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EFFECT OF LEADING EDGE PROTUBERANCE ON THRUST PRODUCTION OF A DYNAMICALLY PITCHING AEROFOIL

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Abstract

The paper presents a computational analysis of the characteristics of a NACA 634-021 aerofoil modified by incorporating sinusoidal leading-edge protuberances at Re = 14,000. The protuberances are from the tubercles of the humpback whale flipper with leading edge acting as passive-flow control devices that improve performance and manoeuvrability of the flipper. They are characterized by an amplitude and wavelength of 12% and 50% of the aerofoil chord length respectively. Three-dimensional CFD on the modified aerofoil oscillating about a point located on the centreline at quarter-chord has been performed with the frequency and amplitude of oscillation being 4Hz and 10 deg respectively. In addition to the lift and thrust coefficients, near wall flow visualisations and the shedding of vortices during oscillations are presented to illustrate the unsteady flow features on the performance of the oscillating flipper. The results show an improvement in the thrust production when compared to previous studies on similar symmetric aerofoil without the leading edge modifications.

Keywords: CFD, NACA 634-021 aerofoil, Leading-edge protuberances, Low Reynolds, Wall shear streamlines, Oscillating aerofoil, Bio-inspired aerofoil, Biomimicry

1 Introduction

Increasingly, the relationship between engineering and biology is becoming closer with natural phenomenon now being investigated and considered as an inspiration for improving mechanical devices and developing new technologies [1, 2, 3, 4, 5, 6]. Novel morphologies and physiological operations investigated by biologists are increasing serving as the inspiration for engineers in technological development [7]. The ultimate goal is to emulate the performance of living systems where the organism's performance exceeds current technologies [8, 9]. Humpback whales (Megaptera Novaengliae) grow to a massive size and weight but yet they can maintain high manoeuvrability and is able to change direction very quickly when travelling at high velocities. This performance is attributed to the presence of tubercles on their flippers and these has inspired the incorporation of tubercle-like structures or protuberances to aerofoils and propellers of turbomachinery [10, 11, 12] and even wind turbine blades [13].

Detailed aerodynamic performance analysis of flippers with leading-edge protuberance has been conducted in the past on different baseline aerofoils. Milkosovic et al. [14] used a baseline of NACA 0020 whilst Johari et al. [15], Wei et al. [16] and Ibrahim et al. [12] incorporated the protuberances on NACA 634-021 and Zhang et al. [13] on the S809 aerofoil. All the studies concluded that aerofoils with leading-edge protuberances are able to increase lift coefficient and reduced drag coefficient at post-stall region by as much as 50% [15]. Milkosovic [14] also reported an increase of stall angle by about 40%.

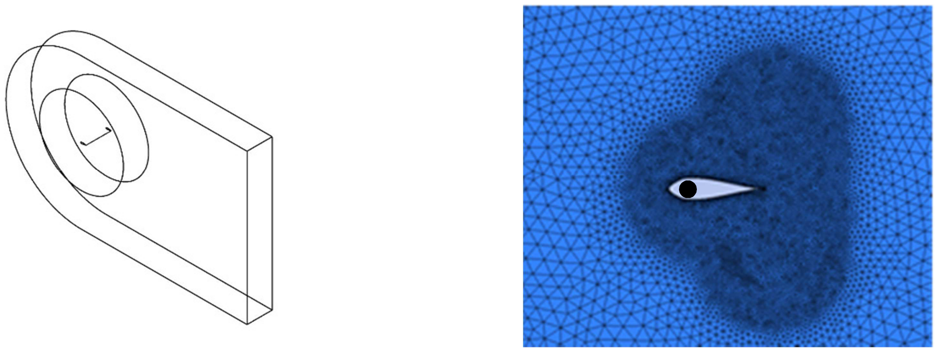
The current study seeks to extend the work of Ibrahim et al. [12] by investigating the characteristics of viscous flows forming around aerofoils with leading-edge protuberance during oscillating motion. Although there has been much previous work detailing the flow field near to oscillating aerofoils [17, 18, 19, 20], these have been confined to smooth conventional NACA type aerofoils or flat plates. There are few studies of flow characteristics about oscillating corrugated bio-inspired aerofoils [21, 22, 23, 24] and to date the authors are unaware of any other work investigating the characteristics of an oscillating aerofoil with leading-edge protuberances. One of the characteristics of flow over such modified aerofoil is the channelling of flow into more narrow streams thus creating higher velocities. These higher velocities could have an effect on the overall thrust produced.

