

Techniques for Reducing Frictional Resistance to Enhance Hydrodynamic Performance and Fuel Efficiency

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Abstract. The rising fuel cost and stricter emission regulations have intensified the need for innovative drag-reduction methods in marine vessels to improve fuel efficiency and reduce environmental impact. A reduction in frictional resistance, a significant contributor to overall drag, is the key to these requests. This review paper explores two innovative strategies for reducing frictional drag: Air Lubrication System (ALS) and Surface Treatment methods, with a focus on Micro-Bubble Drag Reduction (MBDR), Air Cavity System (ACS), and Biomimetic Shark Skin Treatment. ALS involves the injection of air or air bubbles around the hull surface to create a barrier between the hull and water. Through methods like Micro-Bubble Drag Reduction (MBDR) and Air Cavity Systems (ACS), the significant potential was demonstrated, with MBDR and ACS achieving up to an 80% and 35% reduction in drag under ideal conditions respectively. With promising real-world applications like the Mitsubishi Air Lubrication System (MALs) and the Damen Air Cavity System (DACS) reaching fuel consumption improvements of 5% and 7% - 12% namely, the potential of ALS was clearly shown. Meanwhile, Biomimetic surface treatment, a method involving applying shark skin-inspired riblet structures to the hull surface, reducing frictional resistance by minimizing shear stress, achieved a modest reduction of 3.89% to 5.2%. While each method offers substantial benefits, limitations in scalability and applicability across various vessel types remain challenges. Future research is crucial to optimize these technologies for better compatibility and drag reduction efficiency, paving the way for more sustainable and cost-effective marine transportation.

Keywords: Drag Reduction, Hydrodynamic Performance, Air Lubrication, Surface Treatment, Biomimetic.

1. Introduction

The ever-increasing fuel prices and stricter emission regulations put enormous pressure on naval architects to achieve lower fuel consumption with higher cruising speed by cooperating enhancement to the current design of ships with new means of drag reduction using the concept of hydrodynamics and aerodynamics. The importance of marine transportation to the global economy is unmatched. As of 2011, roughly 9 billion tons of cargo are transported by sea, accounting for nearly 95% of the world's goods [1].

When moving through water, a ship experiences drag, which can be further separated into frictional drag and pressure drag [2,3]. Frictional resistance is generated by the friction between the fluid and the surfaces, while pressure drag, or form drag, is caused by a particular distribution of pressure resulting from the separation of flow from a surface [4,5].

Among them, frictional resistance accounts for the dominant part of overall drag, especially for low-Froude-number ships that sail at lower speeds [2]. Statistics show that for moderate-speed ships like oil tankers, frictional resistance contributes to over 80% of overall resistance, while for quick boats like holder vessels, it may account for as much as 50% [6,7]. It is estimated that a typical vessel uses around 60% of its propulsive power to overcome the frictional drag exerted on the ship hull [8].

Therefore, developing techniques to effectively reduce frictional drag is crucial for enhancing the overall efficiency and cruising speed of marine vessels. Among the existing approaches, minimizing the contact area between the vessel hull and the surrounding fluid has proven to be particularly effective [2]. Air lubrication systems, which inject air or bubbles into cavities at the hull's bottom or into the boundary layer between the hull and water, have been extensively researched and developed,

with several real-world applications demonstrating their potential. With further development and proper implementation of these methods, a potential 80% reduction in drag is achievable [9].

This review paper has been separated into two main sections, focusing on the employment of Air Lubrication System (ALS) and Surface Treatment, discussing their performance and applications based on related studies and reports in the following sub-sections.

2. Air Lubrication System

The Air Lubrication System (ALS) involves the injection of air beneath the hull surface, generating a thin film of air that acts as a barrier between the surface of the vessel and the surrounding seawater, reducing the overall area of the hull surface directly in touch with the flowing liquid [2]. First developed in the 1970s, its fascinating drag reduction capability and economic effect attracted a significant amount of research and developments to be conducted. It is estimated that the implementation of air lubrication technology would reduce the fuel consumption of ships by up to 20% [9].

The discussion for Air Lubrication will be divided into two sections, each being Micro-Bubble Drag Reduction (MBDR) and Air Cavity System (ACS).

2.1. Micro-Bubble Drag Reduction

The Micro-Bubble Drag Reduction System (MBDR) is a technology designed to reduce frictional drag by continuously blowing micro-bubbles to the bottom of the hull, creating a cushion between the hull surface and the surrounding fluid [4,10].

