

Optimization of Drag Reduction Using Bio-Inspired Surface Textures in Subsonic Flow

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Abstract--- This research produced an adaptable Drag-Reducing (DR) surface via biomimetic buildings, motivated by dolphins' extensible skin and the lotus leaves' hydrophobic properties. The concept integrates a longitudinal groove foundation with hydrophobic flexible substances, using a hydraulic actuator for dynamic surface changing. This method successfully incorporates non-smooth buildings, adaptable substrates, and hydrophobic DR methods, attaining a DR of up to 29% at a Subsonic Flow (SSF) speed of 0.3 m/s. This technological innovation successfully approaches DR across diverse SSF speeds in intricate underwater settings.

Keywords--- Drag Reduction, Surface Textures, Bio-Inspiration, Subsonic flow.

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I. Introduction

Marine transportation significantly contributes to worldwide freight transit, representing over 82% of international commerce (Vlasenko et al., 2022). However, it produces considerable greenhouse gas emissions, estimated between 1.9% and 3.7% of the global total. Minimizing the resistance boats encounter during navigation results in substantial energy conservation, fewer emissions, and enhancements in vessel length and velocity.

Scientists have investigated many biomimetic Drag-Reduction (DR) substrates, drawing inspiration from natural species, such as the riblet patterns of shark skin, the crescent-shaped plates of aquatic life, and the superhydrophobic exteriors of lotus plants (Chen et al., 2023). These coverings are achieved via techniques including microstructure-induced slipping or applying lower surface energy components. Biomimetic grooves particularly damage Turbulent Kinetic Energy (TKE) (Rohanizadegan et al., 2025) along the wall, resulting in a rise in the dimension of the viscous sublayer. It has been shown that an ideal proportionality (amplitude) is present for various Subsonic Flow (SSF) circumstances in harmonic half-wave patterns with a constant wavelength.

Computer simulations have played a pivotal role in comprehensively understanding and optimizing the behavior of such biomimetic materials. Computational Fluid Dynamics (CFD) (Tsang et al., 2023) has been widely utilized to simulate fluid SSF across diverse surface materials, forecasting DR (Shao et al., 2023) impacts under varying SSF circumstances. These simulations enable scientists to investigate the connections between surface characteristics and turbulent SSF, offering insights into how groove form, surface adaptability, and hydrophobicity affect the efficacy of total DR.

Based on these findings, different surface changes are being developed further for DR. Superhydrophobic surfaces generate air pockets across the liquid and the solid interface. This phenomenon, initially prompted by lotus foliage, is often accomplished using micro-nano-scale surface materials, chemical procedures, or hydrophobic coverings.

Dynamic control techniques are often essential to accommodate varying SSF velocities (Aabid et al., 2021). Injecting microbubbles at the surface modifies the near-wall SSF pattern and decreases friction. In addition, introducing oscillations to the surface disturbs vortices, reducing wall instability and drag. These approaches are energy-intensive, thus limiting their overall effectiveness.

An active, flexible surface architecture was created to enhance DR under diverse SSF circumstances (Rashid et al., 2022). This design enables the dynamic alteration of groove shapes concerning SSF speed, considerably expanding the range of circumstances to which the biomimetic interfaces adjust. Incorporating biomimetic architectures, compliant substrates, hydrophobic slips, and dynamic morphing enhances the DR impact. Numerical models and verification by experiment have substantiated the efficacy of this composite technique, which substantially decreases energy use in maritime navigation.

II. Background

Diverse methods for attaining DR have been explored, such as polymer addition DR, Leidenfrost effect DR, and jet surface DR. Notwithstanding advancements, all these DR solutions remain linked to considerable disadvantages, including environmental contamination, elevated temperatures, electrical use, and intricate manipulation. Compared to these entirely human-engineered methods, natural creatures have remarkable DR capabilities with little energy expenditure and environmental sustainability, having adapted to harsh living conditions over billions of years through natural selection. Based on their distinctive methods and exceptional adaptability, the research shall provide five renowned natural instances in the domain of DR:

1) Shark-skin DR resulting from its distinctive scales that are placoid, which significantly diminish turbulence friction caused by skin drag to attain exceptional speed and flexibility;

2) Dolphin-skin DR, which effectively modulates turbulence through its viscous properties in the human body;

3) Penguin's feather-induced microbubble DR, which alters the porosity of the fluid substance and the unstable boundary level related to its body;

4) The "Lotus impact" superhydrophobic DR exhibits minimal adhesion to water molecules and demonstrates an exceptionally low frictional force against water molecules (large, slip width);

5) Pitching plant-inspired slipping DR involves a thin lubricating layer confined within the micro/nano buildings on the solid base, resulting in a non-zero slip speed at the liquid-liquid interfaces.

