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Leading-edge tubercles delay flow separation for a tapered swept-back wing at very low Reynolds number

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Abstract: Flow separation characteristics for two tapered swept-back wings, one with straight leading-edge (LE) and the other with tubercled LE, were investigated in a water tunnel using time-resolved particle image velocimetry (TR-PIV) technique. The two wings were based on the SD7032 aerofoil profile, with Reynolds number $Re = 1.4 \times 10^4$, close to the working condition for common underwater gliders. The LE tubercles were designed such that the amplitude decreased linearly from the wing root to wing tip, while retaining constant wavelength. Results indicate that the baseline wing shows significantly separated flow in the outboard region at pitch angle of 10° and 20° , and the flow remains attached in the inboard region due to relatively larger local Reynolds number. Implementation of LE tubercles can mitigate flow separation downstream of both troughs and peaks. At higher pitch angles, the separated flows cover most of the baseline wing surface, whereas flow remains attached downstream most of tubercle peaks. Streamwise aligned counter-rotating vortex pairs (CVPs) formed over the tubercles are significantly tilted and asymmetrical due to the sweep and amplitude difference between the two sides of tubercle. Consequently, weaker vortices in CVPs close to the wing root are rapidly dissipated, allowing the CVPs to evolve into a series of co-rotating vortices (CVs), which exerted significant impact on flow separation characteristics downstream of the tubercles.

Keywords: SD7032; Leading-edge tubercles; Tapered swept-back wing; Underwater glider

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1. Introduction

In recent years, the intriguing passive flow control technique of leading-edge (LE) tubercles has attracted increasing research interest to explore potentially wide applications and benefits for aerodynamics and hydrodynamics augmentation, such as aerofoils (Johari et al. 2007, Custodio et al. 2015), hydrofoils (Wei et al. 2015), rudders (Weber et al. 2010), propellers (Ibrahim and New 2015), tidal turbines (Shi et al. 2016, 2017) and other devices. It has been speculated that humpback whales deploy the tubercles distributed along their pectoral flipper LEs to achieve extreme manoeuvrability, such as rolls and loops (Fish and Battle 1995). Since humpback whales use the tubercled pectoral flippers in water, it seems reasonable to consider using tubercles on marine lifting-surfaces, e.g. to improve the hydrodynamic performance of tapered swept-back wing for underwater gliders.

Underwater gliders often use moving mass and small buoyancy variations respectively to alter their pitch angle and make itself float or dive. Employing lift generated by a pair of fixed wings, gliders could propel themselves with very low power consumption, extending ocean sampling missions to months and thousands of kilometres. However, the problem is that the underwater gliders always cruise at very low velocity (i.e., $< 0.5\text{m/s}$), corresponding to Reynolds number $Re < 10^5$ for the wings. The wings are subjected to severe flow separation at this low Re , leading to poor performance. This paper explores improving the hydrodynamic performance of a tapered swept-back wing through LE tubercles, mitigating stall and flow separation. The cruise range of underwater gliders could be improved with the hydrodynamic performance of the wings improved.

To assess the conjecture that LE tubercles contributed to humpback whale manoeuvrability, Watts and Fish (2001) examined the effect of LE tubercles on a whale flipper model at 10° incidence angle using panel simulation. They showed that LE tubercles provided 4.8%

increased lift, 10.9% reduced induced drag, and hence 17.6% enhanced lift to drag ratio. They demonstrated that drag reduction was probably due to compartmentalized lift between the troughs. Van Nierop et al. (2008) confirmed spanwise pressure variation with higher pressure downstream of tubercle peaks and lower pressure downstream of troughs. Subsequently, Miklosovic et al. (2004) conducted a series of flipper model wind tunnel tests for mean chord based $Re = 5.0-5.2 \times 10^5$, and showed that the tubercles could delay stall angle by 40% compared to a smooth LE flipper model. Maximum and post-stall regime lift were also increased, accompanied by decreased drag. They also showed that the tubercles had a similar role as vortex generators (VGs), energizing flow and transport momentum over the wing, which could retain attached flow at higher pitch angles.

Stanway (2008) experimentally studied flapping humpback flipper model performance for $Re = 4.4 \times 10^4$ to 1.2×10^5 , and showed that LE tubercles could not increase the thrust. They speculated that the vortices produced by LE tubercles could interfere with the reverse Kármán vortex street, weakening the thrust jet. Custodio et al. (2015) used wind tunnel tests at $Re = 2.3 \times 10^5$ to show that LE tubercles slightly increased whale flipper model lift in the post-stall regime, while slightly increasing drag in both pre- and post-stall regimes. Although the flipper model was similar to that used by Miklosovic et al. (2004), the different results indicate the effect of Re on the performance of tubercled flipper model.

Johari et al. (2007) studied the effect of tubercle geometry on rectangular wing hydrodynamic performance at $Re = 1.83 \times 10^5$, and they also investigated the effects of tubercle wavelength, λ , and amplitude, A . Their results highlighted that although wings with maximum tubercle A induced gentle stalls, the lift coefficient, C_L , could be enhanced as high as 50% in the post-stall regime. Reducing both tubercle A and λ achieved higher maximum C_L and stall angle. Flow visualizations confirmed that hydrodynamic performance enhancement was due to flow

attachment downstream of tubercle peaks in the post-stall regime. These findings were subsequently confirmed by several studies, including Rostamzadeh et al. (2014), Zhang et al. (2014) and Wei et al. (2015).

