Rapid manoeuvring with spanwise-flexible wings

Jaime G. Wong *, David E. Rival

Department of Mechanical and Materials Engineering, Queen's University, Kingston, ON K7L 3N6, Canada

A R T I C L E   I N F O

Article history:
Received 15 October 2016
Received in revised form 3 July 2017
Accepted 10 August 2017
Available online 1 September 2017

Keywords:
Spanwise flexibility
Swimming and flying
Vortex dynamics

A B S T R A C T

In this study, it is hypothesized that spanwise-profile bending contributes towards limiting leading-edge vortex (LEV) growth and increasing LEV stability in natural swimming and flight, due to the spanwise flow produced by profile bending. Specifically, as a propulsor undulates and subsequently bends, the profile tip can have a phase lag relative to the root, producing both a spanwise flow and an angle-of-attack gradient, transporting vorticity and thus circulation along its span. This relative phase of the profile tip versus the root is investigated experimentally using a combined pitching-and-flapping motion on a nominally two-dimensional NACA0012 profile, utilizing direct measurements of vorticity transport to estimate the circulation budget. In order to measure vorticity transport the entire velocity gradient tensor must be resolved, and therefore 4D-PTV, a high-density, time-resolved volumetric technique, was used to measure the flow around the profile. Tip-leading kinematics were found to increase LEV size and strength due to an unbalanced circulation budget: vorticity was not transported along the span, but instead accumulated to increase circulation. Meanwhile for tip-lagging kinematics, that mimics the bending found in nature, both reduced LEV size and circulation were observed, as vorticity transport acted to balance the circulation budget instead.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Previously, spanwise flexibility has been studied in terms of cruising efficiency. For instance, Heathcote et al. (2007) observed increased propulsive efficiencies for oscillating spanwise-flexible profiles, while Cleaver et al. (2016) observed increased lift coefficients and reduced power coefficients for flexible profiles across a broad range of kinematics. In such cruise conditions, Lucas et al. (2014) found broad evolutionary convergence among flexible appendages, with similar levels and locations of profile bending across a range of Reynolds numbers and species. Similar efficiencies have been observed for flexibility about other axes such as chord wise and twisting deformations, as demonstrated by Young et al. (2009) and Cleaver et al. (2014), respectfully. Taking inspiration from these advantages found for cruising conditions, the current study investigates the role of spanwise flexibility during rapid manoeuvres.

Ellington et al. (1996) identified spanwise flow as critical in controlling the growth of the ubiquitous leading-edge vortex (LEV). This LEV is especially important for rapidly manoeuvring flyers as the bound vortex is of negligible strength on thin, stalled aerofoils, as discussed by Pitt Ford and Babinsky (2013). Thus, maintaining the proximity of this vortex to the profile of a swimmer or flyer is critical in maintaining high instantaneous loads, which is useful for rapid manoeuvring and lift augmentation. The proximity of the vortex to the profile is determined by the relative streamwise velocity of the vortex. Wong and Rival (2015) showed that this streamwise convection speed can be reduced by draining circulation from the LEV through spanwise vorticity convection, as the vortex-detachment process is determined by the vortex size. In particular,
Rival et al. (2014) showed that for a critical vortex size on the order of one chord length, the detachment process is forced to begin by the streamline topology. For rotating kinematics, rotational accelerations can provide the spanwise flow required to maintain a constant vortex size in steady state, as discussed by Lentink and Dickinson (2009). In particular, Lentink and Dickinson (2009) described rotational accelerations with the Rossby number, with smaller values of the Rossby number corresponding to stronger rotational accelerations, and Rossby numbers on the order of $Ro \approx O(1)$ were associated with stable LEVs. Stable LEVs have been observed in this Rossby number range by Ozen and Rockwell (2012), Cheng et al. (2013), and others. At such low aspect ratios, Cheng et al. (2013) observed that convection of the LEV in the remaining two directions, streamwise and chord-normal, as well as vortex tilting, may also be critical in maintaining LEV stability. However, flapping flyers with lower rotational accelerations, or higher Rossby numbers, must pursue alternative strategies. For instance, a flapping profile initially perpendicular to the oncoming flow will passively bend along its profile span due to the lift it generates, resulting in a component of oncoming flow parallel with the span. As all natural propulsors are flexible, it follows that this spanwise flow may be exploited to manipulate LEV growth. However, merely producing any spanwise flow is not sufficient to limit the circulation of the LEV. Beem et al. (2012) showed that a nominally two-dimensional spanwise flow from uniform profile sweep does not limit LEV growth or improve LEV stability. Rather, to produce a stable vortex the circulation produced in the leading-edge shear-layer must be somehow balanced by a vorticity sink. For spanwise flow to act as a vorticity sink, it must couple with a gradient of vorticity magnitude in order to convect vorticity along the profile span. Wong and Rival (2015) has shown that this vorticity convection is able to partially balance the circulation produced in the leading-edge shear-layer of a profile. At low Reynolds numbers, Wojcik and Buchholz (2014) further identified vorticity annihilation as a major vorticity sink, although spanwise convection becomes increasingly important at higher Reynolds numbers. Wong and Rival (2015) gives the spanwise circulation transport as:

$$\frac{\partial \Gamma}{\partial t} = -w \frac{\partial \omega_z}{\partial z} A,$$

(1)

where the mean spanwise-vorticity convection is taken over the vortex area $A$. In the case of spanwise profile bending, the spanwise flow $w$ can be estimated geometrically from the component of the local flapping velocity that is tangential to the span of the deformed profile. However, estimating the spanwise vorticity gradient $\frac{\partial \omega_z}{\partial z}$ requires the assumption that spanwise distribution of vorticity magnitude will scale with the distribution of circulation, given an approximately constant LEV area $A$.

