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An Investigation of Three-Dimensional Effects on the Performance of Tubercles at Low Reynolds Numbers

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Abstract

Force measurement results from this study have revealed that the degree of performance enhancement possible for an airfoil with tubercles is not significantly influenced by three-dimensional effects at Reynolds number, Re = 120,000. Therefore, based on the present results and the available literature, it is postulated that the effectiveness of tubercles as a passive flow control mechanism is more dependent on the Reynolds number than on three-dimensional effects.

Introduction

The idea of using sinusoidal leading edge protrusions, or tubercles, for passive flow control was originally inspired by the leading edge geometry of the Humpback whale flipper. Miklosovic *et al.* [4] found that an idealised scale model whale flipper with tubercles achieves a higher maximum lift coefficient and larger stall angle with minimal drag penalty when compared to an equivalent model with a smooth leading edge. Watts & Fish [10] compared the performance of a finite span (aspect ratio 2.04) NACA 63-021 airfoil with sinusoidally-shaped tubercles to an unmodified airfoil using a numerical model and found that both the lift and drag performance improved. By contrast, Stein and Murray [8] and Johari *et al.* [3] conducted experiments using full-span airfoils with a cross-sectional profile similar to the Humpback whale flipper. These researchers found that in the pre-stall regime, airfoils with tubercles do not perform as well as equivalent airfoils with a smooth leading edge. However, it was also observed that airfoils with tubercles experience a much less severe stall and the amount of lift generated in the post-stall regime is higher [3]. A study carried out by Miklosovic *et al.* [5] compared a model whale flipper with a full-span airfoil and commented that the success of tubercles is related to three-dimensional effects such as span-wise stall progression. On the other hand, results from experiments undertaken at low Reynolds numbers (Re ~ 44,000-120,000) with a model whale flipper [7] indicate that Reynolds number effects may be more important since performance in the pre-stall regime is inferior for models with tubercles at Re < 120,000. A confirmation of this hypothesis is that all studies mentioned above which showed performance enhancement with tubercles were undertaken at Re ≥ 500,000. According to Miklosovic *et al.* [4], the Reynolds number for a Humpback whale flipper is approximately Re ~ 10^6.

The mechanism responsible for performance enhancement is believed to be the generation of stream-wise vortices which increase momentum exchange within the boundary layer [1, 2, 4]. These vortices can increase the extent of flow attachment, leading to delayed stall and hence a larger maximum lift coefficient. It has also been shown experimentally that separation occurs earlier behind the troughs between tubercles than behind the tubercles themselves [1, 3]. van Nierop *et al.* [9] explained this observation theoretically by considering the variation in chord length as a function of span-wise location. The same pressure difference must be overcome over a shorter distance behind a trough than a peak, giving rise to a larger adverse pressure gradient and hence increased susceptibility to separation. A numerical study showed clearly the resulting wavy separation line for model whale flippers with tubercles [6]. In addition, it was revealed that there is a more even distribution of vorticity along the span, which results in a reduced concentration of vorticity at the wing-tip. These results suggest that tubercles may function in a similar way to wing-fences in that they reduce the extent of span-wise flow, hence delaying tip stall and reducing the strength of wing-tip vortices.

The purpose of the present study was to investigate further the differences between full-span and finite-span foils with leading edge tubercles, at low Reynolds numbers. Force measurements show the effects of tubercles on performance characteristics such as maximum lift coefficient, stall angle and drag. Comparison of these values for finite-span and full-span airfoils highlights the effects of tubercles on induced drag and tip stall. The amplitude and wavelength of the sinusoidal tubercles was also varied to determine the influence of these parameters on performance for both finite-span and full-span airfoils.

Experimental Methods

Various tubercle configurations were investigated for a NACA 0021 airfoil. This airfoil profile was chosen because it is similar to that of the Humpback whale flipper [2]. Figure 1 shows the tubercle parameters which were varied and Table 1 lists the variations which were investigated. A baseline airfoil with a smooth leading edge was also manufactured for comparison. All airfoils were machined from aluminium and have a mean chord of c = 70mm.

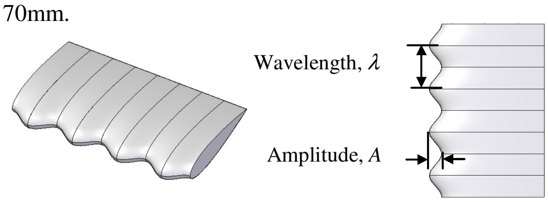

Figure 1. Airfoil section with tubercles (left) and plan-view, showing amplitude and wavelength parameters (right).