Another important feature of LE tubercles is formation of counter-rotating vortex pairs (CVPs) (Johari et al. 2007, Stanway 2008, Wei et al. 2015, Cai et al. 2017). Just due to this feature, the tubercle functions similar to a small delta wing or VG. CVPs can induce downwash behind tubercle peaks, energizing the boundary layer momentum exchange and delaying flow separation, particularly downstream of tubercle peaks (Miklosovic et al. 2004, Rostamzadeh et al. 2014). Wei et al. (2016) also showed that flow separation becomes unstable due to streamwise aligned CVP interaction with their neighbours.

LE tubercles can also cause lower pressure and higher pressure gradients at troughs due to channelled accelerated flows between two adjacent peaks (Van Nierop et al. 2008, Yoon et al. 2011), making the wings less sensitive to varying Re (Guerreiro and Sousa 2012), inducing bi-periodic flow pattern (Cai et al. 2017), re-distributing flow energy behind the tubercles (Wei et al. 2016), and reducing unsteady fluctuations in aerodynamic forces (Favier et al. 2012). These flow features are closely related to flow conditions (Re, finite or infinite), wing shape, aerofoil profile, etc.

Note that the rectangular wings and whale flipper models have been extensively studied previously, but the sweep effects have received little attentions. Bolzon et al. (2014) showed that LE tubercles could reduce both lift and drag at lower pitch angles for a tapered swept-back wing. Wei et al. (2018) examined the effect of tubercle orientation on aerodynamic performance for tapered swept-back wings at $Re = 2.2 \times 10^5$, and showed that tubercles normal to the LE could slightly enhance aerodynamic performance at lower pitch angles. Subsequently, Wei et al. (2018) have further tested the wing with LE tubercles aligned along

the streamwise direction at $Re = 5.5 \times 10^4$ and showed that LE tubercles increased lift at all pitch angles tested and achieved comparative drag levels, which significantly enhanced the hydrodynamic performance at lower pitch angles. Surface flow visualizations also revealed that surface CVPs formed over the tubercles were highly tilted due to the sweep, similar to those discussed by Bolzon et al. (2016). These tilted CVPs enhanced momentum exchange and re-energized the boundary layer to allow flow to remain attached downstream of tubercle peaks at higher pitch angles. However, little is still known about the evolution of these tilted streamwise aligned CVPs and their impact on flow separation characterises downstream of LE tubercles.

The current study addressed this lack by experimentally investigating LE tubercle effects on **flow separation and coherent flow structures** of a tapered swept-back wing, using two-dimensional (2D) **time-resolved** particle image velocimetry (TR-PIV). The Reynolds number was chosen to be $Re = 1.4 \times 10^4$, close to the cruise velocity of common underwater glider. Nevertheless, the local Re varies significantly across the span due to the tapered wing shape. To capture the differences of flow separation between the inboard and outboard regions, consecutive measurement planes were aligned in the spanwise direction in the streamwise experiments. To elucidate evolution of streamwise aligned CVPs, measurement planes were also aligned at five different chordwise locations downstream of the LE tubercles.

2. Experimental methods

2.1 Water tunnel and wing design

Flow fields for both wings were measured in a low speed recirculating water tunnel, as shown in Fig. 1. The experimental setups were similar to Wei et al. (2015). The test section measures 450mm (W) $\times$ 600mm (H) $\times$ 1100mm (L) and was constructed from tampered **glass to allow**

Fig. 1 Schematics of (a) streamwise and (b) cross-stream TR-PIV setup.

good optical access from both sides and bottom. There was also a small window of tempered glass at the back of test section allowing flow fields to be measured along the free stream direction. The recirculating water was seeded with 20 micro diameter polyamide particles. Before entering the test section, the water was conditioned through honeycombs, fine screens, and a contraction section to form uniform free streams with low turbulence.

A rectangular plate with round LE and the same width as the test section was fixed horizontally at the bottom with 100 mm gap between the bottom of the test section and plate, to minimize the boundary layer effects. The wing was fixed vertically to the plate using a 2mm diameter coupling pin at the quarter chord location of its root. Accurate pitch angle variance at $\alpha = 0^\circ$, 10° , and 20° was achieved using a protractor marked on the surface of the plate. Note that the underwater glider always works at optimum pitch angles from $\alpha = 15^\circ$ to 25° . Nevertheless, the pitch angle might be varied in the presence of strong ocean currents. In addition, the underwater glider that the LE tubercles will be applied on is a smart glider combining the function of underwater glider and Argo float, which means that the pitch angle will be very small when it dives or float under the mode of Argo float.

Free stream velocity was chosen approximately at $U_0 = 0.17\text{m/s}$, which was close to the cruise velocity of common underwater gliders and corresponds to $Re = U_0 c / \nu = 1.4 \times 10^4$, based on the mean hydrodynamic chord $c = 81.25\text{ mm}$, where ν is the water kinematic viscosity. It should be mentioned that turbulence intensity of the free stream should be different in varying PIV measurement planes due to effect of the free surface and bottom wall. It was estimated to be 1.1% by using the PIV procedures described in the following section in the streamwise measurement plane aligned at the middle span of the wing with wing model removed. The present free stream turbulence intensity is also relatively higher than that in common wind tunnels. It can influence the flow separation and stall characteristics at the present low Reynolds number, which usually leads to faster transition along wing surface and potentially later stall. The force measurements were not performed here as the present focus is on flow field and coherent structures. In addition, force measurements in low-speed water tunnel tests are very tricky, due to water proof and seal problems, as well as very small force values, which will be performed in the wind tunnel based on a new gamma load cell with high precision in the future.

