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Aerodynamic performance and surface flow structures of leading-edge tubercled tapered swept-back wings

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Effects of leading-edge tubercles on the aerodynamic performance and surface flow structures for tapered swept-back wings have been determined experimentally across a range of Reynolds numbers (Re). The orientation of SD7032 profile and tubercles were also particularly evaluated at $Re=2.2\times10^5$. Lift and drag curve behavior of the baseline wing with SD7032 airfoil profile aligned in the streamwise direction do not vary significantly when Reynolds number exceeds $Re=8.2\times10^4$. Results also indicate that the gross surface flow structures are not too sensitive towards the orientation of the SD7032 airfoil profile and tubercles. Nevertheless, compared with its baseline counterpart, the wing with tubercles normal to the leading-edge can slightly enhance the aerodynamic performance over a lower angle-of-attack (AOA) range of $2^\circ < \alpha < 7^\circ$. The two different tubercle orientations are also observed to improve stall behavior with lift enhancements and drag reductions at AOAs larger than 20° . Surface flow patterns show that highly complicated surface vortex structures and regular critical points are produced at moderate AOAs, where the distribution of critical points is dependent upon the leading-edge tubercle orientation and presence of sweep-angle. Surface vortices are revealed to either modify the laminar separation bubbles (LSBs) or disrupt large-scale recirculating region at smaller or larger AOAs respectively. At moderate AOAs however, surface vortices produced downstream of troughs are speculated to lead to poor drag performance.

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I. Introduction

Tubercles are found along the leading-edges of humpback whale pectoral flippers, upon which the huge humpback whales leverage to achieve high agility during the pursuit of prey, such as executing rolls, loops and banked turns [1-2]. Flow control techniques inspired by these tubercles have seen many studies associated with both aerodynamic and hydrodynamic lifting-surfaces, as described by Fish et al. [3]. This passive flow control technique has been demonstrated to enhance lift for rectangular wings at very large AOA due to more attached flow behind the tubercle peaks [4], as well as increasing stall angle and maximum lift coefficient for flipper model wing [5].

A number of studies aimed at revealing the flow mechanisms associated with the leading-edge tubercles have been carried out previously. Fish and Battle [1], Miklosovic et al. [5] and Johari et al. [4] have reasoned that the tubercles lead to greater momentum exchange within the boundary layer, which in turn enhances flow attachments to the suction surface. Miklosovic et al. [5] found that the tubercles perform as vortex generators, the notion of which was further investigated by Hansen et al. [6]. Findings by Custodio [7], Stanway [8], Weber et al. [9] and Wei et al. [10] also suggested that each tubercle functions as a small delta wing, leading to formation of a streamwise-aligned counter-rotating vortex pair (CVP) behind each tubercle. Later, the formation mechanism and evolution of these streamwise-aligned CVPs were revealed by Rostamzadeh et al. [11] and Hansen et al. [12]. van Nierop et al. [13] and Yoon et al. [14] found that the increased susceptibility of flow separation downstream of a tubercle trough are due to the lower local pressures and higher adverse pressure gradients. In addition, the pressure gradient downstream of a trough is more adverse than that downstream of a peak. Recently, Pérez-Torró and Kim [15] further revealed that aerodynamic performance enhancements could also be attributed to the deterioration of wake vortex shedding due to the spanwise coherent structures.

Other than these explanations, Custodio [7] noticed that the flow separation behavior for rectangular wings implemented with leading-edge tubercles leads to bi-periodic flow patterns at higher AOAs. Goruney and Rockwell [16] also revealed that these tubercles are able to modify the near-surface flow topology and flow of a delta wing. Additionally, Favier et al. [17] found that the leading-edge tubercles affect the recirculation zone and wake vortex-shedding processes. Through a series of particle-image velocimetry (PIV) experiments, Wei et al. [10] discovered that the flow separation behavior for hydrofoils with leading-edge tubercles is more unstable due to mutual interactions between adjacent streamwise-aligned CVPs. Using proper orthogonal decomposition (POD) analysis, Wei et al. [18] further revealed that tubercled hydrofoils lead to redistributions of the flow energy levels associated

with the coherent vortex structures across different POD modes. According to Skillen et al. [19], there exist secondary flows from the peak to the trough of a tubercled wing due to strong spanwise pressure gradient, which enhances momentum transport within the boundary layer. This flow mechanism was also described by Rostamzadeh et al. [11], where critical points were used to explain the more complex flow behavior associated with tubercled wings.

