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The Effects of Tubercles on Swept Wing Performance at Low Angles of Attack

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Abstract

Protuberances on the leading edge of wings, also known as tubercles, offer several benefits during stall. However, little is known about their effects on swept wing performance at low angles of attack. In addition, the exact mechanism that is responsible for these currently known benefits has not been experimentally determined. One possible application that could greatly benefit from such a flow control device, but is hindered by these unknowns, is the modern passenger aircraft. As such, this study investigates the effects of tubercles on wings that are similarly swept and tapered to modern passenger aircraft wings, and at low angles of attack. It was found, through flow visualization that tubercles act like vortex generators. Force measurements obtained at a Reynolds number of 220,000, show that for angles of attack ranging from 1° to 8°, tubercles reduce lift and drag by 4-6% and by 7-9.5%, respectively, resulting in a 2-6% increase in the lift-to-drag ratio, and a 3% increase in the maximum lift-to-drag ratio.

Introduction

Humpback whales are unique among Baleen whales for their agility. They are able to swim at high angles of attack, and even able to perform somersaults. Their nimbleness has been, in part, attributed to the leading edge protuberances on their pectoral flippers, termed tubercles. Previous studies have revealed that the main effect of tubercles on wing performance is a softening and delaying of stall [4, 8], resulting in increased lift and decreased drag during high angles of attack. This allows the Humpback whale to execute the aforementioned manoeuvres.

While these benefits are well-documented, the exact flow mechanism(s) responsible has not been experimentally determined, and currently it is only known that tubercles produce pairs of streamwise, counter-rotating vortices [4]. Several mechanisms have been proposed, and the more likely are: that tubercles compartmentalise the flow [12]; tubercles act like vortex generators [8]; and that tubercles upwash and downwash the flow in the troughs and peaks, respectively [11], which in the extreme case would result in vortex lift [2]. It is an aim of this study to provide experimental insight into the mechanism responsible for these benefits.

There have been few investigations considering the effects of tubercles on swept wings, and this limits the potential applications of tubercles. One of the few investigations considering swept wings was conducted by Murray *et al.* [9], who found that, like unswept wings, tubercles offer lift and drag benefits during post-stall. However, while comparisons were made at higher angles of attack, no significant differences were found at low angles of attack. This may be due to, for example; that the tubercle geometry did not change the wing performance at low angles of attack, or that the instruments used were not sufficiently accurate to determine these changes.

One potential application for tubercles on swept wings are modern passenger aircraft, and as such research into the effects of tubercles on swept wings could greatly benefit this industry, as even a 1% increase in aircraft wing efficiency could result in a saving of $650 million in fuel alone each year in the United States [6, 7]. Therefore, this study will investigate the effects of tubercles on wings similarly swept and tapered to those found on modern passenger aircraft. As these aircraft spend most of their flight time in cruise, typically low angles of attack, this region will be the focus of this study.

Experimental Setup

Wing Models

Two semi-span wings were constructed from aluminium 6061, one with a smooth leading edge, and the other with tubercles. The tubercles have an amplitude of 10.5 mm, and a wavelength of 60mm (A10.5λ60* [4]), as shown in fig. 1, and were constructed such that the wing has a constant thickness-to-chord ratio.

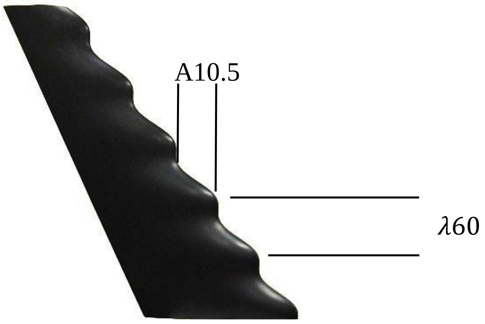

Figure 1. Tubercled wing tested.

The wings have quarter-chord sweep angles of 35^o, and taper ratios of 0.4, which are similar to modern passenger aircraft wings. A NACA 0021 profile has been chosen for testing, which while thicker than modern passenger aircraft wings, reduces the number of variations to previous studies of tubercles, hence simplifies the analysis. The root chord is 175 mm, and the span is 330 mm.

Two limitations of this study, as applicable to modern passenger aircraft, exist. Firstly, the aforementioned thicker wing is used as the vast majority of investigations into “tubercled” wings have considered thicker profiles, hence this simplifies the number of variables to consider during analysis. The second limitation is that the flows considered are laminar and transitional, which are due to limitations in experimental setups. This will be remedied in subsequent investigations.