Two tapered swept-back wings (Baseline and Tubercled) were designed and fabricated by using CNC machining, as shown in Fig. 2. Baseline wing had a straight LE, the span was chosen to be $s = 300\text{ mm}$, based on the depth of test-section of the water tunnel. The present span keeps enough distance between the free surface and wing-tip, as well as the bottom of test section and wing-root, so that effect of free-surface and boundary layer at the bottom of test section can be reduced. The tip chord was $c_t = 37.5\text{ mm}$ and root chord was $c_r = 112.5\text{ mm}$, which aims for a moderate tapered ratio of $\gamma = 0.33$ and to maintain the same planform area with the rectangular wings, as described by Wei et al. (2015). The sweep angle based on the quarter chord line along the span was designed with a moderate value of $\Lambda = 30^\circ$, which was specially chosen for the underwater gliders to avoid being trapped by aquatic plants and

Fig. 2 Wing geometries, streamwise and cross-stream measurement planes for TR-PIV experiments (green dotted lines); C, S, T, and P refer to cross-stream, streamwise, Trough- and Peak-planes, respectively.

fishing nets. Based on the present wing shape, the mean aerodynamic chord was $MAC = 81.25$ mm. The SD7032 aerofoil profile, showing particularly higher hydrodynamic performance at relatively lower Re , was aligned parallel to the free stream direction for Baseline wing.

Tubercled wing had a well-defined wavy LE by modifying the streamwise cross-sections of Baseline wing. The method employed [here](#) was similar to the nonlinear shear transformation described by Wei et al. (2015). The camber line was first fitted through a polynomial curve, which was also extrapolated to the tubercle peak position to create the longer camber line. Then, the cross-sections obtained by using the nonlinear shear transformation method were modified so that the upper and lower surface had the same distance to the camber line. Figure 2(b) shows that tubercle amplitude, A , decreased linearly along the span, maintaining a

Fig. 3 (a) Amplitude on both sides of a tubercle and (b) normalized cross-sections at a tubercle peak and a trough compared to that of Baseline wing.

constant ratio to the local chord c_l , i.e., $A/c_l = 0.12$, for each spanwise position. Figure 3(a) shows the difference between A_L and A_R on the two sides of a single tubercle due to the tubercled LE swept backwards, and Fig. 3(b) shows that the longer camber line along the peak cross-sections was further increased as compared with the SD7032 aerofoil profile. The wavy inflection point was positioned at the wing tip for the tubercled wing, and constant tubercle wavelength $\lambda = s/8.5$ was selected. Note that both tubercle A and λ approach the largest tubercle geometry for humpback whale flippers (Fish and Battle 1995). The planform area was determined to be approximately 0.0225m^2 and 0.0231 m^2 for Baseline and Tubercled wing, respectively. This slight deviation would not be expected to cause significant discrepancies in flow separation behaviour.

2.2 TR-PIV procedures

The flow fields were measured by using time-resolved particle image velocimetry (TR-PIV) technique. The main setups included an IDT NX8 grayscale high speed CCD camera and 2W, 532 nm continuous wave CNI diode pumped solid state (DPSS) laser. As seen from the streamwise schematics in Fig. 1(a), the laser was used in conjunction with beam steering and sheet forming optics to create a 1.5 mm thick horizontal laser sheet. The high speed CCD camera was located under the test section to capture 5,000 raw images at 500 frame per second

(FPS). The cross-stream setup was shown in Fig. 1(b) with the laser sheet normal to the free stream direction. Since the particles stayed in the laser sheet for a relatively short time, slower shutter speed of 200 FPS was also used to capture 5,000 raw particle images. As the present Reynolds number is quite low, the present FPS is higher enough to allow us to analyse a lot of instantaneous flow features, such as roll-up vortices in separated shear layer, unstable flow separation and wake vortex shedding. Nevertheless, the time-averaged flow fields were presented in most cases in this work to indicate the overall flow feature due to the unstable flow characteristics associated with LE tubercles.

The flow structures possibly differentiate in various spanwise and streamwise positions due to sweep and LE tubercles. Hence, 2D TR-PIV measurement cut through the 3D complex flow structures could struggle to show the real flow features. Therefore, four consecutive measurement planes (Fig. 2(a), S1, S2, S3, and S4) were aligned in the spanwise direction in the streamwise experiment for Baseline wing, corresponding to the four different peak-planes (Fig. 2(b), P1, P2, P3, and P4) for Tubercled wing. Four measurement planes (Fig. 2(b), T1, T2, T3, and T4), aligned at the consecutive troughs, were also included neighbouring the four peaks. Five consecutive planes (Fig. 2(b), C1, C2, C3, C4, and C5) were also aligned streamwise at the troughs to measure corresponding cross-stream flow fields for Tubercled wing, and the same locations for Baseline wing.