It should be noted that most of the earlier investigations on aerodynamic characteristics and flow structures associated with leading-edge tubercled lifting surfaces were primarily focused on rectangular wings. However, the aerodynamic efficiency and flow control performance are likely to vary according to the Reynolds numbers, airfoil profiles, wing planforms and tubercle geometries used. So far, few studies have considered the application of leading-edge tubercles on tapered swept-back wings, which might have brought benefits to commercial aviation industries or unmanned aerial vehicle (UAV). Bolzon et al. [20-21] observed that both lift and drag levels are reduced for tubercled tapered wings at smaller AOAs. Bolzon et al. [22] conducted wake surveys and revealed that the presence of the sweep angle can cause non-uniform vortex strengths formed by a single tubercle. Additionally, Custodio et al. [23] found out that drag levels are appreciably larger throughout all AOAs used, while lift levels are only reduced in the pre-stall regime with the presence of tubercles.

To address the lack of details on tubercled tapered swept-back wings, one of the primary interests in this study will be in their aerodynamic characteristics and surface flow structures beyond the AOAs used in earlier studies. Another primary interest is to obtain information on whether the airfoil profile and tubercle orientations with respect to the leading-edge affect the above-mentioned aerodynamic characteristics and surface flow structures. As such, four tapered swept-back wings with two different airfoil profile and tubercle orientations are considered here. Note that only a single tubercle geometrical configuration was studied here, as the emphasis was not on the effects of both tubercle orientation and tubercle geometrical configuration simultaneously. Nevertheless, the latter scenario may be pursued in future studies. The experiments were conducted at Reynolds numbers between $Re=5.5 \times 10^4$ and 4.2×10^5 , though most of the detailed experimental results were taken at $Re=2.2 \times 10^5$, which is close to that used by Bolzon et al. [20-22] and thus allows better comparisons. Lastly, force measurements through a three-component force balance and surface fluorescent oil flow visualization technique were used to characterize these four test wings in detail.

II. Experimental methods

A. Wind tunnel facility and force measurement procedures

Aerodynamic measurements were conducted in a closed-loop wind tunnel at Temasek Laboratories, National University of Singapore. The test section measures 600mm (W) $\times$ 600mm (H) $\times$ 2000mm (L) and the free stream velocity achievable within the test section ranges from $U_0=5\text{m/s}$ to 90m/s . The free-stream turbulence intensity in the test section is below 0.1% for $15\text{m/s} \leq U_0 \leq 70\text{m/s}$ and 0.25% for $U_0 < 15\text{m/s}$ and $U_0 > 70\text{m/s}$ respectively. In addition, flow uniformity in the test section is within 0.25% for $15\text{m/s} \leq U_0 \leq 70\text{m/s}$ and 0.5% for $U_0 < 15\text{m/s}$ and $U_0 > 70\text{m/s}$ respectively. The Reynolds numbers (i.e., based on the mean aerodynamic chord, MAC) investigated here varied from $Re=5.5 \times 10^4$ to 4.2×10^5 , which corresponds to free stream velocities from $U_0=10.2\text{m/s}$ to 77.5m/s . However, to elucidate the flow details, most results were captured at about $Re=2.2 \times 10^5$ and $U_0=40\text{m/s}$.

As shown in Fig. 1, the four wings were fixed vertically to an external three-component force balance system via a circular adapter plate on a rotating turntable mechanism. The use of rotating turntable allowed systematic adjustments of the AOA during the experiments. The mean lift force L and drag force D were measured by the force balance system at a sampling rate of 1kHz with a total sampling time of 10 seconds, for a total of 10,000 samples at each AOA. The AOA α was varied from -7° to 29° , which was positive in the clockwise direction as seen from the top-view of the test section, and was varied with angular increments of 2° for $\alpha \leq 9^\circ$, 1° for $9^\circ < \alpha \leq 19^\circ$, and 2° for $19^\circ < \alpha \leq 29^\circ$. The blockage ratio for the maximum AOA considered here was less than 6%, thus its effects were neglected here [24]. The lift and drag coefficients were determined using $C_L=2L/\rho U_0^2 A$ and $C_D=2D/\rho U_0^2 A$, where L and D are the measured lift and drag forces respectively, ρ is the air density, U_0 is the freestream velocity and A is the planform area for the wing considered.