The current study was conducted on a modified NACA 634-021 aerofoil at Re = 14,000 with the same geometry and upstream flow conditions as the one of Ibrahim et al. [12] undergoing 4Hz 10° two-dimensional oscillation (dynamic pitching) only with about a point along the centreline of the aerofoil at quarter-chord from the leading edge. The axis of oscillation is parallel to the span of the aerofoil. The geometry of the aerofoil is not an exact replica of the geometry found on any humpback whale but is an idealised geometry based on the concept of introducing tubercles on the leading edge just like the humpback whale. The black dot on Figure 1b shows the approximate location of the centre of rotation. The use of leading edge tubercles has been shown to improve the aerodynamic performance of a large range applications and Reynolds numbers [7] not necessarily at the Re where an actual operates. The chosen investigation parameters for the current study correspond to a Strouhal number of 0.37 which is on the higher end of the range for efficient cruising locomotion [24].

2 Geometry, computational domain and methodology

Rigid three dimensional aerofoil were modelled in ANSYS Fluent using version 17.0 The geometry of the aerofoil is the same as that of Ibrahim et al. [12] and will not be presented here except a summary of the characteristics. The modified leading-edge protuberance aerofoil (will be simply called modified aerofoil henceforth) is based on the NACA 634-021 with mean chord (and characteristic mean chord for the modified aerofoil), c = 75mm and span, s = 300mm. The protuberances has amplitude A = 0.12c and wavelength c = 0.75mm. The geometry is oriented such that upstream velocity is in the x-direction and span of the aerofoil in the z-direction. More details about the aerofoil can be found in Figure 1 from the paper by Ibrahim et al. [12].

The overall size computational domain is also identical. The mesh used is also different. Within the computational domain, a circular rotating region is incorporated with a sliding mesh on its boundary to simulate the oscillations. A sliding mesh model was used which incorporated a stationary outer flow domain with a smaller circular flow domain which included the aerofoil section. The inner flow domain was rotated, and the aerofoil along with it, to simulate the desired oscillating motion. When the aerofoil is rotating clockwise and increasing its angle of attack, it is termed as “pitch-up” and vice-versa. The sliding mesh method eliminates the need for any re-meshing or mesh deformation resulting in a simpler, less computationally expensive solution. The domain is showing these two regions is presented in Figure 1(a). The upstream boundary (semi-circle) is set as velocity inlet with inlet velocity giving a Re = 14,000 when calculated with the chord length. The top, bottom and downstream of the boundary is a zero gauge pressure outlet. The boundary between the inner-rotating domain and outer stationary domain are matching interfaces.



(a) Overall domain (b) Mesh around the aerofoil

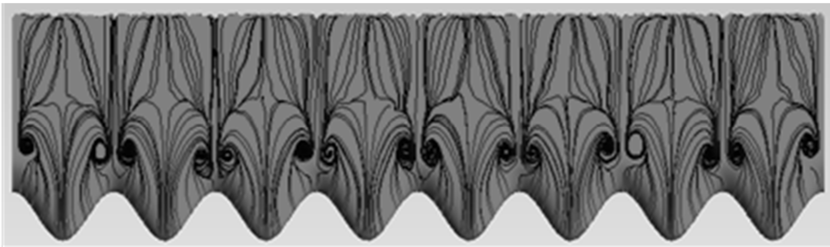
Figure 1: Domain and mesh around the aerofoil

The mesh around the vicinity of the aerofoil is presented in Figure 1(b) and with a region of dense meshing close to the aerofoil body achieved by using the “body of influence” in the meshing tool of ANSYS 17.0. Overall mesh has 10 x 10^6 elements and has an overall y^+ value of less than 10 in most of the domain.