The first developing work on the MBDR technique was conducted by McCormick and Bhattacharya (1973). By wrapping copper wires around a fully submerged hull, small bubbles were created around the hull surface [11].

In 1983, Madavan et al.'s laboratory experiment on micro-bubble injection demonstrated a potential reduction in drag of up to 80% [9]. Despite the attractive results under ideal conditions, this technique proved to be nearly impossible to replicate on a shipping scale. The bubbles' tendency to deform under turbulent and shear fluctuation of the flow increases as the bubbles get bigger, ultimately changing them into non-spherical micro-bubbles, weakening their drag reduction performance.

In 2004, Kawamura T. et al. examined the relationship between bubble size and drag reduction effectiveness using bubbles ranging from 0.3mm to 1.3 mm [12]. According to their findings, bigger bubbles tend to stay closer to the surface and be more resilient to dispersions thanks to their greater buoyancy force. This property allows bubbles with larger sizes to be more efficient at reducing frictional resistance while remaining effective for a longer period [12]. Until today, their laboratory results remained a significant milestone and reference for future developers.

In 2012, Mitsubishi Heavy Industry (MHI) demonstrated the viability and performance of their Mitsubishi Air Lubrication System (MALS), an air lubrication system based on the concept of micro-bubble drag reduction — by installing it on the FERRY NAMINOUE, an 8072 gross ton ship with a length of over 140m and operating this system in open sea conditions [10].

A calibrated fuel consumption improvement of over 5% was observed even with wave heights reaching 2.5m - 3m, proving the unimaginable potential for MHI's MALS and MBDR as a whole [10].

2.2. Air Cavity Systems

An air cavity system (ACS) is a modern hull form design approach based on a series of indentations beneath a vessel's hull that form inflated air cavities by capturing air in it, reducing the amount of frictional resistance by isolating the hull surface from water. Unlike the MBDR method, the ACS technique requires a lower air injection rate to keep the air layer in place, drawing less than 3 per cent

of the total ship power. Therefore, gaining sizable improvements in hydrodynamic performance with neglectable power loss [13].

As per research, the drag reduction performance of planning hulls and semi-planning hulls are 20% - 35% and 15% - 30% respectively [9].

A recalculation for a full-scale ship with a displacement of 4000 tons from a towing test of model ships indicates that within a speed range of 40 to 50 knots, applying an artificial cavity can reduce resistance by 15% - 24%, leading to a potential speed increase of 3-7 knots. At higher speeds, between 50 – 60 knots, a resistance drop may range from 20% - 27%, translating to a speed gain of 6-9 knots [2].

In 2014, research conducted at Newcastle University involved modifying the middle section of a 2.2 m ship model to include a $0.43 \times 0.09 \text{ m}^2$ air cavity at the hull bottom [13]. These experiments demonstrated gross drag reduction ranging from 4% to 16%. An approximate 22% gross energy saving with only a 5% reduction in the contact area was calculated after applying scaling factors [14].

Commercially, in 2023, an air lubrication system based on the concept of the Air Cavity System was developed through a series of collaborations between Damen Shipyards Group and Delft University of Technology. The system is called the Damen Air Cavity System (DACS). In the same year, a sale was made with Amisco, an Estonian-based shipping company, and the DACS was set to be retrofitted onto their cargo vessel Danita shortly. With a promised fuel saving of 7% - 12% and an equivalent decrease in emissions, the DACS not only lowers the operational cost but also lowers the emission of greenhouse gases by a noticeable margin. [15,16].

3. Surface Treatment

Surface treatment refers to the modification of a material's surface by adding physical, chemical, or biological properties that differ from those that were initially present on it [17].

3.1. Biomimetic Shark Skin

Biomimetic Shark Skin surface treatment involves implementing shark skin denticle-like riblet structure onto the vessel hull surface for lower frictional drag and better fuel efficiency.

The primary objective of these microstructures is the effective control over naturally occurring turbulent vortices to obtain a lower shear stress. As the riblet structures lift high-velocity vortices away from the surface, high-velocity flow is confined to only the tips of the riblets. This allows for the formation of a low-velocity zone within the valleys of the riblets, where shear stresses are significantly reduced [18]. Therefore, only small amounts of high shear stress act on the riblet tips, while the overall surface experiences less drag compared to a smooth surface, resulting in a reduction of frictional resistance between the hull surface and water, as shear stress is directly linked to drag [18,19].