Taking into account tolerance limitations of the adapter plate and flow angularity, the maximum uncertainty associated with the AOA is estimated to be $\pm 0.5^\circ$. On the other hand, the accuracy of the force balance was about 0.1% of the full-scale measurements. Considering the flow conditions, rotary table mechanism, force balance and a coverage factor of 1.96 at a confidence level of 95% for assumed T distribution of the sampling number [25], the total uncertainty for the force coefficients was estimated to be approximately 2%, according to the principles described by Moffat [26].

Fig. 1 Schematics of the force measurement setup within the wind tunnel test section.

B. Tapered wing designs

The swept wing geometry was chosen in this work, which is used on flight vehicle of all sizes from UAV [27], underwater glider [28] to passenger aircraft. Four tapered swept-back wings in consideration of two different airfoil and tubercle orientations (i.e., Baseline A, Baseline B, Modified A and Modified B) were designed. The selected SD7032 airfoil profile exhibits high aerodynamic performance at relatively low Reynolds numbers. The four wings were fabricated from aluminum blocks through CNC machining and their geometrical details are shown in Fig. 2. Baseline A wing was designed with SD7032 airfoil profile aligned along the streamwise direction. It has a root chord of 112.5mm, tip chord of 37.5mm and span of $s=300\text{mm}$, thus producing a taper-ratio of 0.33. The sweep-angle is $\Lambda=30^\circ$ based on the quarter-chord line along the wing span. The corresponding MAC was determined to be 81.25mm. For Baseline B wing, the SD7032 airfoil profile was aligned normal to the leading-edge instead, resulting in slightly larger root and tip chords of 39.5mm and 114.5mm, respectively, as well as the MAC of 83.07mm. In view of the overall wing sizes, the slight deviations in the exact dimensions are not expected to produce significant discrepancies.

In this work, the nonlinear shear transformation method as described by Wei et al. [10] was used to design the leading-edge tubercle geometry. This method was implemented by modifying a series of cross-sections for the baseline wing and then creating the solid tubercled wing through CAD software. This maintained the leading-edge radius, maximum thickness position, as well as continuity of the two sections over the maximum thickness point. In

Fig. 2 Geometry of the four tapered swept-back wings.

addition, the geometry of leading-edge tubercles can be precisely controlled. Subsequently, two tubercled wings of Modified A and Modified B were designed correspondingly.

Modified A wing was created by implementing tubercles along the streamwise cross-sections of Baseline A wing. Note that the present tubercle configuration corresponds to the maximum tubercle amplitude (i.e. $A=0.12c$, where c is the mean chord for rectangular wing) and larger wavelength (i.e. $\lambda=0.5c$) used by Johari et al. [4]. To minimize flow separation and hence drag at the wing-tip, a tubercle inflection point was implemented at the wing-tip. This resulted in 8.5 tubercles along the leading-edge and a tubercle wavelength of $\lambda=s/8.5=0.47lc_s$, where lc_s was the local chord at a particular location along the wing span. Since the tubercles were aligned in the streamwise direction, it will be intuitive to design them to be a fraction of the cross-stream wing-span. The tubercle amplitude was $A/lc_s=0.12$. Correspondingly, Modified B wing was to modify a series of cross-sectional profiles of Baseline B wing normal to the leading-edge with $A=0.12lc_n$, where lc_n was the local chord of cross-sectional profile normal to the leading-edge. To ensure that there are still 8.5 tubercles implemented normal to the leading-edge, the tubercle wavelength was designed such that it was $\lambda=LE/8.5$, where LE is the leading-edge length. The planform areas for Baseline A and B wings can be estimated through the area of the trapezoidal wing shapes. And those for Modified A and B wings could be estimated by taking into consideration of the wavy leading-edges through integral methods. As such, the planform areas for Baseline A, Modified A, Baseline B and Modified B wings are approximately 0.0225m^2 , 0.0226m^2 , 0.0231m^2 and 0.0232m^2 respectively. The maximum discrepancy between the smallest and

largest wing planform areas is about 3%, which is due to the fact that all modified wings were designed with an inflection point at their wing-tips to prevent significant wing-tip flow separations.

C. Surface oil flow visualizations

Surface oil flow visualization technique was used to reveal the flow patterns on the tapered swept-back wing surfaces. A thin layer of the fluorescent mixture, derived from the ZnS pigment, engine oil and mineral oil with a volume ratio of 1:1:4, was coated on the wing surface using a fine brush. Five AOAs were considered for the surface visualization experiments, where each wing was immersed within the free-stream for about 5 minutes until the surface flow patterns were stable. A Canon 550D Digital Single-Lens-Reflex (DSLR) camera with a Canon EF 50mm f/1.4 USM lens was used to photograph the surface flow patterns with an exposure time of four seconds in a totally dark environment. As the engine oil and mineral oil could not easily evaporate, the surface flow patterns would show up as time-averaged flow features such as flow streaks, flow separation and reattachment lines, as well as vortical structures and recirculating flows.