NACA 0021			
A/c	**λ /c**	**A/λ ratio**	**Label**
0.03	0.11	0.27	*A2λ7.5*
0.06	0.11	0.53	*A4 λ 7.5*
0.06	0.21	0.27	*A4 λ 15*
0.06	0.43	0.13	*A4 λ 30*
0.06	0.86	0.07	*A4 λ 60*
0.11	0.43	0.27	*A8 λ 30*

Table 1. Tubercle configurations tested for NACA 0021, where amplitude and wavelength are normalised by the chord.

Tests were conducted in the 0.5m x 0.5m closed-loop wind tunnel at the University of Adelaide which has a turbulence intensity of ~0.8%. The free-stream velocity was measured using a Pitot tube and the sampling rate was 1000 Hz. Data were averaged over one minute and collected via a National Instruments USB-6008/6009 data acquisition system. The Reynolds number was Re = 120,000, based on the free-stream velocity of U_∞ = 25m/s and mean chord length. Lift and drag forces were measured using a 6-component load cell from JR3. In the first set of tests, the free end (wing tip) of the airfoil was located very close to the ceiling of the test section to minimise three-dimensional effects, providing a semi-infinite airfoil. In the second set, the free end was located at the centre of the test section so that the model acted as a finite-span airfoil. Three sets of measurements were taken for each airfoil for the range of angles $-4° \leq \alpha \leq 20°$. The average results for the lift and drag coefficients for the tested airfoils were then plotted and compared. No blockage or streamline curvature corrections have been made to the data.

It was desirable that the boundary layer should be laminar as it was believed that tubercles would have a greater benefit for this condition. This is because a laminar boundary layer is much more susceptible to an early onset of separation, which could be mitigated through increased momentum exchange. For this reason, boundary layer trips were not employed, despite the fact that low Reynolds number effects such as separation bubbles were anticipated.

Results

Unmodified NACA 0021 Compared to Airfoil with Tubercles

Comparison of the nominally two-dimensional (2D) and three-dimensional (3D) unmodified airfoil (Figure 2) shows that both the effective angle of attack and the maximum lift coefficient are reduced for the 3D case. This is an expected consequence of downwash effects.

A notable characteristic of both lift plots is that rather than being linear, they have an increasing slope after $\alpha = 4°$. It is possible that this could be the result of a separation bubble, which increases the effective camber of the wing and hence a higher amount of lift is generated due to increased circulation. A negative feature of this airfoil is that it has a very sudden stall, where the amount of lift generated drops by over 50% for a change in angle of attack, $\Delta\alpha = 1°$.

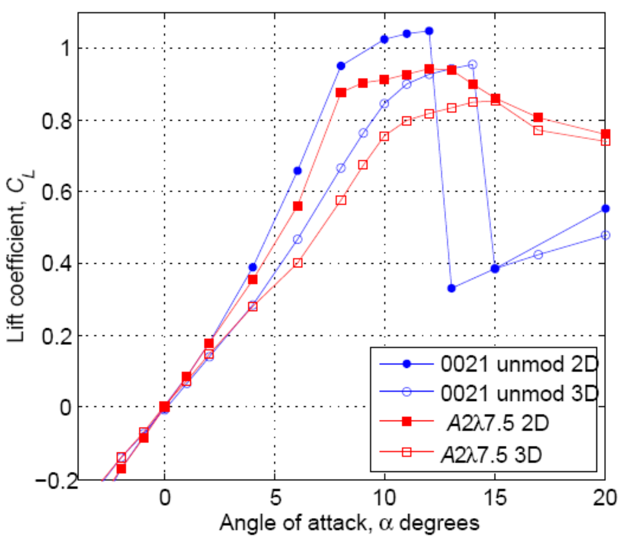

Figure 2 - Lift coefficient plotted against angle of attack for NACA 0021 airfoil (Re ~ 120,000)

It was found that for both the full-span and finite-span airfoil tests, the smallest amplitude and smallest wavelength tubercle configuration demonstrates superior performance. Hence, this airfoil is compared to the unmodified airfoil in Figure 2. It can be seen that the stall behaviour for the modified airfoil is much less severe; however, this comes with a small penalty in maximum lift coefficient. With respect to lift generation, there is no significant additional benefit of incorporating tubercles into the leading edge of a finite-span airfoil.