Raw images were captured when there were at least five bright particles within the 32×32 pixel grid, and particle shift displacement between two consecutive images should not exceed $1/5$ of the grid. Post-processing of the raw images was performed using PIVlab software (Thielicke and Stamhuis 2014) and the procedures were similar to Wei et al. (2015, 2016) and New et al. (2016). Two-step multi-grid cross-correlations and three interrogation windows were applied to consecutive frames to obtain velocity maps, and initial and final interrogation

windows were 128×128 px² and 32×32 px², respectively. Error vectors were removed by a 5×5 grids median filter and replaced by the median value of the grid. Missing vectors within the velocity vector maps were interpolated using neighbourhood vectors. Finally, a total of 4999 instantaneous velocity vector maps were used to obtain the mean time-averaged flow fields. The vector spacing and spatial resolution of the present TR-PIV measurement results was varied according to the laser sheet orientation (i.e., streamwise and cross-stream) and different spanwise or streamwise positions, which showed the maximum value of 1.68 mm per vector in both horizontal and vertical directions in the streamwise velocity field results close to the wing tip. The spatial resolution value was also much smaller than that of separated shear layer, and was able to resolve the boundary layer and separated shear layers (Wei et al. 2015). Based on the image processing procedure described above, measured velocity vector uncertainty was estimated as $\pm 1\%$ following Keane and Adrian (1992).

In this work, the flow separation and reattachment points were determined through in-plane streamlines and vorticity magnitudes derived from the PIV data, [which is relatively crude near wall surfaces](#), hence it could not provide very accurate flow separation and reattachment points even using the surface shear stress data due to the spatial resolution. In the future, the surface shear stress could be accurately measured through other experimental techniques so that more detailed flow features can be revealed.

2.3 Proper orthogonal decomposition technique

The snapshots proper orthogonal decomposition (POD) technique similar to that used by Wei et al. (2016) was also used to further process the 4999 instantaneous flow fields (i.e., snapshots) for the present data set. Lumley (1967) proposed the POD technique to identify lower order dynamic information in various fluid flows and can find a series of modes as the physical orthonormal basis expanding the entire 4999 TR-PIV flow fields. The POD technique is

Fig. 4 Mean 2D streamlines and vorticity field at $\alpha = 0^\circ$ along the four different spanwise planes defined in Fig. 2(d) for (a) Baseline wing, (b) Trough- and (c) Peak-planes for Tuberled wing.

well-suited for PIV experiments to capture coherent structures with significant contribution to turbulent kinetic energy. By projecting onto the instantaneous flow fields, the eigen modes exhibit coherent structure spatial and temporal evolution where such structures are dominant in a turbulent energy sense. Based on the energy distribution, the first several POD modes capture the most energetic and hence dominant flow structures.

3. Results and discussion

In this section, flow fields measured by 2D TR-PIV along streamwise and cross-stream directions at $\alpha = 0^\circ$, 10° , and 20° are presented to provide insight into near-field flow separation and vortex structures over the upper surfaces of the two tapered swept-back wings.

3.1 Flow separation and vortex structures at $\alpha = 0^\circ$

Figure 4 shows mean streamlines and vorticity fields along the streamwise direction for both

Fig. 5 Mean 3D vorticity fields corresponding to Fig. 4.

wings at $\alpha = 0^\circ$. There are no significant differences in flow separation between the four spanwise locations for either wing type. Figure 5 shows three-dimensional (3D) views of the 2D flow fields on solid wing models to connect the measurement with their real positions over the wings. Undoubtedly, low Re effects are quite significant. The flow always separates at approximately 2/3 chord location along the different spanwise planes of Baseline wing, similar to that downstream of tubercle peaks (Figs. 4(c) and 5(c)). The trough-plane is relatively more susceptible to flow separation (Figs. 4(b) and 5(b)), with flow always separating from the LE at the maximum thickness point with a thicker separated shear layer (SSL). This is consistent with previous studies that showed the troughs were sensitive to flow separation due to local lower pressure and higher pressure gradient (Van Nieop et al. 2008, Yoon et al. 2011). Referring to Wei et al. (2016), negative and positive SSLs located above and below the wings, respectively, are associated with streamwise coherent wake vortex shedding (WVS).

Figure 6 shows mean streamlines and vorticity fields for the five consecutive streamwise planes for both wings, and Fig. 7 shows their corresponding 3D views on the solid wing models. SSLs indicating mild flow separation also occurs in the cross-stream results of Baseline wing, as shown in (Fig. 6(a)). In contrast, segregated SSLs formed over the tubercled

Fig. 6 Mean streamlines and vorticity fields at $\alpha = 0^\circ$ along the five streamwise planes defined in Fig. 2 for (a) Baseline wing and (b) Tuberled wing.

wing surface are associated with regularly streamwise aligned vortices. Collating with the streamwise aligned CVPs generated over the LE tubercles for rectangular wings (Custodio 2007, Wei et al. 2015), these segregated streamwise aligned vortices are actually streamwise aligned CVPs. However, they become significantly asymmetrical, and only one sign of vorticity can be seen in C2 and C3 planes in Fig. 6(b). In fact, Fig. 3(a) shows that the tubercle amplitude A_L at the left side is much smaller than A_R at the right side due to the sweep and decreasing tubercle A along the span, which indicates that stronger vortex can be generated at the right side. In addition, Fig. 3(b) shows that the tubercle peak is slightly curved downwards due to the present tubercle geometry design procedure. Therefore, the tubercles induce less spanwise flow from the windward region towards the leeward region, causing relatively weaker streamwise aligned vortices for Tuberled wing at $\alpha = 0^\circ$, especially for these at the left side of tubercles.