*Note: The tubercle geometry detailed in the original version of this conference proceeding was incorrect. This version of the conference proceeding corrects the tubercle geometry from A7.7λ57.5 to A10.5λ60.

Flow Visualisation

The flow visualization was performed in the University of Adelaide closed return water tunnel, and utilised the hydrogen bubble technique. The working section was 0.5 x 0.5 m, and the flow speed was 125 mm/s, giving a mean aerodynamic chord (MAC) Reynolds number of 9,000. The wings were suspended into the water with the tip approximately 200 mm from the bottom of the working section, which allowed the wingtip vortex to form and develop without interference [1]. The wings were tested from 0^o to 30° angle of attack.

The hydrogen bubbles were formed by passing a low current at 70 volts through a 40 μm crinkled platinum wire. The bubbles were then illuminated from the rear of the working section with a 1,000W light. Video was taken from a position approximately 135 degrees from the light source.

Force Measurements

Force measurements were performed in the open-return “KC wind tunnel” at the University of Adelaide. The working section was 0.5 x 0.5 m, and the turbulence intensity was 0.8%. The freestream velocity was 28 m/s^{-1}, giving a MAC Reynolds number of 220,000. The temperature and dynamic pressure were recorded at each angle of attack and used to determine the density and velocity of the air. The wings’ tips were 170mm from the working section ceiling, which allowed three-dimensional effects to occur without hindrance [1].

The wings were mounted on a six-component JR3 load cell, which was used to determine lift and drag. This setup was then mounted on a Vertex rotary table, which was used to change the angle of attack. From calibration, it was found that the uncertainties of the load cell ranged from ±1.75% for a force of 0.5 N to ±1% for a force of 2.2 N in the x direction, and the y direction corresponded to ±1.76% for a force of 0.5 N to ±1.5% for a force of 5.9 N.

An alignment uncertainty arose from the interface between the wings and the load cell. This uncertainty was accounted for by performing two sets of three runs for each wing. For each set of three runs, the wings were not detached, and the wing was tested from -2 to 10^o, then rotated back for the next run. When the final run of each set was completed, the wing was detached from the load cell and replaced with the other wing, and the next set of three runs was conducted. The uncertainty in the alignment was corrected through drag symmetry. Wake blockage, solid blockage, and downwash corrections were applied as outlined by Barlow et al. [1].

Results

Flow Visualisation

Figure 2 was obtained by producing hydrogen bubbles in line with the leading edge stagnation line of the wing. This was done to see how the counter-rotating, streamwise vortices, created by the tubercles, affect the flow. It shows that over the troughs there are pockets of streaklines, while over the peaks there is a distinct lack of streaklines. This is caused by the vortices upwashing over the troughs and downwashing over the peaks. In other words, the streaklines that should be seen over the peaks are now on the other side of the wing.

From fig. 2 it can be seen that all streaklines are affected by these vortices, even the ones very close to the surface, as shown in the peaks. Hence, this suggests that tubercles do act like vortex generators, whereby the vortices created by the tubercles are mixing the freestream and boundary layer flows.

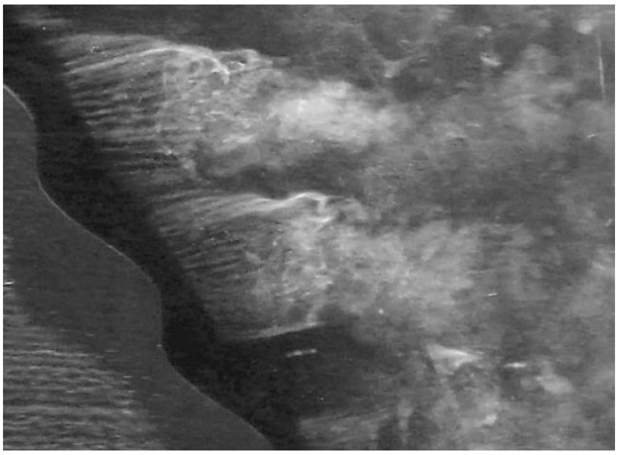

Figure 2. Flow visualization of tubercled wing at an angle of attack of 8^o, hydrogen bubble wire located in line with the leading edge stagnation line.

Figure 3 was obtained by allowing all hydrogen bubbles to travel over the suction side of the wings. Figure 3 a) shows that for a smooth wing, there is a strong wingtip vortex, as shown by the circular patterns created by the hydrogen bubbles in the red ellipse. Figure 3 b) shows that the wingtip vortex is severely reduced for the tubercled wing, to the point of being almost negligible. This suggests that the induced drag of the tubercled wing has decreased. Tubercles could also have additional effects on other components of drag.

