Aerodynamic Optimization of Humpback Whale Based Leading-Edge Protuberanced Aircraft Wing

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Humpback whale, a species of baleen whales, has been existing for the past 55 million years. It is known for its most recognizable, distinctive body shape, long fins and its knobbly head. These whales can grow up to 60 feet in length and can weigh up to 36 tonnes. Because of its huge size, humpback whales cannot hunt down its prey like other whales. Generally, the humpback whales feed on plankton and fish schools of euphausiids, herring and capelin. Therefore, it uses a specialized feeding system, known as bubble net feeding. It is a cooperative feeding method used by humpback whales in groups. From the group, the leading whale dives first (alpha whale), it is the alpha whales duty to find the fish while the other whales (Slave) follow the alpha whale in formation. Once the alpha whale finds the fish, it starts creating bubbles encircling the schools of small fish. Studies suggest that these bubbles and its associated acoustics arise from the exhalations of the whales. In addition to that, those airy bubbles make the water opaque, creating an imaginary wall. The following group of slave humpback whales maintains the bubble netting effectively trapping the entire schools of fish. Whales gradually reduce the diameter of the bubble netting eventually creating a small zone around the prey. Using the element of surprise, the whale escapes from the formation one by one and suddenly lunging towards them. During this feeding, it has been observed that ~~the~~ humpback whales travel at a speed of 2.6m/s towards the prey exhibiting its acrobatic behaviour~~s~~ like sudden manoeuvres and underwater somersaults.

* Mr. Arunvinthan S, Ph.D. Scholar from Sastra Deemed to be University, Thanjavur, Tamil Nadu, is pursuing his research on "Aerodynamic Characteristics of Leading-Edge Protuberanced Wing." His popular science story entitled "Aerodynamic Optimization of Humpback Whale based Leading-Edge Protuberanced Aircraft Wing" has been selected for AWSAR Award.

A breaching humpback whale showing its flipper (Leading-edge protuberances) followed by the bubble net formation

Inspired by this highly agile acrobatic manoeuvres performed by humpback whales, researchers look at its control surface the pectoral flippers. They found unique wavy structures over its flippers while majority of the fish belong to this order possess only smooth curvy surface. Initially, it was believed that these bumps on the flippers of the humpback whale made it difficult to swim faster like other whales, but when the aerodynamics of the humpback whale got tested, it turned out that in contrast to the smooth curvy fins, the leading-edge protuberanced wing had 32% less drag, 8% more lift eventually leading to the increased aerodynamic performance.

The marine biologist Fish, investigated the flipper morphology of the humpback whale and identified that they exhibitsymmetrical profile resembling NACA 63_4-021 airfoil. Also, professor Fish and Battle have drawn an analogy between the humpback whale flippers with aircraft wing and wind turbine blades with leading-edge protuberances. One might speculate that the whales move at 2.6m/s in the water while the aircraft moves at relatively higher speeds. This can be substantiated with the explanation that, the sea water density ranges from 1020 to 1030kg/m^3 whereas the density of air is 1.225 kg/m^3 only. Consequently, the speed of the whale when corresponded to operate at the density of air is almost 1000 times higher. Hansen et al. approximated that the whale operates at a Reynolds number of 1.1×10^6. Studies suggest that Aircraft wings, and wind turbine blades all operate in the same Reynolds number. Following that, Miklosovic with his group of researchers roughly modelled the pectoral flipper of a humpback whale with and without leading-edge protuberances and tested in a low-speed wind tunnel. Experimental results revealed that in addition to the aerodynamic performance enhancement they have also observed delay in stall characteristics. Another major finding was that these leading-edge protuberances results in loss of lift associated with an increase in the drag during the pre-stall regime and henceforth no improvement in performance was observed between the conventional smooth wing andthe modified leading-edge protuberanced wing. Researchers suggested that understanding the flow behaviour to gain a much deeper insight in to the underlying dynamics is deemed necessary to resolve the pre-stall performance degradation issue by identifying the optimum leading-edge protuberance geometry parameters for various applications.

A study focused on this issue performed by Arunvinthan (the author of this story) under the guidance of Nadaraja Pillai at SASTRA Deemed University presented on 8th National conference on wind engineering held at IIT (BHU) – Varanasi, reported all possible underlying mechanisms of leading-edge protuberance working mechanisms. Followed by the subsequent computational and experimental studies, it was identified that out of all the mechanisms studied, the "non-uniform separation characteristics" induced by the leading-edge protuberances was the primary reason behind the delayed stall characteristics as well as the pre-stall performance degradation. The oncoming freestream flow is bifurcated by the leading-edge protuberance in such a way that the majority of the flow is directed towards the trough region, thereby, creating enhanced acceleration. This enhanced accelerationat the trough region forms a low pressure region i.e. suction which in turn re-energizes the boundary layer behind each peak by drawing out the low inertial boundary layer fluid from the peak surface resulting in delayed separation. While it is found that this non-uniform separation induced by the leading-edge protuberances is responsible for the delayed stall characteristics over an airfoil, the amount of knowledge over the spanwise vortex formation still remains unclear and is less explored.Additionally, the vortex formed between the leading edge protuberances due to the local spanwise pressure gradient affects the overall favourable pressure gradient existing between the upper and the lower surface of the airfoil. Thereby it results in the pre-stall performance degradation both in terms of decrease in lift and increase in the drag.

Our research group at "Turbulence and Flow control" lab [TFCL] performed several computational investigations and found that the spanwise pressure gradient which is believed to be the reason behind the pre-stall performance degradation as true. Upon continuing the research, the team found that the leading-edge protuberanced wing undergoes sequential stall condition i.e. a combination of stalled and non-stalled region appearing alternatively along the spanwise surface. In the stalled regions, the small vortex formed between the leading-edge protuberances converge together forming a large separation bubble over time. In TFCL, it is discovered that imparting additional momentum in terms of surface blowing near the vicinity of the leading edgeat the point of separation bubble tends to divide the larger separation bubble in to smaller ones, thus, enhancing the quality of the flow over the airfoil. This enhanced airflow along with the reduced spanwise vortex thereby enhances the overall favourable pressure gradient resulting in the increase in the pre-stall performance.

Overall, the research showed that the tangential surface blowing near the vicinity of the leading-edge has the ability to augment aerodynamic performance with associated stall delay characteristics in pre-stall angles. The study has been conducted over wide variety of blowing amplitudes and different surface locations. The computational study focussed on this title has been communicated to the "Chinese Journal of Aeronautics", of which the author is also a contributor. Upon successful practical application, it is believed that this technology will bring India to the forefront of the civil aviation industry.

The research team includes Dr. S. Nadaraja Pillai and S. Arunvinthan. The author, S. Arunvinthan is a Junior Research Fellow pursuing a PhD in the field of Aerodynamics under a sponsored project titled "Influence of leading-edge protuberances on the aerodynamic characteristics of tapered and swept wings at subsonic speeds" funded by DST/SERB/ECR under File No: ECR/2017/001199.