III. Results and discussion

A. Reynolds number sensitivity

Baseline A wing was first tested over different Reynolds numbers to evaluate how sensitive the present tapered wing is towards the exact Reynolds number and the resulting lift and drag coefficients are shown in Fig. 3. At a very low Reynolds number of $Re=5.5 \times 10^4$, both the lift and drag coefficients show significant deviations before and at the stall point. It can be noticed that the local Reynolds number in outboard region of the wing is smaller than 5.0×10^4 . In this flow regime, the free shear layer downstream of the LSB normally does not reattach back to the wing surface [29]. Thus, the lift decreases discernibly while drag increases abruptly in the post-stall regime. As the Reynolds number increases to $Re=8.2 \times 10^4$ and beyond however, the lift and drag coefficients show much smaller data scatters. Equally importantly, the lift coefficient gradually increases while the drag coefficient gradually reduces as the Reynolds number increases correspondingly. The stall angle can also be observed to remain approximately at $\alpha=15^\circ$ throughout the Reynolds number range used here. Compared to the sharp stall for the tapered whale flipper model investigated by Miklosovic et al. [5] and the tapered swept-back wing described by Custodio et al. [23], Baseline A wing stalls more gently with the lift coefficient decreasing gradually. It should be

Fig. 3 (a) Lift and (b) drag curves for Baseline A wing across different Reynolds numbers.

noted that while the airfoil profiles used by Miklosovic et al. [5] and Custodio et al. [23] differ from that used by the present study, there exist limited studies on tapered tubercled wings for which the present study can be compared with, based on the range of AOA tested here. From the preceding results, it can be discerned that the present tapered wings are not too sensitive towards Reynolds number changes and hence, a moderate Reynolds number of $Re=2.2 \times 10^5$ was considered for subsequent experiments, similar to that used by Bolzon et al. [20-22].

B. Aerodynamic characteristics

The lift and drag coefficients for the two groups of test wings at the above-mentioned Reynolds number are now shown in Fig. 4. Since the present wings are based on cambered SD7032 profile, it is not surprising that their zero-lift AOA are about $\alpha_{L=0} = -4.2^\circ$ and lift coefficients at AOA of $\alpha=0^\circ$ are approximately $C_L=0.35$, as shown in Fig. 4(a). It is also found that the lift and drag coefficients for the two baseline wings with different airfoil profile orientations are quite close. It indicates that besides comparing the aerodynamic performance of the modified wings with their baseline counterpart, general comparisons of aerodynamic performance between the two groups of wings can also be drawn. Lift curves for the two baseline wings show approximately linear relations between the lift coefficients for $\alpha < 7^\circ$. As the AOA increases, their lift coefficients increase non-linearly until reaching maximum values of approximately $C_L=1.16$ and 1.1 for Baseline A and B wings respectively at $\alpha=15^\circ$. Subsequently, their lift coefficients reduce gradually, though it should be mentioned that the losses in lift are quite moderate.

Fig. 4 (a) Lift and (b) drag curves for the four wings at the Reynolds number of $Re=2.2 \times 10^5$.

For instance, the reductions in lift coefficients in the post-stall regime are approximately 16.4% and 12.7% respectively for Baseline A and B wings, based on the values at $\alpha=15^\circ$ and 29° , the latter of which was the maximum AOA used here. These small losses in lift should be due to the fact that spanwise flow propagates gradually from the wing-tip region towards the wing-root region as a result of stall occurring earlier at the wing-tips (refer to Figs. 6 and 7). The locally smaller Reynolds number flows in the more tapered outboard portion of the wings are also more likely to cause earlier flow separations. It can also be observed that the overall lift performance for Baseline A wing is slightly better than that of Baseline B wing throughout the AOA range studied, particularly before their stall points.