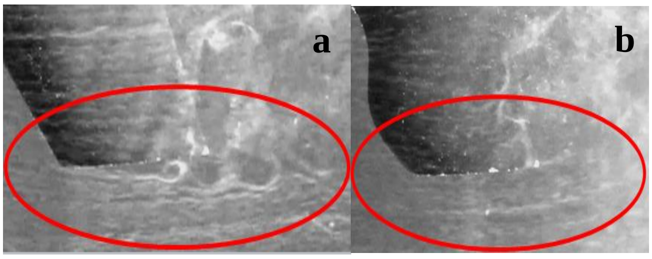

Figure 3. Wingtip vortex strength of a smooth wing (a) and tubercled wing (b) at a 12^o angle of attack.

Force Measurements

Figures 4 and 5 show the average lift and drag of the wings, respectively. The error bars were obtained from the aforementioned calibration, and processed according to [3]. No error bars overlapped.

Figure 4 shows that tubercles reduce the lift for low to moderate angles of attack, which is consistent with what has been found from other studies [4, 5]. While previous studies have also demonstrated that at higher angles of attack tubercles increase lift, this effect is not seen here as the wings stalled past the maximum angle of attack considered. Figure 4 also shows that at moderate angles of attack the lift curve slope of both wings increase, which is attributed to the formation of a separation bubble (LSB) on the suction side of each wing [4]. However, the lift curve slope for the baseline wing increases at a greater rate than the tubercled wing, suggesting that the addition of tubercles reduces the tendency of LSB to form. While LSBs are more typical of low Reynolds number applications, and not modern passenger aircraft, it seems pertinent to discuss this phenomenon, as it occurs in this investigation, and another investigation [4].

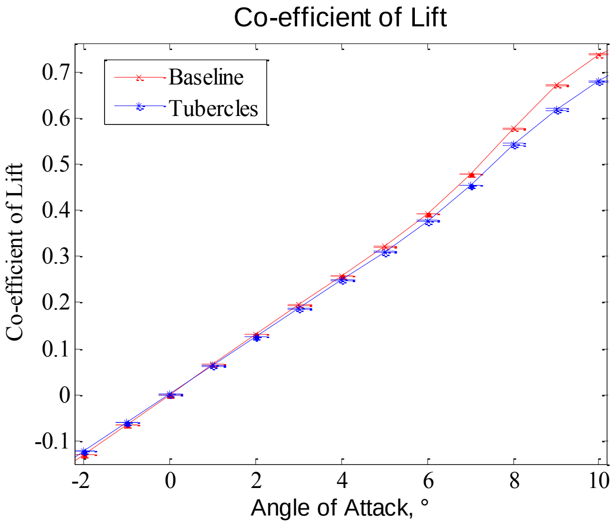

Figure 4. Lift of smooth and tubercled wings, 35° quarter chord sweep angle.

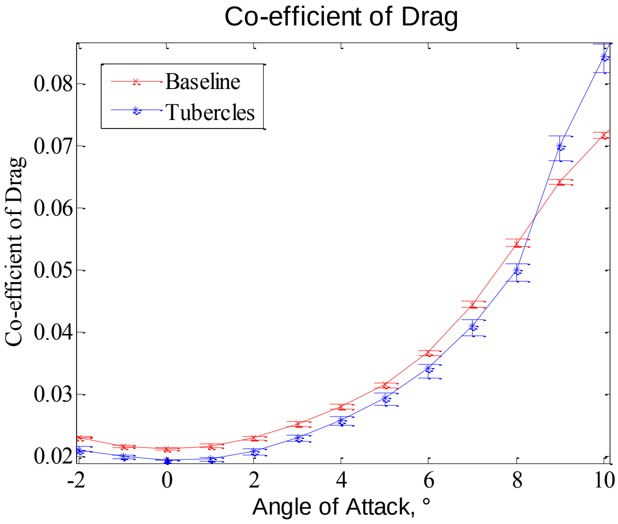

Figure 5. Drag of smooth and tubercled wings, swept at quarter chord angle of 35°.

Figure 5 shows that tubercles reduce drag at low angles of attack, and increase drag for angles of attack greater than 8 degrees. This increase starts at approximately the same angle of attack as when the LSB forms, suggesting that the interaction between the LSB and the vortices is responsible for this increase.

The sudden increase in drag at 8° angle of attack in fig. 5 is typical when the LSB "bursts", i.e. when the bubble increases in length. This bursting also reduces the lift, which is consistent when comparing the lift of the smooth wing to the tubercled wing from 7° to 10° angle of attack. However, what is unusual is that the tubercled wing still has a slightly higher lift curve slope than at lower angles of attack, suggesting that perhaps bursting has not occurred for the entirety of the LSB, and perhaps the spatially periodic nature of tubercles results in a spatially periodic bursting of the LSB.