Given this scaling relationship between vorticity magnitude and circulation, we speculate that spanwise profile bending controls LEV stability through the following mechanisms. First, a higher vorticity magnitude is anticipated in spanwise locations with a larger effective velocity or effective angle of attack. In order to accomplish this, a higher profile displacement and a higher effective velocity will be prescribed towards the tip of the profile in the experimental setup to follow. Second, a spanwise flow must be produced, through profile bending, rotation or sweep, to couple with this vorticity gradient and convect vorticity along the span of the profile. A flying animal can exploit this convection to control LEV circulation, either increasing it to produce higher instantaneous force coefficients, or reducing it in order to prolong LEV attachment.

While a passively bending profile is expected to deform away from the direction of motion, it is interesting to consider the consequences of a flyer bending their wing actively into the direction of flapping. This active bending would reverse the direction of spanwise flow, for instance to alter the circulation budget of the LEV to increase vortex strength at the cost of LEV stability. Thus, we can consider three general bending cases: ‘passive’ bending away from the direction of motion, ‘active’ bending into the direction of motion, and rigid profiles that do not bend. Herein, these cases will be referred to by the phase of the profile tip relative to the root, where bending away from the direction of flapping produces a tip-lagging phase, bending into flapping produces a tip-leading phase, and a rigid case has no phase change, respectively.

The augmentation of circulation through profile bending is illustrated for each of the two-dimensional, tip-leading, and tip-lagging cases in Fig. 1. First, in the two-dimensional case no spanwise gradients or spanwise flow is present, and a two-dimensional vortex is expected to form. Second, in the tip-leading case it is expected that vorticity magnitude grows towards the profile tip while spanwise flow is directed towards the root, resulting in a negative vorticity transport, increasing circulation and reducing LEV stability. Lastly, in the tip-lagging case, vorticity magnitude is expected to grow towards the profile tip while spanwise flow remains directed outboard, reducing circulation and increasing LEV stability. Therefore, it is hypothesized that tip-lagging kinematics directs circulation along the profile span towards the profile tip, mediating LEV growth, and thus stabilizing the vortex structure and extending force augmentation. Meanwhile, tip-leading kinematics directs circulation inboard, increasing LEV growth, and therefore increasing force generation at the cost of reducing LEV stability. In order to produce tip-leading and tip-lagging profile kinematics to test the above hypothesis, a combined pitching–flapping system was developed in order to manipulate a nominally two-dimensional profile, outlined in the following section.

2. Methods

Isolating the effects of tip-leading versus tip-lagging kinematics poses a number of experimental challenges. For instance, if passively-flexible structures are used, the possibility of animals actively deforming their propulsors can be obscured. In particular, selecting particular materials and root kinematics that produce tip-leading and tip-lagging motions constitute additional constraints, which can obfuscate the relationship between profile bending and vortex growth. As such, in this
Fig. 1. A two-dimensional plunging wing provides a reference with which to compare tip-leading and tip-lagging kinematics (grey). It is hypothesized that a tip-leading motion directs vorticity convection towards the wing root, reducing LEV stability (red). Meanwhile, a tip-lagging case is expected to direct vorticity convection away from the wing root, improving LEV stability by balancing the circulation generated at the leading-edge (blue). Here, $U_\infty$ is the free-stream velocity, while $v$ is a vertical velocity from plunging of flapping motions at points along the span 1 and 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. The angle of attack experienced at the tip of a flexible profile has a phase-leadr lag relative to the root, as well as a change in magnitude (left). The effective incidence at the root and the tip, shown in blue and red, respectively, can be recorded (centre). By carefully combining pitching and plunging motions, the same angle-of-attack history can be prescribed onto the root and tip of a rigid wing through combined pitching and flapping (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

A first-approximation to the kinematics of spanwise-flexible profiles was produced using a combined pitching and flapping motion of a rigid profile instead. Note that in this case, we are assuming negligible effects from the free ends. Previously, Bansmer and Radespiel (2012) have similarly sought to investigate combined pitching and flapping while avoiding free-end effects, using rubber segments to bridge their apparatus with wind tunnel walls. Such a method was not possible given the physical limitations of a towing tank, so here the tip gaps were merely kept as small as practicable, detailed below. This methodology is demonstrated in Fig. 2, where the history of effective angle-of-attack of a hypothetical spanwise-flexible profile is extracted at the profile root and tip, and then is subsequently applied to a rigid profile undergoing a combined pitching and flapping motion

$$\alpha_{\text{eff}} = \alpha_{\text{geo}} + \tan(\Omega R/U_\infty) ,$$

where $\alpha_{\text{geo}}$ is the pitching angle, and $\Omega R$ is the flapping velocity at the mid-span.