There is a negligible difference in the amount of drag generated for the 2D and 3D NACA 0021 airfoil at low angles of attack (Figure 3). As the angle of attack is increased, the amount of drag for the 3D airfoils is larger due to the induced drag component, which increases in magnitude as lift becomes higher. The extent of the drag 'bucket' is greater for the finite-span airfoils because stall occurs at a higher angle of attack.

At low angles of attack, the drag performance of airfoils with and without tubercles is very similar (Figure 3). As the stall angle is approached, the airfoil with tubercles experiences a larger increase in drag compared to the unmodified airfoil. After stall, however, the modified airfoil experiences a lower drag. The differences in performance for the airfoil with tubercles are very similar for the 2D and 3D cases which implies that there are also no additional drag benefits for finite-span airfoils with tubercles.

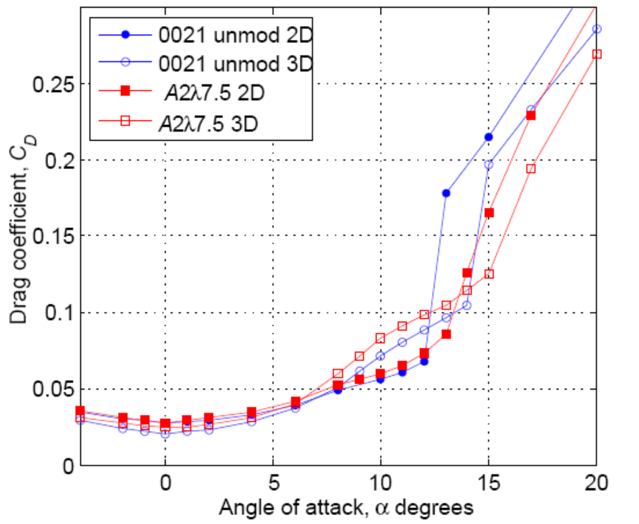

Figure 3 - Drag coefficient plotted against angle of attack for NACA 0021 airfoil (Re ~ 120,000)

Performance Effects of Variation in Tubercle Amplitude

Figure 4 shows the differences in lift performance as the tubercle wavelength is kept constant while the amplitude is varied. For the smaller amplitude tubercles, the maximum lift coefficient, stall angle and post-stall lift are higher for both 2D and 3D cases. There is a high correlation between the differences in lift performance for full-span and half-span airfoils for these two tubercle configurations.

At low angles of attack, the tubercle configuration with larger amplitude has slightly higher drag (Figure 5). This airfoil continues to experience a higher amount of drag as the stall angle is approached and the difference in drag compared with the smaller amplitude configuration becomes more pronounced. This behaviour is observed for both the 2D and 3D results, except that in the latter case, the point at which the difference in drag between the two configurations becomes apparent occurs at a higher angle of attack. This is a direct result of delayed stall which occurs for the 3D airfoil due to downwash effects.

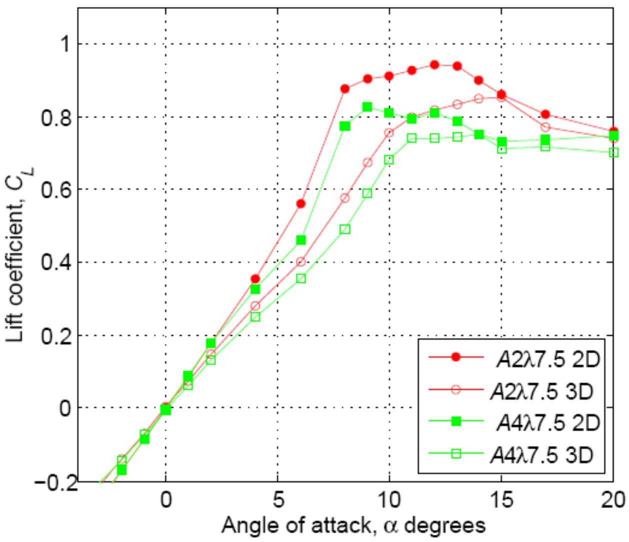

Figure 4 – Effect of tubercle amplitude variation on lift coefficient as a function of attack angle for NACA 0021 airfoil (Re ~ 120,000)