Moving to the modified wings, Fig. 4(a) shows that the stall angles for Modified A and B wings occur at $\alpha=19^\circ$ and 17° respectively. Some slight increase in the maximum lift coefficient over their baseline counterparts can be observed for Modified B wing. The lift coefficients for Modified A and B wings also tend to be higher than their baseline counterparts as $\alpha \geq 17^\circ$ and 13° respectively, which demonstrate more gradual lift reductions as the AOA is increased. However, closer inspections reveal that the lift slopes for the two modified wings are smaller than those of the two baseline wings in the pre-stall regime. This is most likely due to deterioration of the LSB associated with the leading-edge tubercles. As described by Hansen [30], the presence of a LSB on the baseline wing surface could increase the effective camber and thus enhance the lift slope in the pre-stall regime. In contrast, the deterioration of

LSB for the modified wing might reduce the effective camber and leads to a slightly smaller lift slope. Surface oil flow visualization results taken during the present study also lend support towards this postulation, as will be shown later in the next section.

As for the drag performance, the two baseline wings with different airfoil profile orientations are practically similar throughout the measurement range here, registering significant increases after stall. The drag coefficient for Baseline B wing is slightly larger for AOA between $\alpha=12^\circ$ and 17° but remains within the present experimental uncertainty levels. The drag curves for both modified wings with different tubercle orientations are quite similar with each other as well. Furthermore, both incur significantly higher drag levels than their baseline counterparts between AOA of $\alpha=9^\circ$ and 20° , which encompass both pre- and post-stall regimes. Beyond $\alpha=20^\circ$ however, the opposite is true. It is worth mentioning that drag curves for the two modified wings demonstrate an almost linear trend from an AOA of $\alpha=9^\circ$ to the limits of the present measurement range. Based on observations in earlier studies, the linear increasing is likely caused by the gradual flow separation behind the troughs due to higher adverse pressure gradient as the AOA is increased.

From the lift and drag coefficient results shown in Figs. 4(a) and (b), the L/D ratio or aerodynamic efficiency can be estimated and compared in Figs. 5(a) and (b). The present two baseline wings with different airfoil profile orientations attained relatively similar L/D ratios throughout the measurement range, though Baseline A wing performs marginally better up to a stall AOA of $\alpha=15^\circ$. Compared to the study based on NACA0021 profile by Bolzon et al. [20], the present two baseline wings attained comparatively better performance. More specifically, the two baseline wings maintain L/D ratios of over 10 in a rather broad AOA range between $\alpha=-2^\circ$ to 12° . Peak L/D ratios occur at about $\alpha=1^\circ$, where $L/D=14.1$ and 13.6 for Baseline A and B wings respectively. Interestingly, despite the similarities in the L/D ratio seen between both baseline wings in the present study so far, implementation of tubercles leads to rather different behavior for their modified counterparts.

For example, Modified A wing perform worse than the Baseline A wing with lower L/D ratios for AOA lower than $\alpha=7^\circ$. In fact, the former attains a peak L/D ratio that is lower than that of the latter. In contrast, Modified B wing is able to achieve a peak L/D ratio that is 7% higher than its baseline counterpart. This is believed to be linked to the lower drag coefficient for the Modified B at AOA of $2^\circ < \alpha < 7^\circ$, as shown in Fig. 4(b). Correlating to the surface oil flow visualizations to be presented later, the reduction in the drag coefficient is at least partially linked to the significantly smaller LSB sizes produced by the Modified B wing at very small AOA here (refer to Figs. 7(a),

Fig. 5 (a) L/D ratios for the four wings and (b) relative aerodynamic performance of the two modified wings respect to the two baseline wings at a Reynolds number of $Re=2.2 \times 10^5$. “MA”, “MB”, “BA” and “BB” refer to Modified A, Modified B, Baseline A and Baseline B wings respectively.

10(a)(i) and 11). More details will be provided later when those results are discussed later.

Most interestingly, it can also be observed that the L/D ratio for Modified B wing is comparatively higher than those with different airfoil and tubercle orientation (i.e. Baseline A and Modified A) for AOA of $2^\circ < \alpha < 7^\circ$, which reflects upon certain favorable aerodynamic effects when the tubercles are aligned normal to the leading-edge. This observation also suggests that there should be an optimal tubercle orientation angle, which might be or not be associated with the airfoil profile orientation to further enhance the L/D ratio. However, there is insufficient data within the present study to infer much on this possibility since only two groups of wings have been investigated here, where the tubercle orientation is also based on different airfoil profile orientations. Both modified wings also lead to much more rapidly declining L/D ratio than the baseline wings after $\alpha=7^\circ$. This points towards the notion that, while implementing tubercles upon the Baseline B wing may be able to increase its peak L/D ratio significantly, it comes at a price of rapidly deteriorating performance shortly after. In particular, the L/D performance of the two modified wings are far worse than their baseline counterparts between AOA of $\alpha=7^\circ$ and 15° . Lastly, Fig. 5(b) provides details on the various performance ratios of the two modified wings relative to their baseline counterparts. It can be readily appreciated that drag levels for both modified wings have increased to a maximum of about 60% over their baseline counterparts at approximately $\alpha=12^\circ$. On the other hand, the L/D ratio

for both modified wings are also enhanced over their baseline counterparts when the AOA exceeds $\alpha=20^\circ$ and are shown up to 10% improvement at the maximum AOA of 29° tested here.

