

From Whales to Wings: How Humpback Whale Tubercles Inspired Aerodynamic Design

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Project S-ETSD-002

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Tubercles, the sinusoidal pattern on the leading-edge of a humpback whale flipper, have been an adaptation used by humpback whales that improves the aerodynamic performance of their flippers. This research effort experimentally explored the effect of leading-edge humpback whale tubercles on the aerodynamic performance of a wing. Two model wings were tested: one with leading-edge tubercles (scalloped wing) and one without leading-edge tubercles (smooth wing). The lift coefficient and drag coefficient for both wings were measured at angles of attack ranging from 0 degrees to 25 degrees in 2.5 degree increments using the CFD software, SimScale. The scalloped wing reached its stall point at an angle of attack of 12.5 degrees where the smooth wing stalled at an angle of attack of 7.5 degrees. The delay in stall allowed the scalloped wing to produce a maximum lift force 6.4% greater than the smooth

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I. Introduction

In recent years, the formidable climate crisis has become an inescapable reality that threatens the very existence of our planet. The signs are all around us - rising temperatures, extreme weather, and melting glaciers. The consensus amongst the scientific community is that the clock is ticking toward a point of no return. We find ourselves at a crossroads in history, where decisive action must be taken.

Renewable energy offers potential in combating the climate crisis by utilizing sources like sunlight, water, and wind. Unlike fossil fuels, renewable energy produces electricity without the emission of greenhouse gasses, which is crucial for reducing our carbon footprint. It serves as a sustainable alternative to energy sources, capable of achieving more than 90% of the necessary reductions in carbon emissions related to energy usage (according to [IRENA](#)). At this juncture, renewable energy represents a beacon of hope guiding us toward a future that prioritizes sustainability and the environment. Each technology we adopt to increase our energy efficiency will help us to mitigate the extent of climate change. To explore potential new technologies, scientists often look to nature to supply them with novel ideas.

For millions of years, aquatic creatures have undergone morphological adaptations to travel through the dense and viscous water medium. These adaptations pose various biomimetic solutions for the reduction of drag, an increase of lift, maintenance of maneuverability, enhanced maneuverability, and prevention of stall. By implementing these morphologies in situations where animal performance is superior to that of man-made devices, the performance of aquatic and air devices can be maximized.

Humpback whales have adapted to have a sinusoidal pattern on the leading edge of their flippers called tubercles. Tubercles serve to improve the swimming efficiency and maneuverability of the whales. When eating krill and small fish, the whales must make sharp and quick turning movements. The tubercles change the flow over the flippers, preventing stall which allows for a greater maximum lift and a lower overall drag to be achieved. These aerodynamic enhancements allow the whales to feed more efficiently and conserve energy.

Through extensive research on tubercles, we can gain an understanding of their aerodynamic properties in various conditions. Knowing how tubercles function at different angles of attack, sweep angles, and Reynolds numbers will allow them to be implemented in the real world. The function of boat propellers can be enhanced by adding tubercles to their leading edge. Increasing the lift created by the propellers would allow them to produce more force. This allows them to travel further with less fuel.

Additionally, adding tubercles to the leading edge of a wind turbine will increase energy production severely. Increasing the maximum lift will allow the turbines to spin faster in smaller wind forces, producing more energy over time. Before tubercles can be implemented in the real world, there is much more research to be done on how tubercles impact the aerodynamic performance of a wing in various conditions.

Previous literature on leading-edge tubercles has discovered their potential aerodynamic benefit. As stated previously, leading edge tubercles reduce stall, which increases the maximum lift and reduces drag (Miklosovic et al., 2004). Further research found that tubercles have the most aerodynamic improvements on angles of attack greater than 15° but have no penalty at angles of attack lower than 15° (Fish et al., 2011). Due to these findings, tubercles have the potential to improve the efficiency of propellers and turbines (Fish et al., 2011).

The purpose of this study will be to design a wing with leading-edge tubercles and assess its performance against an identical wing without leading-edge tubercles. Lift and drag will be measured to observe the aerodynamic performance of each wing. I hypothesize that leading-edge tubercles will improve the aerodynamic performance of a wing by increasing the maximum lift produced and reducing drag.