Fig. 7 3D view of the mean vorticity fields corresponding to shown on the wings for Fig. 6.

Figures 6(a)(v) and 6(b)(v) show that the tip vortex (TV) for Tubercled wing is slightly weaker than that of Baseline wing based on the value of vorticity ($1/s$). Note that the critical point of bifurcation line (BL) is shown on the downstream flow fields (Figs. 6(a)(iv), 6(a)(v), 6(b)(iv) and 6(b)(v)), indicating the boundaries for either far field free stream and near field flow over the wings or flow field on the windward and leeward sides of the wings. Figures 6(a)(v) and 6(b)(v) also show significantly positive and negative SSLs are formed downstream of both wings. Closer inspection indicates these SSLs are associated with regularly spanwise and streamwise WVSs, and the streamwise WVSs for rectangular wings have been previously discussed by Wei et al. (2016). In this work, the POD technique is still employed to process instantaneous flow fields associated with Figs. 6(a)(v) and 6(b)(v) to confirm the spanwise WVS.

Fig. 8 (a) POD mode energy at $\alpha = 0^\circ$, coefficient scatter distribution for POD modes 1 and 2 of (b) Baseline and (c) Tubercled wings.

Fig. 9 POD modes 1 and 2 of the C5 streamwise measurement plane at $\alpha = 0^\circ$; U and W refer to velocity components along the horizontal and vertical directions, respectively.

Figure 8(a) shows that POD modes 1 and 2 for Baseline wing are associated with quite dominant energy content of approximately 0.3, and Fig. 8(b) shows that the coefficients of POD modes 1 and 2 have approximately circular distributions, indicating cyclic flow pattern variation. Referring to Wei et al. (2016), it is known that this cyclic variation was associated

Fig. 10 Spectral analysis for the coefficients of POD modes 1 and 2 of both wings at $\alpha = 0^\circ$. Each spectrum curve is stepped by an order of magnitude to present them separately.

Fig. 11 Instantaneous wake vortex shedding evolution within one cycle at $\alpha = 0^\circ$; sampling frequency for TR-PIV is $f_s = 500\text{Hz}$.

with coherent spanwise WVS, and Fig. 9(a) confirms that alternate signed vortices are shedding and arranged in the spanwise direction in both POD modes 1 and 2. Thus, wake

vortices are shed both in both streamwise and spanwise directions from Baseline wing due to sweep. Figure 10 shows the results of fast Fourier transforms (FFTs) for the coefficient of POD modes 1 and 2. Baseline wing WVSs retain approximately $f = 15.9\text{Hz}$ spectrum, which is also confirmed by the instantaneous vorticity field shown in Fig. 11(a).

In contrast, LE tubercles create completely different vortex structures. Figure 8(a) shows that the energy content of POD modes 1 and 2 for Tubercled wing is much smaller than that for Baseline wing, just 24% in total, which is also not dominant as compared with subsequent POD modes. Coefficient scatter distributions are also not as circular as that for Baseline wing (Fig. 8(c)). Although both POD modes also indicate remarkable spanwise WVS (Fig. 9(b)), they exhibit only weak cyclic variation and phase convection between the two POD modes. Figure 10 shows a sharp peak at $f \approx 22.5\text{Hz}$, but the spanwise WVS is irregular, as shown in the instantaneous vorticity fields (Fig. 11(b)), which could be due to CVP interactions with neighbours inducing spanwise flow exchange within the boundary, dissipating wake vortices relatively more quickly.

3.2 Flow separation and vortex structures at $\alpha = 10^\circ$

Figure 12 shows mean streamlines and vorticity fields for both wings at $\alpha = 10^\circ$, and Fig. 13 shows their 3D views. It is notably found that the flow separation bubble (FSB) increases rapidly in the outboard region for Baseline wing, but the SSL reattaches to the wing surface with a laminar separation bubble (LSB) formed in the inboard region (Figs. 12(a)(iv) and 13(a)), due to relatively larger local Re. In contrast, LE tubercles significantly influence flow separation on Tubercled wing surfaces. Figures 12(b)(i) and 12(b)(ii) show that although stronger SSLs are formed downstream of troughs in the outboard region, FSB is slightly smaller than these over Baseline wing. Strong SSLs in the inboard region reattach to the wing surface downstream of troughs (Fig. 12(b)(iii) and Fig. 12(b)(iv)), hence flow separation was

Fig. 12 Mean streamlines and vorticity fields at $\alpha = 10^\circ$ along the four spanwise planes defined in Fig. 2 for (a) Baseline, (b) Trough- and (c) Peak-planes for Tubercled wing.

Fig. 13 3D view of the vorticity fields on the wings corresponding to Fig. 12.

already mitigated, as shown particularly in Fig. 12(b)(iii). Figures 12(c) and 13(c) show that flow separation is significantly mitigated with only mild SSLs observed in the peak planes.