C. Surface flow patterns

Before the qualitative surface flow visualization results are presented, it should be noted that they themselves alone cannot adequately infer which test wing will perform better or worse. However, they can be very useful when it comes to understanding the differences in the quantitative aerodynamic performances between the various test wings or airfoil profile and tubercle orientations. Surface flow visualization images captured along the suction surface of Baseline A wing at $Re=2.2\times 10^5$ and $\alpha=0^\circ, 9^\circ, 15^\circ, 19^\circ$ and 29° are shown in Fig. 6. Figure 6(a) shows that a LSB is formed along the suction surface of the wing even at $\alpha=0^\circ$ and extends almost throughout the entire wing span except for close to the wing-tip and wing-root regions. The formation of such a LSB for a baseline tapered swept-back wing has been mentioned by Bolzon et al. [20] previously and can be attributed to the Reynolds number being close to the transitional flow regime [29]. The LSB region is located slightly aft of the wing mid-chord and formed as a result of the flow separating and then reattaching back to the wing surface. As the AOA increases to $\alpha=9^\circ$ as shown in Fig. 6(b), the LSB not only becomes significantly shorter and narrower, but also moves upstream to a position that more or less coincides with the maximum thickness point in the inboard region. At the same time, a narrow leading-edge separation bubble and another flow separation bubble appear to form close to the wing-tip and trailing-edge respectively. The phenomenon was in sharp contrast to the tapered whale flip-like model observed by Miklosovic et al. [5] and the tapered swept-back wing as described by Custodio et al. [23], both of which show sharp stall with trailing-edge turbulent flow separation only manifesting in the post-stall regime. As the AOA continues to increase in Figs. 6(c) to (e), the LSB ceases to exist and the trailing-edge flow separation appears to manifest into a large-scale recirculating region that propagates gradually towards the wing-root region as the AOA is increased.

As for the Baseline B wing with airfoil profile normal to the leading-edge, flow visualization images in Fig. 7 show that the flow structures are quite similar to Baseline A wing, with some minor exceptions. A narrow and well-defined LSB still extends along most of the wing span at $\alpha=0^\circ$ as shown in Fig. 7(a), though it resides much closer to the trailing-edge. As the AOA increases to $\alpha=9^\circ$, the LSB preserves much of its original form but moves upstream and is roughly located at the maximum thickness point. It should be noted from Figs. 4(a) and (b) that the exact location of the LSB does not significantly affect the lift and drag levels for the two baseline wings with different

Fig. 6 Surface oil visualizations along Baseline A wing suction surface at $Re=2.2 \times 10^5$.

Fig. 7 Surface oil visualizations along Baseline B wing suction surface at $Re=2.2 \times 10^5$.

airfoil orientations. Additionally, no trailing-edge separation is observed at this point, which is in sharp contrast to that of the Baseline A wing as shown in Fig. 6(b). As the AOA continues to increase however, the general flow behavior becomes much closer to that of Baseline A wing with formation of the large-scale recirculating region, which moves towards the wing-root region.

Figure 8 shows the surface flow visualizations for Modified A and the more detailed flow patterns of Close-up view I. It can be immediately discerned that as compared with its baseline counterpart, the flow fields are dramatically modified by the tubercles and become apparently more complex across all AOAs. The LSB can still be observed at $\alpha=0^\circ$, while its distribution along the wing span appears to have taken a waviness-like pattern and segregated by small surface vortices (i.e. vortices forming along the surface) at the tubercle troughs in a regular fashion. The flows adjacent to the suction surface are relatively parallel to the free-stream direction as well. Interestingly, surface vortices that rotate anticlockwise in the LSBs are also found close to the trailing-edge between the adjacent surface vortices as shown in the two close-up images (Figs. 8(b)(i) and 9). As shown in Fig. 9, the

Fig. 8 (a) Surface oil visualizations along Modified A wing suction surface at $Re=2.2 \times 10^5$ and (b) the detailed flow patterns of Close-up view I.