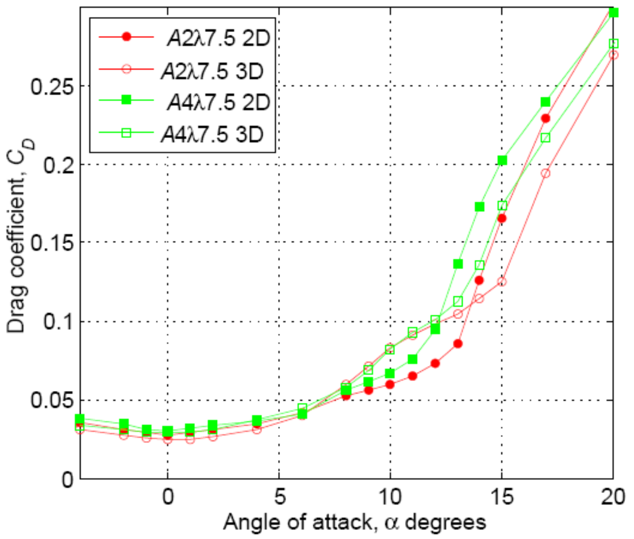

Figure 5 – Effect of tubercle amplitude variation on drag coefficient as a function of attack angle for NACA 0021 airfoil (Re ~ 120,000)

Performance Effects of Variation in Tubercle Wavelength

Initial experiments suggested that as the spacing between successive tubercles decreases, the performance improves. However, it was found that there was a certain point beyond which further reduction in tubercle wavelength led to deterioration in performance. For a normalised tubercle amplitude of A/c = 0.06, the optimum performance in terms of maximum lift coefficient, lowest drag and highest post-stall lift was achieved with a normalised wavelength, λ/c = 0.21.

Figure 6 shows that the tubercle arrangement with the largest wavelength experiences an earlier onset of stall, which is characterised by a sudden loss of lift. Generally, as the wavelength between tubercles decreases, the stall angle and maximum lift coefficient increase. In addition, the stall occurs more gradually and hence the post-stall lift is higher. However, the tubercle configuration with the smallest wavelength does not follow this trend and it can be seen that there is an unexpected loss of lift in the linear region of the lift plot.

Each of these characteristics can also be observed in Figure 7, which depicts the lift behaviour for finite-span airfoils. This implies that the free end has negligible influence on the changes in performance which result from wavelength variation.

Significant differences in drag for variation in tubercle wavelength are mainly observed at angles of attack near stall (Figure 8). Since stall occurs earlier as the tubercle wavelength becomes larger, the point at which there is a large increase in drag occurs at a lower angle of attack. In the pre-stall regime, the tubercle arrangement with the smallest wavelength experiences the highest amount of drag. The optimum tubercle configuration in terms of lowest drag for the majority of attack angles corresponds to the same configuration which demonstrates optimal lift performance. All airfoils with tubercles generate a lower drag in the post-stall regime. Comparison with Figure 9 reveals that the overall trends are consistent for the 2D and 3D cases. There is a slight improvement in drag performance for the $A4\lambda15$ configuration with respect to the unmodified airfoil for the 3D case. This suggests that three-dimensional effects cannot be completely ignored but are relatively small nonetheless.

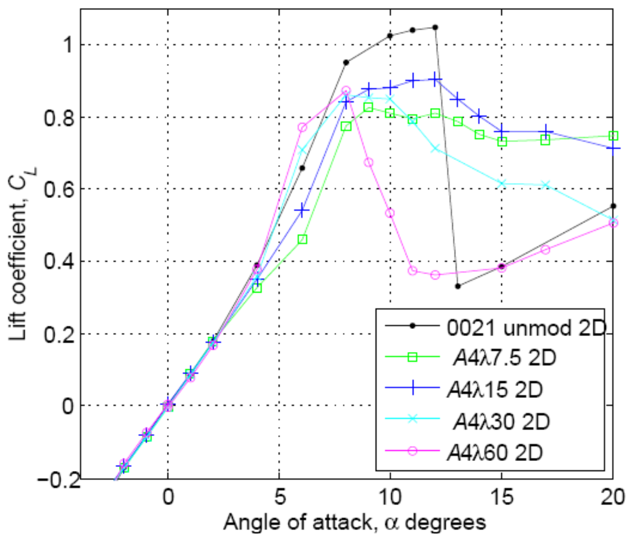

Figure 6 – Effect of tubercle wavelength variation on lift coefficient as a function of attack angle for 2D NACA 0021 airfoil (Re ~ 120,000)