Fig. 14 Mean streamlines and vorticity fields at $\alpha = 10^\circ$ along the five streamwise planes defined in Fig. 2 for (a) Baseline wing and (b) Tubercled wings.

Figure 14 shows mean streamlines and vorticity fields along the five streamwise measurement planes for both wings at $\alpha = 10^\circ$, and Fig. 15 shows the corresponding 3D views. Vortex structures are closely associated with those in Fig. 12 and 13. For example, Figs. 14(a)(i) and 14(a)(ii) correspond to the inboard region, where flow attaches to Baseline wing surface with just mild SSLs noticed. In contrast, Figs. 14(a)(iv) and 14(a)(v), corresponding to FSB in outboard region flow, show formation of very strong SSLs. Figures 14(b)(i) and 14(b)(ii) show that the streamwise aligned CVPs generated over the tubercles have been rendered incoherently, due to the presence of sweep and asymmetrical tubercle geometry. Figure 14(b)(iii) also shows that negative vortices have already been dissipated and positive vortices are significantly increased as CVPs are convected downstream.

Figure 15(b) shows that the Peak-planes roughly coincide between the two positive vortex cores, where attached flow is evident. In contrast, positive vortex cores are approximately located downstream of tubercle troughs, where the flow is susceptible to separation. POD analysis of instantaneous vorticity fields associated with Figs. 14(a)(v) and 14(b)(v)) show that

Fig. 15 3D view of the mean vorticity fields corresponding to Fig. 14.

wake vortices still shed in both spanwise and streamwise directions. Nevertheless, energy content of the POD mode 1 for both wings is less than 10%, indicating that flow structures are much more incoherent than that at $\alpha = 0^\circ$. It is interesting to see that the critical point of saddle of detachment (SD) is formed over Baseline wing tip, which is also associated with tip flow separation. In contrast, only a critical point of BL occurs for Tubercled wing (Fig. 14(b)(v)), roughly marking the boundary for the main free stream and flow separation regions over the wing surface. It can also be interestingly seen that Tubercled wing tip and the tubercle at the wing tip both generate positively streamwise aligned vortex. Since these streamwise aligned vortices combine, the TV is relatively stronger than that for Baseline wing.

3.3 Flow separation and vortex structures at $\alpha = 20^\circ$

Figure 16 shows mean streamlines and vorticity fields along the four spanwise measurement planes for both wings at $\alpha = 20^\circ$, which is also associated with the post-stall regime, and Fig. 17 shows the corresponding 3D views. Baseline wing is subjected to severe flow separation

Fig. 16 Mean streamlines and vorticity fields at $\alpha = 20^\circ$ along the four spanwise planes defined in Fig 2.

(Figs. 16(a) and 17(a)), with very large FSB formed in the outboard region accompanied with a critical point of SD close to the TE (Figs. 16(a)(ii) and 16(a)(iii)). Since local Re is relatively larger in the inboard region, although thick SSL is formed on the LE, flow still reattaches to the wing surface forming an LSB, similar to the $\alpha = 10^\circ$ case (Figs. 12(a)(iv) and 16(a)(iv)).

Similar to the pre-stall regime at $\alpha = 10^\circ$, LE tubercles have significant flow control effect. Figures 16(b) and 17(b) show that FSBs in the outboard region downstream of tubercle troughs are notably smaller than that for Baseline wing. Note that Trough-planes are generally more susceptible to flow separation for rectangular wings, as discussed above, due to the

Fig. 17 3D view of the mean vorticity fields corresponding to Fig. 16.

relatively lower pressure and higher pressure gradient. In the inboard region (Figs. 16(b)(iv) and 17(b)), although thick SSL forms a small flow recirculating region downstream of the trough, it reattaches back to the wing surface. Mean streamlines and vorticity fields along Peak-planes (Fig. 16(c) and (c)) show that flow separation has been significantly mitigated. FSB is just formed downstream of the peak close to the mid-span, and flow topology is also correspondingly modified, with critical points of two SDs, two foci (F) and one BL observed in Fig. 16(c)(iii). Although mild SSL is also formed downstream of other Peak-planes in the inboard and outboard regions, flow generally attaches to the whole surface.

Figure 18 shows mean streamlines and vorticity fields along the five consecutive streamwise measurement planes for both wings at $\alpha = 20^\circ$, and Fig. 19 shows the corresponding 3D views. Apparently, flow features for Baseline wing still agree well with the streamwise results. Figures 18(a)(i), 18(a)(ii), and 18(a)(iii) indicate thick SSL with flow reattaching to the wing surface in the inboard region, whereas the other two downstream measurement planes are associated with larger FSBs (Figs. 18(a)(iv) and 18(a)(v)). In contrast, regular streamwise aligned CVPs are observed for Tubercled wing over the tubercles at the two upstream measurement planes (Figs. 18(b)(i), 18(b)(ii) and 19(b)), but these CVPs are quickly

Fig. 18 Mean streamlines and vorticity fields at $\alpha = 20^\circ$ for the five streamwise planes defined in Fig. 2.

dissipated as they are convected downstream (Figs. 18(b)(iii), 18(b)(iv) and 18(b)(v)). Similar to the $\alpha = 10^\circ$ case, the energy content of POD mode 1 is less than 10% for both wings. Although the POD modes 1 and 2 for both wings are still associated with spanwise WVS, the significant difference between POD modes 1 and 2 shows that flow structures are significantly more complicated and incoherent.