The superhydrophobic surface, including micro-grooved patterns, entraps gas at the base of the microstructures, and this trapped gas, referred to as plastron, elevates the liquid, leading to a significant Contact Angle (CA). The plastron is unstable and revolves at a certain velocity like bearing wheels. Therefore, the viscous force at the solid-liquid boundary is the viscous force at the solid-gas contact. A slip, defined as slip width, happens at the junction, with the slip duration at the solid-gas contact being greater than that at the solid-liquid contact. The efficient slip is a crucial metric for assessing the super-hydrophobicity of unidirectional streams. The DR of superhydrophobic surfaces in turbulent fluids is attributed to the combined effects of contact slip and alterations in turbulent organization. Recent investigations indicate that the extent of DR is contingent upon the dimensions of the microstructures and the Reynolds number of the basic SSF. Parameters must be adequately decreased to achieve substantial DR.

III. Proposed Biomimetic Adaptable DR Interface

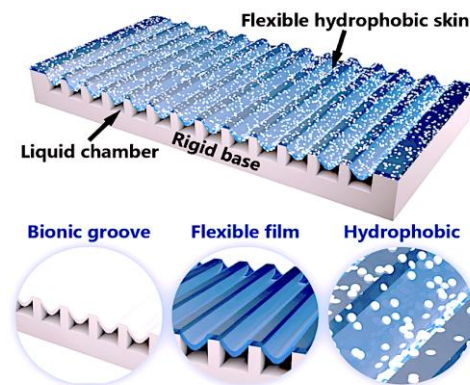


Figure 1: Bio-Inspired DR Interface

This paper introduces the concept of a biomimetic grooved adaptable surface for DR, using structural, flexible, hydrophobic, and dynamic morphing mechanisms (Figure. 1) (Lu et al., 2025). Active DR is achieved by the rhythmic half-wave displacement of the hydraulically actuated bendable wall. Half-wave thicknesses are generated based on SSF velocity, enhancing DR across different SSF rates. The adaptable wall contorts in reaction to fluid contact, mitigating part of the shocks generated by the liquid SSF. This adherence to the SSF lowers surface opposition, facilitating flexible resonance attenuation and a DR. The bendable wall is enhanced to include a hydrophobic coating, which reduces frictional forces when liquid traverses it, thereby aiding in hydrophobic DR. The structure attains optimum DR by integrating these three processes of DR under diverse SSF circumstances.

IV. Impact of Variable Surface Characteristics on DR

Figure. 2(a) illustrates the adaptable surface’s simulated DR at different SSF speeds, with the material's elasticity modulus established at 100 kPa. The DR effect is almost imperceptible at a SSF speed of 0.05 m/s. As the SSF speed escalates, the DR% progressively increases, reaching around 3.7% at 1 m/s. Above this threshold, any increments in SSF velocity result in a slow decrease, with a bit of DR of 0.5% at 3 m/s. Fig. 2(b) illustrates the flexible surfaces’ DR% across different elastic moduli, with the constant SSF speed at 1 m/s. A significant DR impact is shown throughout a broad spectrum of modulus of elasticity, with the DR% exhibiting a peak-like pattern. As the modulus of elasticity ranges from 50 to 250 kPa, the DR rises with the modulus of elasticity. Throughout 200-1000 kPa, the DR% remains at around 5%, diminishing with additional increments in elastic modulus.

The simulation outcomes conform to the concepts of adjustable DR. At reduced SSF speeds, the fluid has limited influence on flexible substrates, leading to minor deformation relocation, hence limiting the effective incorporation of disturbance. The DR% of the bendable wall stays initially minimal. As the SSF accelerates, the relationship between the field of motion and the malleable wall intensifies, resulting in significant distortion. This deformation facilitates efficient vibration attenuation and DR. At this point, the DR% escalates with SSF velocity.