I. Methodology

Originally, this study planned to use full-sized wind tunnel testing, but faced logistical and budgetary problems. This forced a new approach. The eventual solution utilized Computational Fluid Dynamics (CFD) as it's efficient and cost-effective. CFD is a computer-run simulation that uses various equations to predict the flow of a fluid over a surface. After contacting several professionals in the field, advice was given on using CFD including which programs would be best suited for the study. With the way of testing now established, it was decided to test two model wing designs: one with tubercles and one without tubercles. The wings began their design on AutoCAD 2024 but after technical issues with filleting the front and back edges of the wings, it was decided to switch to Onshape, a newer and more modern software. This resolved the problem. Both wing models were originally supposed to be tested in the CFD software, Autodesk CFD 2024. After switching to Onshape from AutoCAD 2024, it was decided to switch to a CFD that would be more compatible with Onshape. This CFD program is called SimScale. Each wing was tested in both conditions, at angles of attack from 0 degrees to 25 degrees in increments of 2.5 degrees. The lift coefficient and drag coefficients were measured at each angle of attack for both wings. After the lift and drag coefficients were collected, graphs were created displaying angle of attack

as a function of lift, angle of attack as a function of drag, and angle of attack as a function of the lift-to-drag ratio.

II. Results

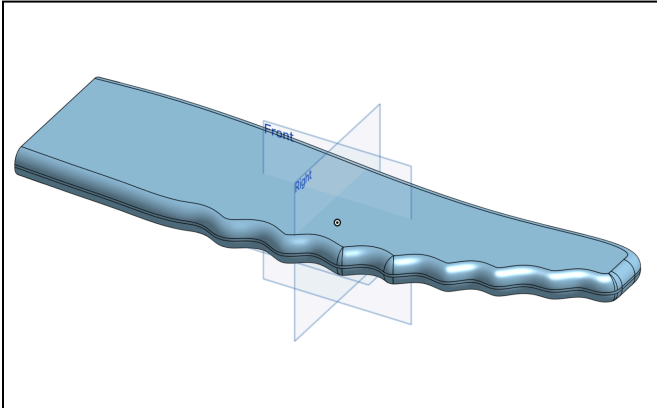


Figure 1: Image displaying CAD model of the scalloped wing

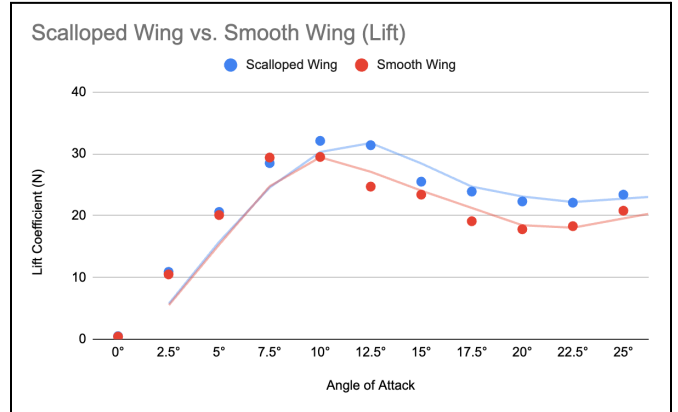


Figure 2: Graph displaying angle of attack vs. lift the scalloped and smooth wings

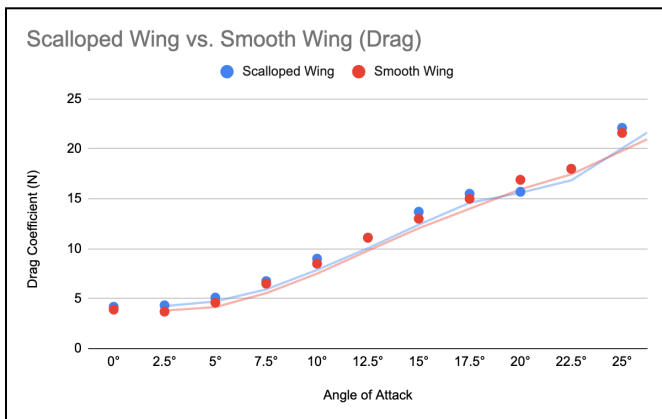


Figure 3: Graph displaying angle of attack vs. drag for the scalloped and smooth wings