A paper published in 2018 demonstrated that biomimetic shark skin structures applied to ship hull surfaces resulted in a 3.89% reduction in drag force and a 3.75% drop in drag coefficient [18].

Another experiment conducted by Volkmar Stenzel et al. measured a 5.2% drop in total drag force from a torpedo-shaped object in a large hydrodynamic tunnel [20]. These promising outcomes testified to the huge potential for this drag reduction technology for future researchers and developers.

4. Comparison of Techniques Reviewed

Table 1 provides an in-depth comparison of three drag reduction techniques: Micro-Bubble Drag Reduction (MBDR), Air Cavity System (ACS), and Shark Skin Biomimetic Surface Treatment. The table highlights their drag reduction performance under ideal conditions, real-life applications, and the observed or calculated improvements in fuel efficiency.

Table 1. Three Techniques comparing

Name	Drag Reduction Performance Under Ideal Conditions (%)	Real-Life Application	Fuel Efficiency Improvement (%)
MBDR	Up to 80%	Mitsubishi Air Lubrication System (MALS)	Around 5%
ACS	20% - 35% for planning hulls 15% - 30% for semi-planning hulls 15% - 27% from laboratory results	Damen Air Cavity System (DACS)	7% - 12%
Biomimetic Surface Treatment	3.89% - 5.2%	N/A	N/A

MBDR appears to have the highest drag reduction potential, with performance reaching up to 80% under ideal conditions. The real-life application is demonstrated by the Mitsubishi Air Lubrication System (MALS), which shows an approximate 5% improvement in fuel efficiency [2][10].

ACS shows a varied drag reduction performance ranging from 20% to 35% for planning hulls and 15% to 30% for semi-planning hulls. Laboratory results indicate a drag reduction of 15% to 27%. The Damen Air Cavity System (DACS), representing the real-life application of ACS, is set to reach an estimated fuel efficiency improvement of 7% - 12% for marine vessels [2,9,15,16].

Biomimetic Surface Treatment demonstrates a more modest drag reduction, ranging from 3.89% to 5.2%, without any specific real-life application or fuel efficiency improvement data available [18,20].

5. Conclusion

In summary, this paper explored the most effective and innovative methods for reducing frictional resistance of ships to improve hydrodynamic characteristics and fuel efficiency, focusing on Air lubrication System and advanced Biomimetic Surface Treatment. For each method, the key benefits and drag reduction performance were highlighted after reviewing related studies and experiments conducted by other researchers. In summary, these technologies have shown promising potential to reduce overall resistance, improve fuel efficiency, and lowering environmental impact.

Despite the assuring numbers and their bright future, several challenges remain concerning. For instance, due to limitations such as incompatibility with certain types of hull forms, and restrictions on cruising speed and ship size, the application of ALS is often constrained. For the Air Cavity System (ACS), a large modification at the bottom of the hull is required. Therefore, a significant change in overall hydrodynamic performance is unavoidable, making it almost inapplicable to already existing ships. Then, for Micro-Bubble Drag Reduction (MBDR), since it is powered by the ship's power unit, it takes up a significant amount of propulsive power when sailing too slowly. As a result, micro bubble injection technology is best suited for moderately fast mid-ship with a Froude number between 0.05 and 0.30. Therefore, in ideal conditions, the micro-bubble method could reach a 6% - 9% reduction of drag. By far the greatest limitation of Air Lubrication System (ALS) is that they can only be installed on vessels with flat bottoms. As a result, V-shaped hulls found on warships and recreational vessels are not suitable for this technology and won't benefit from the drag reduction capacity offered by ALS.

The effectiveness and functionality of Shark Skin Biomimetic Surface Treatment are restricted by the lack of surface deformation. In 2012, Oeffner and Lauder demonstrated the significance of deformation in enhancing drag reduction efficiency for shark skin structures. Under similar testing conditions, a more rigid riblet structure resulted in a 7.2% increase in swimming speed, while a softer shark skin membrane achieved a remarkable 12.3% rise. This highlights the importance of flexibility in drag reduction. However, since a ship's hull is significantly more rigid than shark skin, riblets can only be installed at specific angles and patterns, limiting their drag-reducing potential.