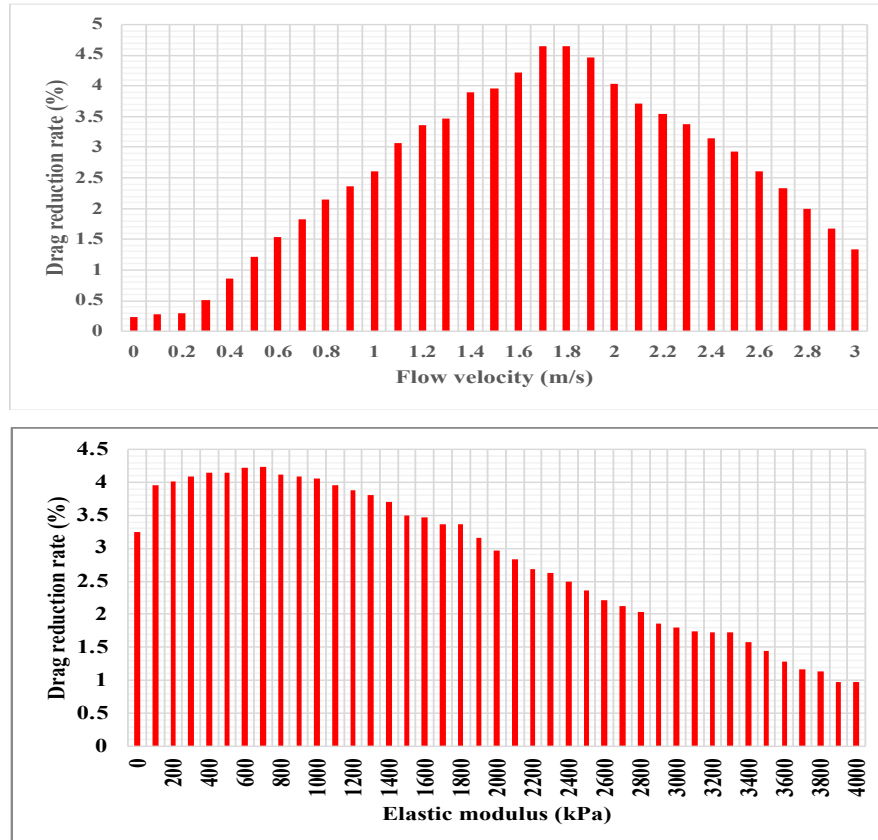


Figure 2: DR Rate Analysis

Upon reaching peak distortion, further increments in SSF velocity squeeze the malleable surface distortion, decreasing the effective distortion and impairing the vibration absorbcency. As a result, the DR properties are not completely exploited. A low modulus of elasticity might increase deformation at a certain SSF speed under a strong impact force, possibly causing stable confinement. This diminishes some efficient deformations, thereby impairing the overall DR efficacy. As the modulus of elastic force rises, the constrained effective displacement is alleviated, leading to an elevated DR%. However, the total displacement capacity diminishes once the elasticity modulus exceeds a certain point. This lessens the malleable surfaces' operation, decreases the shaking absorption capacity of the flexible material, and leads to a decrease in DR% %, ultimately failing with subsequent rises in modulus of elasticity.

V. Conclusion

A DR surface motivated by the structures of grooved, adaptable, and superhydrophobic materials has been developed and constructed, utilizing biomimetic pores, with the adaptable stretching scheme derived from principles regarding surface morphology change. The dynamically actuated adaptive surfaces were evaluated for their composites' DR efficacy, and an explanation of the coupling improvement process was provided. The adaptable DR surfaces employ flexible vibration absorption for SSF correction and hydrophobic slipping effects to enhance the SSF speed of the reversed primary vortex at the grooved lows, thereby augmenting the effective diameter. This decreases the near-wall SSF rate and turbulent kinetic energy, leading to a reduction in surface drag. A maximum DR% of 29% was attained in the water-circulating tube at a velocity of 0.3 m/s. The biomimetic grooved adaptable DR surface integrates active changing, adaptable vibration digestion, and hydrophobic slipping properties, demonstrating significant flexibility and superior DR efficacy. This adaptable composite covering is a premier approach to potential ship DR, offering extensive application possibilities and the capacity to provide substantial financial benefit.

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