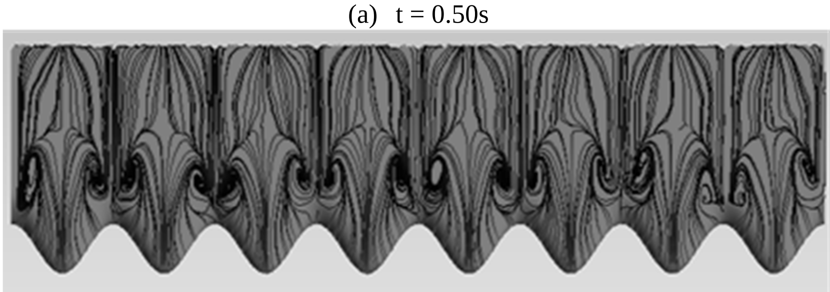
The simulations were modeled using the Scale Adaptive Simulation Turbulence (SAS) method [25, 26]. The SAS method is useful in unstable regions by providing well-resolved fluctuating quantities. Once the flow rate is stable, the method returns to a k-w SST (Shear Stress Transport). It changes the degree of resolution with respect to local flow conditions.

The PRESTO scheme was adopted for pressures and is suitable for swirling flow which is expected in our present study. The other variables were calculated using second-order upwind discretization. The gradients were evaluated using the cell-based least squares method. Concerning precision and stability, the use of a higher order term relaxation proved useful given our study, thus a double precision solver and a second order implicit transitional formulation were chosen. The initialization was made from a stationary state solution with the SST-Kω turbulence model and parameters equivalent to those used in the transient simulation with pseudo-transient turned on. A user defined function was compiled to regulate the oscillation of the domain where the aerofoil is located.

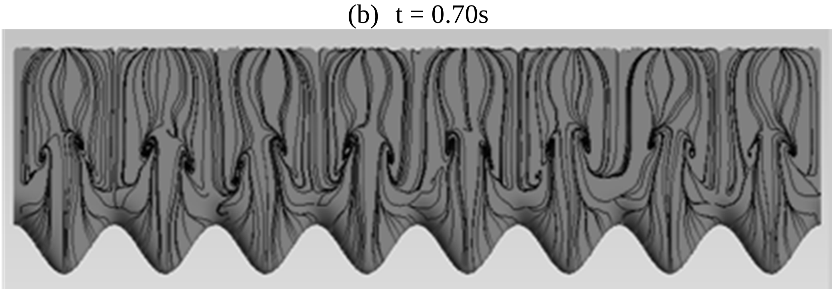
The time step used is 0.004 s for all computations and each simulation is run to achieve 2 cycles for the oscillation of flow-field at convergence criteria of 10^{-5}.



(a) t = 0.50s



(b) t = 0.70s



(c) t = 0.78s

Figure 2: Wall Shear on a static aerofoil at AOA of 20°

3 Mesh Validation

The modified aerofoil model was first set to a fixed angle-of-attack of 20° and streamlines compared with those presented by Ibrahim et al. [12]. Due to re-publication restrictions, pictoral results from Ibrahim et al. [12] will not be shown here and readers are encouraged to refer to the article for details. Wall shear streamlines from that study (on the modified aerofoil) show significant spanwise variation (refer to Figure 6 of Ibrahim et al. [12]). It was reported that the key feature of these were the "presence of regular recirculation zones about 60% dowstream along the chord-wise direction". These recirculation zones were hypothesized to be formed “via streamlines enjoined from the leading and trailing edges”. These recirculating zones are associated with streamwise vortices produced by the leading-edge protuberances.

The same spanwise variations and recirculation zones are also present in our model and are shown in Figure 2. As time progresses, it can be observed that the streamwise variation and location of the recirculation zones tend to convect downstream. In Figure 2a, at t = 0.5s, the recirulation zones seem to be located somewhere between a-quarter and a-third downstream of the leading edge and progresses to about half of the chord by t = 0.98s in Figure 2c. The recirculation zones are also very symmetrical about an imaginery axis running through the trough of the protuberance initially but gets progressively less so. Ibrahim et al. [12] solved for 20s which is much longer than the current validation exercise and their results showed the recirculation zone to be further downstream and also slightly higher spanwise variation than the current result. This is in line with the trends shown in Figure 2 and the slight differences in the spanwise variation could be due to the differences in the mesh. The current comparison is sufficient to indicate that the mesh used is sufficient to capture the necessary flow features and further solution of this static validation case was not deemed necessary.