Figure 6 shows the lift-to-drag ratio of these two wings, and shows that for angles of attack between 0° and 8° the tubercled wing is more efficient. It also shows that tubercles increase the maximum lift-to-drag ratio, which occurs at approximately 6°, by 3%. It also shows, expectedly, that past approximately 8° the lift-to-drag ratio for the tubercled wing drops dramatically. The reduction of lift for angles of attack between 0° and 8° ranges from 4% to 6%, as shown in fig. 7, while the drag reduction ranges from 7-9.5%. These respective reductions result in a 2-6% increase in the lift-to-drag ratio of the tubercled wing between 1° and 8°angles of attack, as seen in fig. 7.

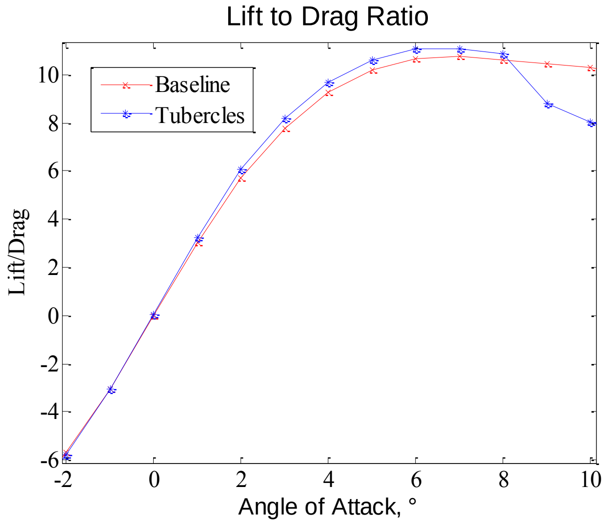

Figure 6. Lift-Drag ratio of the smooth and tubercled wings.

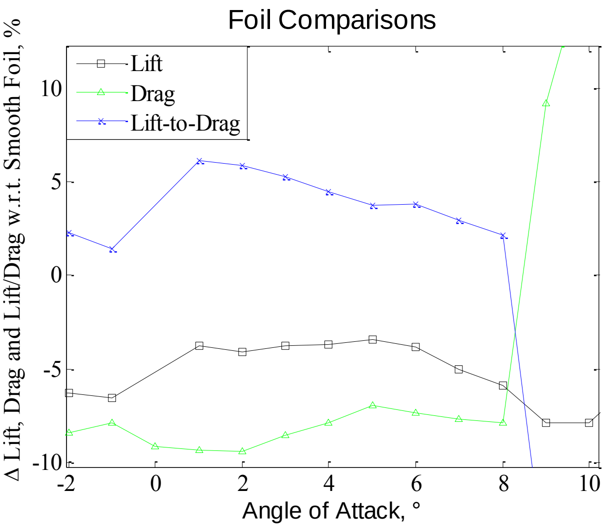

Figure 7. Change in lift, drag, and lift/drag of the tubercled wing with respect to the smooth wing.

Discussion

The Effects of Tubercles on Pressure Drag

This study considered a symmetric wing profile, as at an angle of attack of 0° it would not produce lift, and consequently would not produce induced drag. At 0° angle of attack fig. 5 and 7 show a 9.5% reduction in drag for the tubercled wing, which must be due to a reduction of either the pressure drag or the friction drag.

By applying the method of images to the vortices on the tubercled wing, it can be seen that the vortices with a common downwash [10] move away from each other, while the opposite occurs for the vortices with a common upwash. Pauley and Eaton [10] experimentally demonstrated that this indeed occurs, and that the regions of boundary layer thinning, caused by common downwash vortices, are bigger than the regions of boundary layer thickening, caused by common upwash vortices. Therefore, it is expected that the net result of tubercles is to increase the total boundary layer momentum at all angles of attack, thereby reducing the pressure drag. However, this does not mean that the friction drag increases, as the pressure drag at low angles of attack is usually much smaller than the friction drag. There magnitude of the pressure drag reduction at low angles of attack is unclear, and the overall reduction in drag may be contributed to by a reduction in friction drag as well.

The Effects of Tubercles on Friction Drag

The boundary layer thinning cause by common downwash vortices has two effects on friction drag. Firstly, it suppresses T-S waves, which are precursors to turbulent transitioning, and subsequently reduces friction drag. Secondly, reduction of the boundary layer thickness results in a greater near wall velocity gradient, thereby increasing friction drag. Therefore, the question arises as to when the first effect will outweigh the second effect.