Fig. 9 Detailed flow patterns for the Close-up view II as shown in Fig. 8(a)(i).

direction of surface vortices in the distorted LSB (i.e. the congregated oil blob) can be deduced by the direction of surrounding flow streaks. They are going around the oil blob in a counter-clockwise fashion.

As the AOA increases to $\alpha=9^\circ$, these surface vortices at the troughs migrate towards the leading-edge with rotational senses indicated in Fig. 8(b)(ii). It is now apparent that they resemble surface CVPs. Figure 8(a)(ii) also indicates that the physical size of surface CVPs grows discernibly bigger as it is located nearer to the wing-tip region. In earlier studies by Rostamzadeh et al. [11] and Hansen et al. [12], it had been established that these surface CVPs

are caused by relatively larger adverse pressure gradients behind troughs, as well as spanwise pressure gradient where peaks and troughs are associated with higher and lower pressures respectively. Generally, higher spanwise pressure gradient gives higher spanwise shear velocity, which could cause the streamwise flow to be skewed and tilted along the wing surface. As shown in Figs. 8(a)(ii) and (b)(ii), the flow streaks close to the wing root are slightly skewed from the peak region towards to trough region, and no reversed flows are observed. In contrast, the flow streaks close to the wing-tip are significantly skewed from peak region towards the trough region, and reversed flows could be observed to form a surface CVP. The size of surface CVP close to the wing-tip is also much larger than that close to the wing-root, as seen in Fig. 8(a)(ii). This suggests that the tapered swept-back wing configuration here might induce higher spanwise pressure gradient at the troughs in the outboard region. Nevertheless, the flow remains attached to most of the suction surface at this point. Collating with the aerodynamics characteristics, it would appear that these surface CVPs and increasingly flow separation behind the troughs serve to increase the drag and reduce the L/D ratio drastically between $\alpha=9^\circ$ and 20° , as shown in Figs. 4(b) and 5(a).

As the AOA increases further to $\alpha=15^\circ$ and beyond however, flows adjacent to the suction surface no longer remain parallel to the free-stream direction. Instead, flow patterns indicate significant flow separations and distorted flow paths for the surface CVPs downstream of the troughs. In fact, Figs. 8(b)(iii) and (b)(iv) show that these surface CVPs are being increasingly distorted. In particular, a large-scale recirculating region (i.e. surface vortex), presumably formed by the trough surface CVPs and junction flows originated at the wing-root location, can be seen to gradually move towards the wing-root, as seen in Figs. 8(a)(iv). This is somewhat similar to the general behavior seen for both baseline wings earlier. Similar to the work by Rostamzadeh et al. [11] where critical-flow theory via saddles and nodes was used to explain the flow topology produced by the rectangular tubercled wings, the flow features found in Figs. 8(a)(iii) and (b)(iii) support that the presence of saddles and nodes can apparently be detected here as well. However, due to the use of sweep geometry here, the saddles are significantly skewed towards the tubercle peak downstream regions.

At the highest AOA of $\alpha=29^\circ$, trailing-edge flow separations can be discerned and the surface flows have already become highly distorted. It is worthwhile to note that although force measurement results suggest that the stall angle is approximately $\alpha=15^\circ$, the lift level as shown in Fig. 4(a) do not exhibit any abrupt reductions due to significant flow attachment region behind the peaks especially close to the wing-root.

Fig. 10 (a) Surface oil visualizations along Modified B wing suction surface at $Re=2.2 \times 10^5$ and (b) the detailed flow patterns of Close-up view I.

As for Modified B wing, the surface flow visualizations are presented in Fig. 10, where close-up views are included as well. The general flow patterns as seen in the images are by and large similar to those seen for Modified A wing previously. This is despite the fact that the tubercles are implemented such that they are normal to the tapered wing leading-edge, it may also explain why the lift and drag performance for both modified wings are relatively similar. Nevertheless, closer inspection reveals that some differences observed in the flow visualization images may be related to their aerodynamic performances.