4 Results and Discussion

A set of full oscillation of the aerofoil is presented in Figure 3 and it shows that vortex shedding at the wave-trough is always ahead of the wave-crest. This is indicates that the flow at wave-trough is faster than at wave-crest which is due to the flow being channeled into narrower streams closer to the wave-trough location due to the unique geometry of the tubercles . The difference in the relative velocity over the aerofoil at the wave-trough and wave-crest location. Figure 4 shows the streamlines on the underside and and topside of the aerofoil during one oscillation cycle with the addition of a side view to illustrate the oscillation position of the aerofoil at that instant. It can be observed that at any point in time, only one (either topside or underside) shows the complex streamlines and it is always on the side that is “approaching the flow” i.e. if the aerofoil pitching up (Figure 4a to Figure 4b), the topside is “moving away” whilst the underside is “approaching” the flow. In this case, the complex streamlines is shown only on the left (underside) whilst the right shows very simple straight streamlines with only a slight hint of the streamlines converging towards the wave-crest location. The reverse is seen from Figure 4c to Figure 4d and the trend reverts back from Figure 4d to Figure 4e.

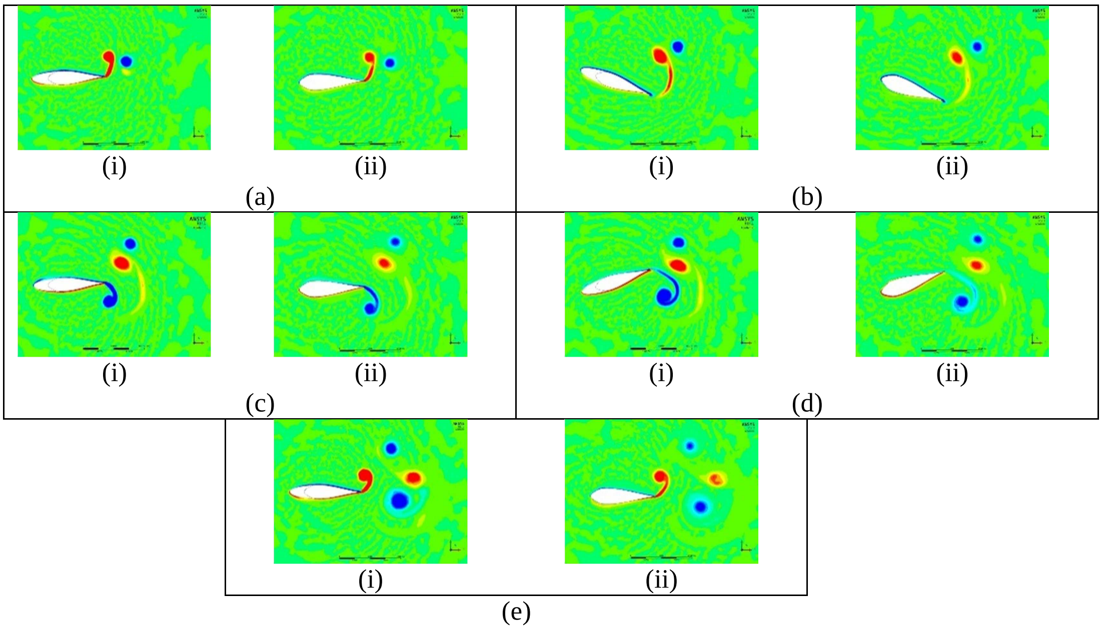


Figure 3: Vorticity contours at the wave-crest (i) and wave-trough (ii) locations