The first effect will only be effective at reducing friction drag during transitional regimes, whereas the second effect will always increase friction drag. Therefore, it is only under transitional flow conditions that friction drag might be reduced by tubercles. This study considered transitional flow, however, no quantitative measurements of the boundary layer were taken, therefore, it is not possible to determine whether the friction drag has increased or decreased.

The Effects of Tubercles on Induced Drag

The strength of the wingtip vortex is an indication of the magnitude of the induced drag. Figure 3 shows that the addition of tubercles to a wing significantly reduces the size of the wingtip vortex. This reduction in size indicates that the strength of the vortex has also reduced, hence suggests that the induced drag has been reduced.

As sweptback wings typically experience a higher induced drag, it is expected that this potential reduction in induced drag will be greater for sweptback wings than unswept or forward swept wings.

Conclusion

Flow visualization results show that the streamwise, counter-rotating vortices produced by tubercles affect the flow close to a wing's surface, hence providing further evidence that tubercles act like vortex generators. The flow visualization also showed that tubercles reduce the wingtip vortex strength, thereby potentially reducing induced drag.

Wind tunnel results have shown that the addition of tubercles onto a swept, tapered, thick wing resulted in a reduction in lift for all angles of attack considered, and a reduction of drag at low angles of attack. For angles of attack in the range of 1^o to 8^o the lift reduction ranged from 4-6%, while drag was reduced from 7-9.5%. The lift-to-drag ratio, in this range of angles of attack, subsequently increased by 2-6%, and the maximum lift-to-drag ratio increased by 3%.

Acknowledgements

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References

[1] Barlow, J.B., Rae, W.H., Jr. and Pope, A., *Low-Speed Wind Tunnel Testing*, 3rd ed., Wiley, New York, 1999.

[2] Bolzon, M.D., Kelso, R.M. and Arjomandi, M., A Review of Tubercles and Their Applications, *Revised manuscript submitted to Journal of Aerospace Engineering*, 2014.

[3] Dieck, R.H., *Measurement Uncertainty, Methods and Applications*, The Instrument Society of America, North Carolina, 1992.

[4] Hansen, K.L., Effect of Leading Edge Tubercles on Airfoil Performance, Ph.D. Thesis, The University of Adelaide, S.A., Aus., February 2012.

[5] Johari, H., Henoch, C., Custodio, D. and Levshin, A., Effects of Leading-Edge Protuberances on Airfoil Performance, *American Institute of Aeronautics and Astronautics* (AIAA) Journal, Vol. 45, No. 11, November 2007, pp. 2634-2642.
doi:10.2514/1.28497.

[6] Karp, A., FAA: US Commerical Aircraft Fleet Shrank in 2011, *Air Transport World*, 12th March, 2012, URL: http://atwonline.com/aircraft-amp-engines/faa-us-commercial-aircraft-fleet-shrank-2011 [Cited 31st December 2013].

[7] Martin, G., These Fancy New Winglets Will Save United $200 Million Each Year, *Forbes Logistics & Transportation*, 7th August, 2013, URL: http://www.forbes.com/sites/grantmartin/2013/07/18/scimitar-new-winglets-united/ [Cited 31st December 2013].

[8] Miklosovic, D. S., Murray, M. M., Howle, L. E. and Fish, F. E., Leading-edge Tubercles Delay Stall on Humpback Whale (Megaptera Novaeangliae) Flippers, *Physics of Fluids*, Vol. 16, No. 5, 2004, pp. L39-L42,
doi:10.1063/1.1688341.

[9] Murray, M. M., Miklosovic, D. S., Fish, F. and Howle, L., Effects of Leading Edge Tubercles on a Representative Whale Flipper Model at Various Sweep Angles, *Proceedings of Unmanned Untethered Submersible Technology*, Durham, NH, 2005.

[10] Pauley, W.R. and Eaton, J.K., Experimental Study of the Development of Longitudinal Vortex Pairs Embedded in a Turbulent Boundary Layer, *American Institute of Aeronautics and Astronautics* (AIAA) Journal Vol. 26, No. 7, 1987.
doi:10.2514/3.9974.

[11] Van Nierop, E.A., Alben, S. and Brenner, M.P., How Bumps on Whale Flippers Delay Stall: an Aerodynamic Model, *Physical Review Letters*, PRL 100, 054502, February 2009.

[12] Watts, P. and Fish, F.E., The Influence of Passive, Leading Edge Tubercles on Wing Performance, *Unmanned Untethered Submersible Technology (UUST)*, Autonomous Undersea Systems Inst. , Lee, NH, 2001.