Therefore, further research is required to refine these technologies and assess their scalability for larger vessels. Research and development are needed for ALS to optimize its integration with diverse

vessel designs and operational conditions while future work is needed for Shark Skin Biomimetic Treatment to focus on improving surface flexibility or developing a structure where each riblet can change its angles as needed to maximize their drag reduction efficiency and performance.

As the marine industry evolves, integrating these drag-reduction strategies will play a vital role in achieving a more ecologically friendly and sustainable future.

References

- [1] Royal Academy of Engineering. Future Ship Powering Option, 2013. Available at: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/Future_ship_powering_options_report.pdf.
- [2] George K.M. and Bharotiyal P.K. Drag reduction on vessels and study on its viability. *International Journal of Advance Research, Ideas, and Innovations in Technology*, 2019, 5(1): 610-614.
- [3] DRAG REDUCTION IN SHIPS USING MICRO-BUBBLE TECHNOLOGY, 2014.
- [4] Form drag. Form Drag | SKYbrary Aviation Safety. (n.d.). <https://skybrary.aero/articles/form-drag>.
- [5] Flight (Aerodynamics) John D. Anderson Jr., in *Encyclopedia of Physical Science and Technology* (Third Edition), 2003.
- [6] Kim Y.R. and Steen S. Potential energy savings of air lubrication technology on merchant ships. *International Journal of Naval Architecture and Ocean Engineering*, 2023, 15.
- [7] Ship frictional resistance. SHIP DESIGN | NAVAL ARCHITECTS | MARINE CONSULTANTS | OFFSHORE ENGINEERING | INDIA. (n.d.). <https://www.mermaid-consultants.com/ship-frictional-resistance.html>.
- [8] Mäkiharju S.A., Perlin M., Ceccio S.L. On The Energy Economics of Air Lubrication Drag Reduction. *International Journal of Naval Architecture and Ocean Engineering*, 2012, 4(4): 412-422.
- [9] Ahmadzadehtalatapeh M., Mousavi M. A Review on the Drag Reduction Methods of the Ship Hulls for Improving the Hydrodynamic Performance. *International Journal of Maritime Technology*, 2015, 4: 51-64.
- [10] Mitsubishi Heavy Industries, Ltd. global website: MHI INSTALLS MALS (Mitsubishi Air Lubrication System) on a ferry, 2012. <https://www.mhi.com/news/1210031580.html>.
- [11] McCormick, M.E. and Bhattacharya, R. Drag reduction of a submersible hull by electrolysis. *Naval Engineering Journal*, 1973, 85: 11-16.
- [12] Kawamura T., Fujiwara A., Takahashi T., et al. The Effects of the Bubble size on the Bubble Dispersion and Skin Friction Reduction, 2004.
- [13] Air-cavity ships are ready for a wider market. *Speed at Sea*, 2003.
- [14] Butterworth J., Atlar M., Shi W.C. Experimental analysis of an air cavity concept applied on a ship hull to improve the hull resistance. *Ocean Engineering*, 2015, 110(B): 2-10.
- [15] Html5TemplatesDreamweaver.com. (n.d.). Yardtech Marine Services S.A. https://www.yardtech.gr/damen_acs/dacs.html.
- [16] Mandra J.O. Damen Seals first sale of its Air Cavity System. *Offshore Energy*, 2023. <https://www.offshore-energy.biz/damen-seals-first-sale-of-its-air-cavity-system/>.
- [17] Surface Modified Nanomaterials for Applications in Catalysis, 2022.
- [18] Ibrahim M.D., Amran S.N.A., Yunus Y.S., et al. The Study of Drag Reduction on Ships Inspired by Simplified Shark Skin Imitation. *Applied Bionics and Biomechanics*, 2018, 2018(1).
- [19] Fu Y.F., Yuan C.Q., Bai X.Q. Marine drag reduction of shark skin inspired riblet surfaces. *Biosurface and Biotribology*, 2017, 3(1): 11-24.
- [20] Stenzel V., Wilke Y., Hage W. Drag-reducing paints for the reduction of fuel consumption in aviation and shipping. *Progress in Organic Coatings*, 2011, 70(4): 224-229.
- [21] Oeffner J., Lauder G.V. The hydrodynamic function of shark skin and two biomimetic applications. *Journal of Experimental Biology*, 2012, 215(5): 785-795.