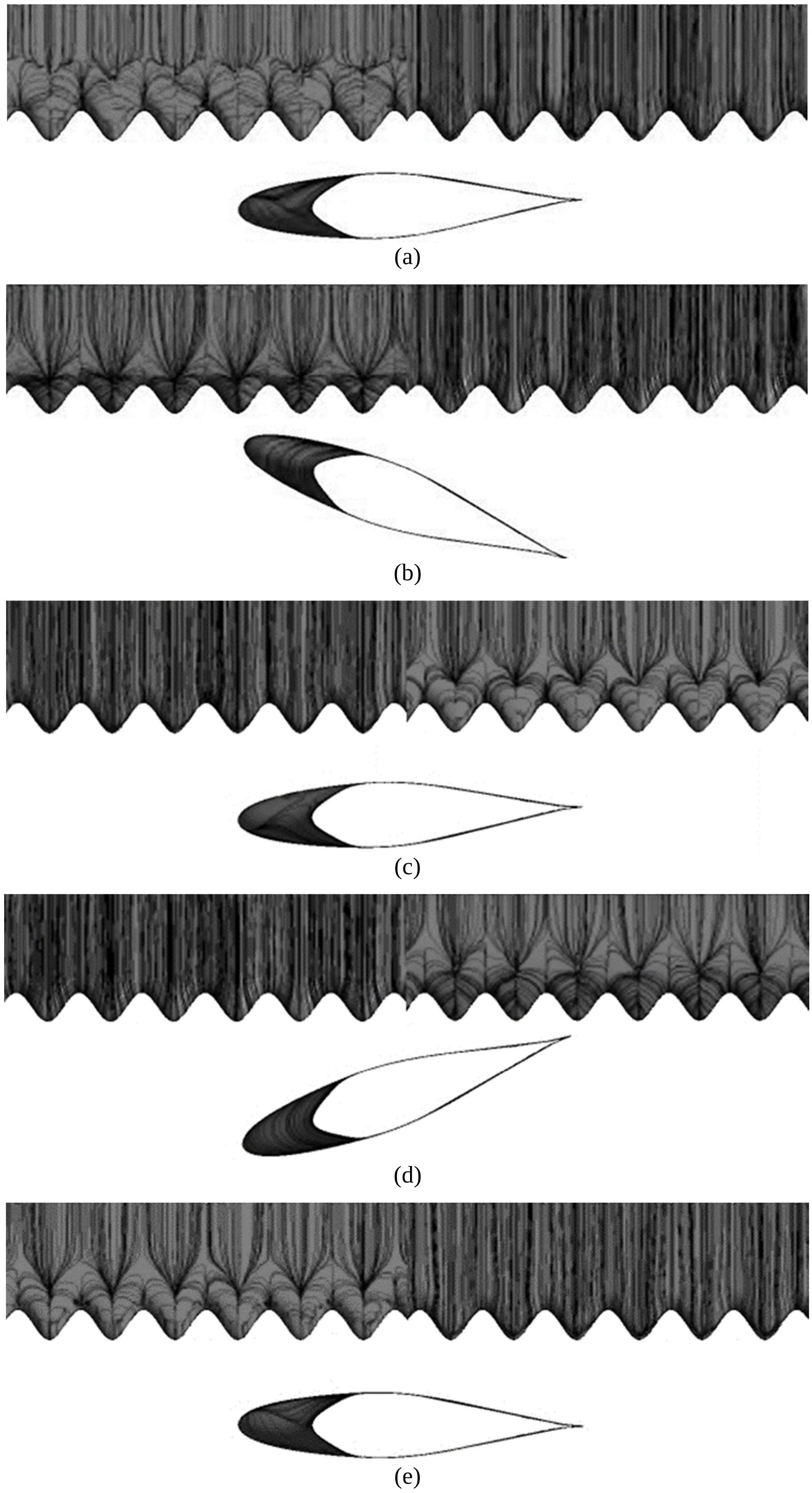


Figure 4: Streamlines on the underside (left) and topside (right) of the aerofoil during its oscillating motion

The temporal lift and drag coefficients and drag hysteresis are shown in Figure 5 and Figure 6 and the general trend agrees very well with previous studies of oscillating aerofoils [23]. Similar to that study, there is a lag between peak lift and peak oscillation. The thrust produced by this aerofoil is of interest as mentioned above and the drag hysteresis clearly shows a much larger area below the x-axis with an average value of -0.63 (i.e. thrust coefficeint Ct of 0.63) at a strouhal number of *St* = 0.37 according to the definition by Triantafyllou [27]. Comparing the current result with previous studies on NACA0012 symmetric airfoil [28, 29, 30] shows that the current airfoil generates higher thrust at this operating point. This supports the earlier stated hypothesis that the protuberances could induce flow structures that increases overall thrust production.