In addition, flow topology has become more complicated (refer to Figs. 14 and 18(b)), with wing tip and trough flow exhibiting the critical points of SD when strong separated flow or

Fig. 19 3D view of the mean streamlines and vorticity fields corresponding to Fig. 18.

SSL is formed. The flow feature also resembles critical points of Foci close to vortex cores in streamwise aligned CVPs (Figs. 18(b)(ii), 18(b)(iii) and 18(b)(iv)).

3.4 Flow separation control mechanisms

Comparing Figs. 7, 15 and 19, regular streamwise aligned vortices formed over the LE tubercles are notable flow features. Considering similar flow control mechanisms of VG and small delta-wings (Custodio 2007, Stanway 2008, Wei et al. 2015), it is speculated that these streamwise aligned vortices have significant influence on flow separation. Flow separation delay behind the tubercle peaks for rectangular wings due to the streamwise aligned vortices through downwash and momentum exchange within the boundary layer has been discussed previously (Rostamzadeh et al. 2014, Wei et al. 2018), but the flow control mechanism and associated flow characteristics are relatively different due to wing model employed.

Fig. 20 Streamwise aligned vortex effects on flow separation at $\alpha = 10^\circ$.

The flow separation in Figs. 12 and 16 can be compared with the evolution of streamwise aligned vortices in Figs. 14 and 18, aiming to reveal the influence of streamwise aligned vortices on the FSB. Figures 20 and 21 compare the two cases at $\alpha = 10^\circ$ and 20° , respectively, where vorticity maps downstream of troughs and peaks are combined for clearer understanding of the flow control mechanism (Figs. 20(a) and 21(a)). **It needs to be mentioned that these time-averaged flow fields at varying wing cross-sections are measured at different time, and the instantaneous flow fields over the LE tubercled are also quite unsteady with flow separation region varying in time, as revealed by We et al. (2015, 2016). Nevertheless, the time-averaged flow fields based on 4999 snapshots are able to reduce both the overall errors and effect of any unsteady flows at the present low Re, which allows us to combine them together to reveal the overall flow structures and flow control mechanism.**

As mentioned above in Fig. 3(a), distinct amplitude differences exist between the two sides of a tubercle, i.e., $A_L < A_R$. Following Rostamzadeh et al. (2014), strength of vortex within streamwise aligned CVPs at the side close to wing root is also quite weak, consistent with the

Fig. 21 Streamwise aligned vortex effects on flow separation at $\alpha = 20^\circ$.

results shown in Figs. 15(b) and 19(b). The weak vortex is also rendered much weaker rapidly as convected downstream, possibly due to the mechanisms of viscous dissipation, vortex stretching or compression associated with spanwise flow effect. Therefore, CVPs evolve into a series of co-rotating vortices (CVs) at the measurement planes downstream of LE (Fig. 20(b) and 21(b)).

Referring to Figs. 14(b) and 18(b), flow directions over streamwise aligned vortices can also be marked on the measurement planes (Figs. 20(b) and 21(b), [close-up views](#)). Figure 20(b) shows downwash induced along all the four measurement planes for peaks and troughs, hence flow separation can be mitigated even along Trough-planes at $\alpha = 10^\circ$. The induced downwash can transport high momentum flow within the boundary layers. Streamwise aligned vortices also induce remarkable spanwise flow in the outboard region, and the flow streaks are significantly curved (Fig. 20, [close-up views](#) (i) and (ii)). These cross-stream flows possibly induce mild SSLs formed downstream of tubercle peaks (Figs. 12(c) and 20(a)), though the flows remain attached to the wing surface.

Figure 21(b) shows that both negative and positive vortices in the CVPs are rendered into the series of CVs more rapidly at $\alpha = 20^\circ$, and the CVs are also not as coherent as those at $\alpha = 10^\circ$. Close-up views (i), (ii) and (iv) of Fig. 21(b) show that downwash is seen along both Trough- and Peak-planes in the outboard and inboard regions, which mitigates flow separation downstream of the peaks and troughs (Figs. 16(b)(i), 16(b)(ii), 16(b)(iv), 16(c)(i), 16(c)(ii), 16(c)(iv) and 21(a)). However, the opposite occurs for close-up view (iii), Fig. 21(b), where flow directions indicate that upwash is generated along Trough- and Peak-planes, which is consistent with Figs. 16(b)(iii) and 16(c)(iii), indicating a large FSB compared with Baseline wing.

Although streamwise aligned vortices have significant impact on flow separation mitigation for the present tapered swept-back wing, the flow control mechanism differs somewhat from rectangular tubercled wings (Johari et al. 2007, Custodio 2007, Wei et al. 2015). As discussed above, streamwise aligned CVPs for Tubercled wing will be asymmetrical. When they are convected downstream, negative vortex in the CVPs can be easily dissipated, and flow separation is mainly influenced by the CV series. Thus, regular downwash distribution downstream of tubercle peaks and upwash downstream of troughs induced by streamwise aligned CVPs in the case of rectangular wings will not occur for the tapered swept-back wings.