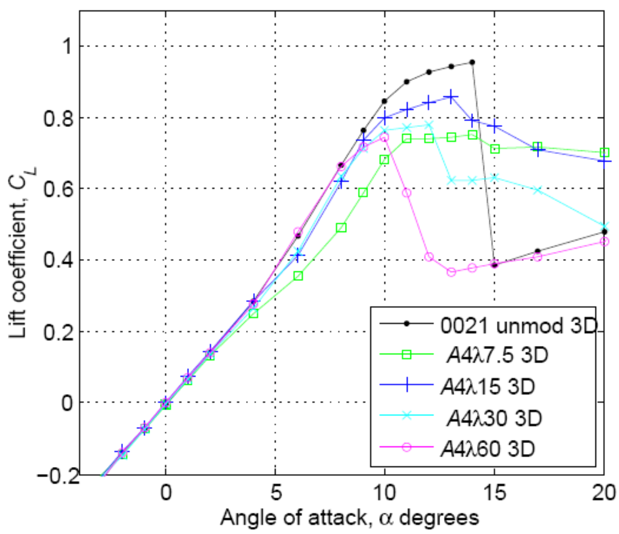

Figure 7 – Effect of tubercle wavelength variation on lift coefficient as a function of attack angle for 3D NACA 0021 airfoil (Re ~ 120,000)

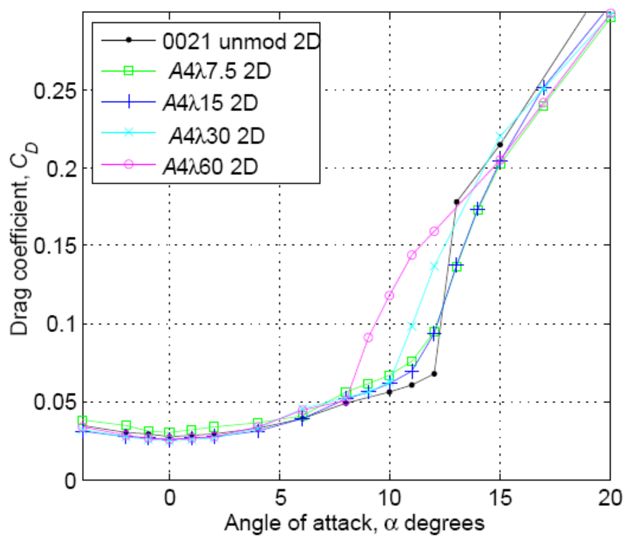

Figure 8 – Effect of tubercle wavelength variation on drag coefficient as a function of attack angle for 2D NACA 0021 airfoil (Re ~ 120,000)

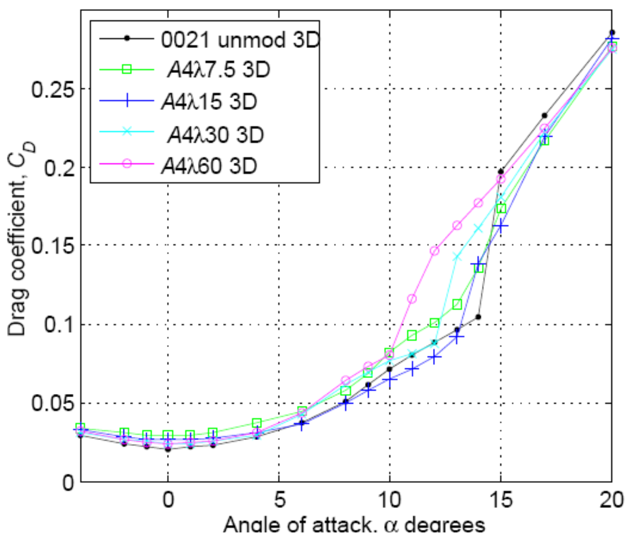

Figure 9 – Effect of tubercle wavelength variation on drag coefficient as a function of attack angle for 3D NACA 0021 airfoil (Re ~ 120,000)

Discussion

It has been shown in previous studies that incorporating tubercles into the leading edge of an airfoil can lead to significant performance enhancement [4, 5, 6, 10]. However, other previous investigations did not obtain such optimistic results [1, 3, 7, 8]. The most obvious difference between the airfoils which showed performance enhancement and those that did not was the nature of the wing tip. In the former cases, the airfoils were all finite-span models, whereas in the latter cases, they were mostly semi-infinite span models. This implied that the benefits of tubercles may only be realised for three-dimensional cases. Experiments by Stanway [7] created an element of doubt with regards to this idea because of the fact that the model whale flippers tested did not show performance enhancement at low Reynolds numbers.