At $\alpha=0^\circ$, it can be seen that the size of segmented LSBs behind the peaks is discernibly smaller than its baseline counterpart, as shown in Fig. 7(a) and 10(a)(i). Close-up views in Fig. 11 also confirm that the segmented LSBs for the Modified B wing almost disappear in the inboard region, while those for the Modified A wing still occupy a moderate portion of the wing surface behind the peaks, which indicates that the orientations of tubercles should be an important factor that influences the size of the segmented LSBs. The present mechanism of flow compartmentalization [31] relating to the segmented LSBs possibly supports the above speculation that the tubercles may reduce drag levels for Modified B wing at lower AOAs, as shown in Fig. 4(b). Note that the compartmentalized flows with surface vortices and flow separation at the troughs are induced by the local lower pressure and higher

Fig. 11 Detailed flow patterns for (a) Close-up view III of Modified A as shown in Fig. 8(a)(i), and (b) Close-up view II of Modified B as shown in Fig. 10(a)(i).

adverse pressure gradient [12,14]. As shown in Fig. 11(b), the mechanism of flow compartmentalization appears to play an even more significant role in the inboard region, with the flow downstream of surface vortices reattaching to the wing surface due to the relatively larger local Reynolds number. Considering that the LSB can modify the suction surface profile, parasite drag due to the LSB could be reduced correspondingly, as the size of the LSB segments is decreased [29]. It may then contribute to the L/D ratio enhancement of the Modified B wing for $2^\circ < \alpha < 7^\circ$, as shown in Fig. 5(a). At $\alpha = 9^\circ$, it can be observed that the segmented LSBs on the Modified B wing completely disappear. Compared with its baseline counterpart, the disappearance of LSBs may reduce the effective camber and subsequently reduce its lift slope in the pre-stall regime [30], as shown in Fig. 4.

Additional differences can also be observed in the visualization images taken at $\alpha = 29^\circ$. For the Modified A wing, significant flow attachment occurs behind all the peaks, including those in the outboard region, as shown in Fig. 8(a)(v). In contrast, limited flow attachments are noticed behind the peaks in the outboard region for the Modified B wing, as shown in Figs. 10(a)(v). This might be part of the reason that the lift for Modified A wing is higher than that of the Modified B wing in the post-stall regime, as seen in Fig. 4(a). Based on the surface flow visualization results, it would appear that the presence of the tubercles produces two favorable flow behavior. Firstly, they produce surface CVPs which are also closely related to the streamwise-aligned CVPs as deduced from the leading-edge separation bubble as shown in Figs. 8(a)(v) and 10(a)(v). As described by Johari et al. [4] and Custodio [7], the streamwise-aligned CVPs are generated due to the similar function of tubercles to small delta wings. These surface CVPs mitigate flow separation behavior (i.e., as seen by the relatively more attached flows along the wing suction surface), even if the latter lead to more turbulent flows. Secondly, the presence of these surface CVPs disrupts formation of the large-scale recirculating region that exists in both baseline wings.

IV. Conclusions

Aerodynamic characteristics and surface flow patterns for four tapered swept-back wings based on two fundamentally different design rules were experimentally investigated in a low speed wind tunnel. Each group comprised of one baseline wing and one wing modified with leading-edge tubercles, where the SD7032 airfoil profile and tubercles were aligned in the streamwise direction or normal to the leading-edge. Results show that the gross aerodynamic behavior of the non-modified tapered wing with airfoil aligned in the streamwise direction is not too sensitive towards the Reynolds numbers studied here, provided that the latter is $Re=8.2 \times 10^4$ and above. The present two airfoil profile orientations and alignment of tubercles relative to the leading-edge does not lead to significant changes to the major surface flow features. Nevertheless, aligning the tubercles normal to the leading-edge shows tangible improvement in the L/D ratio for of $2^\circ < \text{AOAs} < 7^\circ$, as compared with its baseline counterpart wing and the other group of wings with airfoil aligned in the streamwise direction. Stall behavior is improved slightly for both modified wings with different tubercle orientations as compared with their baseline counterparts, where both lift enhancement and drag reduction can be achieved at higher AOAs above $\alpha=20^\circ$. L/D ratio is however worse than their baseline counterparts between $\alpha=7^\circ$ and 20° .

Flow visualizations show that the highly complicated surface vortex structures for the two groups of wings are generally similar. Both a saddle and a node are produced by each tubercle on the two modified wings especially in the outboard region, where the saddles are significantly tilted to be located behind the peaks due to the presence of the sweep-angle. These surface vortex structures not only modify the distribution of LSBs, but also disrupt large-scale recirculating region that are associated with wing-root stall for the two baseline wings. These flow features and behavior are likely to account for the improvements observed in the lift and drag performance earlier. On the other hand, poor drag performance for moderate AOA are likely due to the more complex flow separation behind the tubercles.

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