Figures 20(b) and 21(b) show that the spanwise shifting of the CVs are quite different, the CVs at $\alpha = 10^\circ$ shift towards the tip, while it is opposite for those at $\alpha = 20^\circ$. It is speculated that this flow feature is closely related to the spanwise pressure difference on the wing surface. As the separated and attached flows show quite different characteristics at $\alpha = 10^\circ$ and 20° , and they are also different in the inboard and outboard regions. Hence, the spanwise pressure distributions are also quite different for those at $\alpha = 10^\circ$ and 20° .

Figure 20(b) shows that streamwise aligned vortices formed at $\alpha = 10^\circ$ are convected downstream approximately parallel to the free stream in the inboard wing section, while slightly shifted along the spanwise direction towards the wing tip. Downwash and upwash regions also shift correspondingly. Figure 20(b) also indicates that as soon as streamwise aligned CVPs are formed over LE tubercles, both negative and positive vortices induce downwash and attached flow downstream of the peaks. The size of positive vortices significantly increase as the negative vortices subsequently dissipate, and positive vortices almost occupy the entire spanwise section of the tubercle λ . These streamwise aligned vortices also induce cross-stream flows and possibly mild SSL. Spanwise shifting of CVs let downwash located further downstream of tubercle peaks, where flow separation can still be mitigated (Fig. 12(c)). Apparently, the evolution of CVs and their shifting help flow mixing within the boundary layer, re-energizing the boundary layer and possibly helping to mitigate flow separation.

Figure 21(b) shows that as the CVs shift, different spanwise locations exhibit different downwash and upwash distributions. For example, the upwash region might occupy the region downstream of both trough and peak, and consequently induce separation flow (Figs. 16(b)(iii) and 16(c)(iii)). The downwash can also shift to both Trough- and Peak-planes in the inboard region (Fig. 21, [close-up view](#) (iv)), where the flows reattach to the wing surface. This flow feature is more or less similar to that for rectangular wings (Joy et al. 2016), where separated flow differs along different troughs and peaks. This unstable flow behaviour is significantly impacted by tubercle geometry for rectangular wings, i.e., A and λ , which affect convection distances for streamwise aligned CVP interactions with neighbours. However, strength and position for CVP formation along the spanwise position are quite different for the swept-back wing case due to asymmetrical tubercles, sweep and taper ratio. The inboard region is located relatively upstream and CVPs formed over tubercles in the inboard region have already been

dissipated as they are convected to the tubercle in the middle span position (i.e., downstream) to interact with the local CVPs. Neighbouring CVP size and strength also differ slightly.

However, more tubercle geometries, streamwise and spanwise aligned measurement planes must be considered in future work, which aims to accurately elucidate CVP interactions and suggest an optimum tubercle geometry of flow separation control for the tapered swept-back wings. Undoubtedly, flow separation control indicates the enhancement of hydrodynamic performance of these wings. If applied to the underwater gliders, the LE tubercles may lead to a longer cruise range due to the enhancement of the hydrodynamic performance of the pair of fixed-wings.

4. Conclusions

Flow separation characteristics for two swept-back wings were experimentally investigated in a low speed recirculating water tunnel. Both wings were based on tapered swept-back profile, one with straight and the other with tubercled LE, where A decreased linearly from wing root to wing tip. The Reynolds number based on the mean hydrodynamic chord was just $Re = 1.4 \times 10^4$, chosen to be close to common underwater glider working conditions (i.e., cruise speed). Flow fields were measured using [time-resolved](#) particle image velocimetry (TR-PIV) at $\alpha = 0^\circ$, 10° and 20° pitch angles.

The results show that mild separated flows can be seen over the baseline wing surface in both inboard and outboard regions at $\alpha = 0^\circ$, and the wake vortex is also shedding both streamwise and spanwise due to the presence of sweep. As the pitch angle increases to $\alpha = 10^\circ$, the outboard region shows significantly flow separation, while flow still attaches to the wing surface in the inboard region due to the relatively larger local chord. At $\alpha = 20^\circ$, the separated flow reattaches to the wing surface in the inboard region, exhibiting a laminar separation

bubble (LSB). In contrast, the tubercled wing can apparently mitigate flow separation downstream of both tubercle peaks and troughs in either outboard or inboard regions, particularly for higher pitch angles. The flow separation mitigation possibly enhances the hydrodynamic performance for the present tapered swept-back wing, and hopefully leads to a longer cruise range for the underwater gliders.

Cross-stream vorticity fields of the tubercled wing show that regularly streamwise aligned counter-rotating vortex pairs (CVPs) are formed over each tubercle especially at higher pitch angles. Effects of both sweep and the difference of tubercle amplitudes at the two sides of a tubercle cause asymmetrical CVPs, with the vortex at the side of tubercle close to the wing root significantly weaker than the vortex at the other side. These weaker vortices in the CVPs can be rapidly dissipated, hence the CVPs evolve into a series of co-rotating vortices (CVs) downstream of the tubercles. These CVs shift in both streamwise and spanwise directions due to the spanwise pressure difference associated with the sweep, and consequently the downwash region also shift spanwise and is alternatively located downstream of troughs and peaks. The downwash helps transport momentum energy, mix the boundary layer, and hence delay flow separation downstream of both tubercle troughs and peaks in either inboard or outboard regions. However, as streamwise aligned CVs evolve, the upwash shifts and might occasionally cover the region downstream of tubercle trough and its neighbouring peak, making the flow more susceptible to separation.

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