These results suggest that three-dimensional effects may not be as important as previously suggested [5]. It is believed that a more important factor to consider when predicting the potential benefits of tubercles is the Reynolds number. All studies mentioned in this paper which reported performance enhancement with tubercles were carried out at Re ≥ 500,000. Conversely, studies which reported deterioration in performance were undertaken at low Reynolds numbers (Re < 300,000).

Other important factors to take into account when considering three-dimensional effects are the sweep and taper of the airfoil. In the study undertaken by Pedro *et al.* [6], it was found that the region in which tip stall occurred was reduced in size for airfoils with leading edge tubercles. Therefore, the nature of stall for a given airfoil as well as the extent of span-wise flow may affect the amount by which tubercles can improve performance when compared to a baseline airfoil.

It has been suggested that the success of tubercles is connected with inhibition of span-wise stall progression [5]. While this is plausible, there is no evidence to suggest that semi-infinite airfoils with tubercles do not show improvements in performance at Re ≥ 500,000.

Conclusions

The relative performance of airfoils with tubercles compared to an unmodified baseline NACA 0021 airfoil is similar for full-span and half-span models with no sweep or taper. This implies that the presence of tubercles does not significantly affect the formation of wing-tip vortices for these airfoils. Variation of the tubercle amplitude and wavelength leads to similar differences in performance for the half-span and full-span airfoils. In both cases, the most successful configuration is the one with the smallest amplitude and wavelength tubercles.

It is believed that tubercles may offer more obvious benefits for airfoils with sweep and/or taper where there is a much larger amount of span-wise flow. It can also be concluded from the literature that tubercles do not achieve significant performance enhancement at low Reynolds numbers, except post-stall.

Acknowledgments

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References

[1] Custodio, D., The Effect of Humpback Whale-Like Leading Edge Protuberances on Hydrofoil Performance, *Thesis submitted to Worcester Polytechnic Institute*, Dec 2007.

[2] Fish, F.E. and Battle, J.M., Hydrodynamic Design of the Humpback Whale Flipper, *J. Morp.,* 225, 1995, pp. 51-60.

[3] Johari, H., Henoch, C., Custodio, D. & Levshin, A., Effects of Leading Edge Protuberances on Airfoil Performance, *AIAA Journal*, **45**(11), Nov 2007.

[4] Miklosovic, D. S., Murray, M. M., Howle, L. E., and Fish, F. E., Leading Edge Tubercles Delay Stall on Humpback Whale Flippers, *Phys. Fluids* **16**(5): L39-L42, 2004.

[5] Miklosovic, D.S. & Murray, M.M., Experimental evaluation of sinusoidal leading edges, J. Aircraft, **44**:1404–1407, 2007.

[6] Pedro, H.T.C. and Kobayashi, M.H., Numerical Study of Stall Delay on Humpback Whale Flippers, *Proceedings of 46th AIAA Aerospace Sciences Meeting and Exhibit*, 7-10 Jan 2008, Reno, Nevada.

[7] Stanway, M.J., Hydrodynamic Effects of Leading-Edge Tubercles on Control Surfaces and in Flapping Foil Propulsion, *Thesis submitted to Massachusetts Institute of Technology*, Feb 2008.

[8] Stein, B. & Murray, M.M., Stall Mechanism Analysis of Humpback Whale Flipper Models, *Proc. of Unmanned Untethered Submersible Tech. (UUST)*, Durham, NH, Aug 2005.

[9] van Nierop, E., Alben, S & Brenner, M.P., How Bumps on Whale Flippers Delay Stall: an Aerodynamic Model, *Physical review letters*, PRL 100, 054502, Feb 2008.

[10] Watts, P. and Fish, F.E., The Influence of Passive, Leading Edge Tubercles on Wing Performance, *Proc. of Unmanned Untethered Submersible Tech. (UUST)*, Durham, NH, Aug 2001