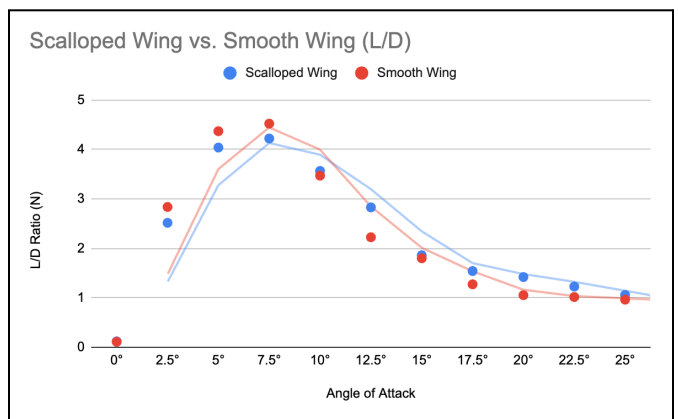


Figure 4: Graph displaying angle of attack vs. the L/D ratio the scalloped and smooth wings

Computational fluid dynamics tests on SimScale were used to determine the lift coefficients and drag coefficients from angles 0 degrees to 25 degrees in 2.5 degree increments. As with other studies, the

lift produced by the smooth wing and the scalloped wing for smaller angles of attack ranging from 0 degrees to 7.5 degrees was very similar. As the smooth wing stalled at an angle of attack of around 7.5 degrees, the scalloped wing did not stall until it reached an angle of attack of 12.5 degrees. This delay of stall for the scalloped wing allowed it to produce a greater maximum lift than the smooth wing.

An unanticipated result was that the drag produced by both wings was very similar throughout all angles of attack tested. This result was different from other studies which found the scalloped wing to reduce drag when compared to the smooth wing.

Finally, while the smooth wing had a slightly greater lift to drag ratio for angles of attack from 0 degrees to 7.5 degrees, the addition of tubercles seemed to help with a greater lift to drag ratio with angles of attack from 7.5 degrees to 25 degrees.

III. Discussion

Overall, the tubercles appeared to create a delay in the stall point of a wing. Where the smooth wing began to stall at an angle of attack of 7.5 degrees, the scalloped wing stalled at an angle of attack of 12.5 degrees. Due to the delayed stall point, the scalloped wing produced 6.4% more maximum lift than the smooth wing. This was inline with other research finding the scalloped wing to produce 6% more maximum lift than the smooth wing (Miklosovic et al., 2004). On the other hand, the drag produced was merely identical for both wings which differed from past studies finding that the scalloped wing decreased drag by 34% (Miklosovic et al., 2004). This may have been due to the certain variables when running a CFD simulation that were different such as wind speed or the object material. Additionally, it could have come down to the shape of the wings being different.

The application of tubercles can be utilized in numerous different fields both pertaining to efficient technologies designed to reduce greenhouse gas emissions, as well as additional commercial applications. The company Fluid Earth markets a surfboard fin with tubercles. The addition of tubercles provides enhanced control when surfers perform sharp turning maneuvers. The application of tubercles to the mast of a sailboat could have advantages in terms of drag. Lastly, tubercles can be an extremely effective addition to the next generation of propellers and turbines for energy production, aviation, and aquatic travel. Tubercles will allow for a higher effective angle of attack, producing more lift to achieve a greater thrust and increase the pitch of the propeller. Wind turbines can increase electrical generation at moderate wind speeds with the addition of tubercles due to this phenomenon. Additionally, the addition of tubercles on propellers and turbines can decrease noise pollution, benefitting marine organisms.

IV. Conclusion

Methods to alter flow around a wing-like structure to delay stall while increasing lift and reducing drag are novel and valuable. This makes leading-edge tubercles a potential groundbreaking addition to various aerodynamic technologies. The flow over the wing reacts with paired vortices in the troughs of the tubercles. This causes the flow over the wing to stay attached to the surface and delay stall. Delaying stall causes a greater maximum lift to be achieved which has potential implications to improve the efficiency of turbines and propellers. Before this is possible, more research, specific to the potential implementation, is needed.

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