidase mechanisms. Table 1 provides a cost-benefit analysis comparing biomimetic and traditional antifouling strategies, highlighting the advantages of biomimetic solutions. The analysis indicates that while TBT is a cheap, reliable, and effective solution, biomimetic haloperoxidases outshine it. This can be seen in their minimal environmental impacts and potential to be just as reliable and cheap as TBT after further research and development.

Table 1: Cost-benefit analysis comparing TBT and biomimetic haloperoxidases antifouling solutions. While TBT remains a highly effective and economically attractive antifouling agent, its severe environmental and regulatory drawbacks limit its long-term viability. On the other hand, biomimetic haloperoxidases offer substantially lower environmental impacts and the potential for future improvements in cost and commercial feasibility. Table created by the author.

	Benefits	Costs
TBT	TBT is incredibly effective and durable, lasting 4-5 years. ¹⁸	TBT significantly negatively impacts the environment. For example, in 1962, TBT significantly impacted oyster farms in France. 80-100% of Oysters affected by TBT experienced developmental anomalies and shell malformations. ¹⁸
	TBT was invented in the 1950's and is incredibly well tested compared to more innovative antifouling solutions. Although TBT is well tested compared to Haloperoxidases, this is a weakness of all emerging technologies. ²⁷	TBT is heavily restricted legally, following TBT's environmental impacts. In 2008, the International Maritime Organization banned use of TBT on all vessels. ²¹
	TBT is significantly cheaper than newer Biomimetic Antifouling solutions. ²⁷	TBT's environmental impact reaches far beyond marine biology. Studies have found TBT in humans. Additionally, there is a wide range of potential adverse effects of TBT exposure. ²⁴
Biomimetic Haloperoxidases	Biomimetic solutions have significantly less environmental impact compared to TBT. ⁵	This solution is currently not fully developed compared to a much more accessible and cheaper TBT. ⁵ As biomimetic haloperoxidases continue to develop, this problem will most likely be minimized.
	Biomimetic haloperoxidases for antifouling solutions have the potential for much higher stability and lower costs. ⁵	The current use of naturally produced enzymes for antifouling struggles with high production costs and long-term stability. ⁵

Conclusion

The field of biomimetics has immense potential in revolutionizing both the hydrodynamics and antifouling of maritime transportation. As ocean exploration expands, new biological discoveries will continue to drive biomimetic innovations, enabling ongoing improvements in maritime technology both now and in the future. Despite its potential, biomimet-

ics suffers from the complexity of nature. Most organisms and their functions perform multiple roles on many different layers. Consequently, biomimetic solutions might suffer from side effects that aren't yet fully understood. The complexity of reproduction in nature also doesn't mimic modern manufacturing logistics, making many biomimetic solutions challenging logistically.

Although antifouling can improve the sustainability of maritime transportation, traditional antifouling solutions have the opposite result. TBT, a common traditional antifouling solution, has immense negative impacts on the environment, which greatly outweigh the positives of antifouling itself. Fortunately, biomimetic solutions reduce the environmental impacts of TBT, providing an overall boost to the sustainability of maritime transportation. Future research regarding this subject should involve a more in-depth cost-benefit analysis of TBT, Biomimetic Haloperoxidases, and other biomimetic antifouling solutions, such as the use of capsaicin films. Another area where biomimetics improves the sustainability of maritime transportation is the hydrodynamics of maritime vessels. Improved drag can not only reduce fuel consumption but also transportation time, emissions, and costs. The use of shark denticles to reduce the hydrodynamic drag of aquatic vessels is delved into, along with the logistics and physics behind it. Along with antifouling and drag reduction, biomimetics could be applied to other fields within maritime transportation, such as propulsion and communications.

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