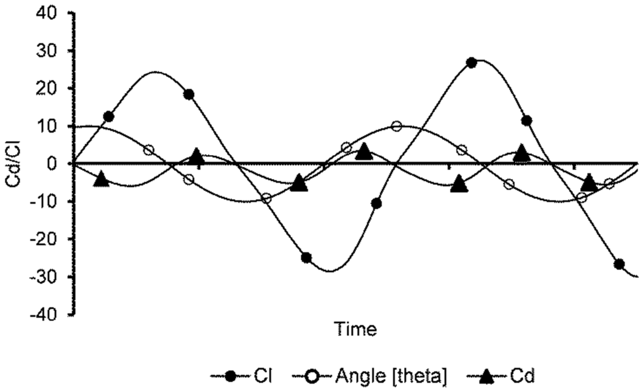


Figure 5: Temporal lift and drag coefficients

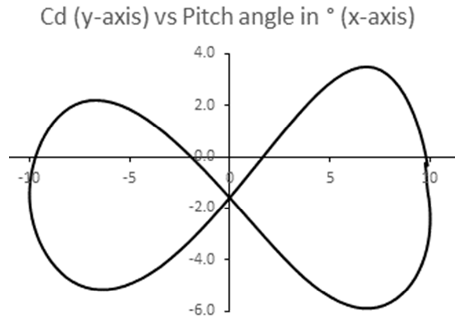


Figure 6: Drag Hysteresis during oscillation

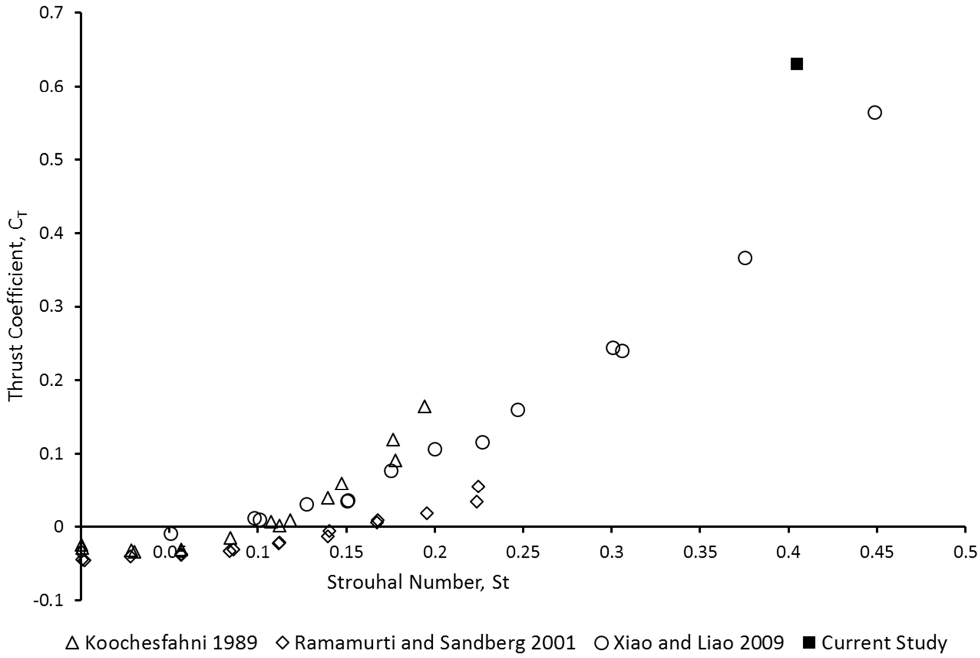


Figure 7: Comparison against previous experimental data of smooth 3D aerofoils undergoing oscillations

5 Conclusions

A computational study of a oscillating symmetrical aerofoil modified with leading edge proturberances have been conducted with the hypothesis that the unusual streamlines may result in improvements in thrust generation. Current results with oscillation frequency and amplitude of 4Hz and 10° shows a higher thrust coefficient Ct compared to previous studies on another symmetric aerofoil with no modifications, although the baseline aerofoil is not the same the results provide confidence on the possible advantages of the tubercles. Further studies on this modified aerofoil compared to its own baseline aerofoil will be conducted to further investigate the effect such protuberances have on lift and thrust generation however those simulations have not been completed at the time of this manuscript. This is the first reported study on the lift and thrust generation of oscillating aerofoils with leading edge proturberances and are showing positive results.

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