Herein, the kinematics of the hypothetical profile will be referred to as the modelled motion, while the pitching–flapping analog will be referred to as the physical motion. The specific modelled motion, along with the corresponding physical motion required to generate the same angle-of-attack history, is shown in Fig. 3. This pitching–flapping analogue captures the angle-of-attack history of a spanwise-flexible profile at the root and tip, and approximates the angle-of-attack gradient linearly between these two points. No twisting or deformation of the physical wing is required. Meanwhile, as spanwise flow can only be directed towards the profile tip in this arrangement, when the angle-of-attack gradient is reversed the physical profile tip will represent the modelled profile root and vice versa. The approximation of plunging with pitching in this way is imperfect. However, as the purpose of this study is to investigate the applications of various combinations of spanwise angle-of-attack gradient and spanwise flow on LEV formation, as opposed to a true model of a flexible wing, these approximations are not expected to affect the conclusions of this study. Thus, the physical pitching and flapping motion is intended to mimic the vorticity transport properties of the modelled spanwise-flexible profile, and the system allows the modelled root kinematics and profile flexibility to be adjusted independently of one another.
plunging motion, the model root kinematics are defined entirely by two dimensionless parameters: the Strouhal number $St = \frac{f h_0}{U}\text{.}$ The reduced frequency $k = \frac{f c}{\omega_{\infty}}$, where $c$ is the profile chord; and the Reynolds number $Re$. In this study, the Strouhal number was selected to match the evolutionary convergence of propulsion found in nature by Taylor et al. (2003) of $St = 0.25$. This Strouhal number range is also low enough to avoid the lift-reducing formation of an LEV dipole, reported by Cleaver et al. (2016) for Strouhal numbers of $St > 1$. Meanwhile, the Reynolds number has been shown by Garmann et al. (2013) to have only a secondary effect on LEV size and convection within the range $10^5 \leq Re \leq 10^7$, and therefore a Reynolds number of $Re = 10^5$ was selected along with enforced turbulent boundary layers. The range of reduced frequencies found in nature vary substantially even within a single species, for instance Tobalske and Dial (1996) observed that magpies fly with an approximately constant wingbeat frequency across their entire flight envelope, resulting in a range of reduced frequencies $0.1 \leq k \leq 0.5$. Furthermore, Baik et al. (2012) found that only reduced frequencies lower than approximately $k \leq 0.5$ resulted in LEV detachment before the aerofoil reached the bottom of the motion, due to the timescale of LEV development relative to profile motion. Therefore, as we are interested specifically in the timescales of LEV detachment, a reduced frequency of $k = 0.4$ was selected in order to produce a highly unsteady motion where LEV detachment was nevertheless expected.

As the modelled tip kinematics can be imposed arbitrarily, it was decided to match the flexion observed by Lucas et al. (2014), equivalent to a flexion angle of $\pm 25^\circ$ at the 60% span location. Lastly, a ‘rigid’ two-dimensional case with no physical flapping motion was included as a reference. The modelled effective incidence for each of these three cases is shown in Fig. 3, along with the corresponding physical pitching and flapping programmes of each case. The average effective angle-of-attack $\alpha_{\text{eff}}$ at the root for all three cases (black). Meanwhile, the modelled deformation resulted in a different effective incidence history at the profile tip for the tip-leading case (red) and tip lagging case (blue). (right) This effective incidence history resulted in a common pitching angle $\alpha_{\text{geo}}$ (black) for all three cases, and flapping angles $\theta$ for the tip-leading (red) and tip lagging (blue) cases as shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Given this approach, a single set of profile kinematics within the bounds of natural flight can be defined for the modelled motion, while the tip can be modelled with a phase lead or lag relative to the root independently. Prescribing a harmonic plunging motion, the model root kinematics are defined entirely by two dimensionless parameters: the Strouhal number $St = \frac{f h_0}{U}\text{.}$ where $f$ is the frequency of motion and $h_0$ is the plunging amplitude; the reduced frequency $k = \frac{f c}{\omega_{\infty}}$, where $c$ is the profile chord; and the Reynolds number $Re$. In this study, the Strouhal number was selected to match the evolutionary convergence of propulsion found in nature by Taylor et al. (2003) of $St = 0.25$. This Strouhal number range is also low enough to avoid the lift-reducing formation of an LEV dipole, reported by Cleaver et al. (2016) for Strouhal numbers of $St > 1$. Meanwhile, the Reynolds number has been shown by Garmann et al. (2013) to have only a secondary effect on LEV size and convection within the range $10^5 \leq Re \leq 10^7$, and therefore a Reynolds number of $Re = 10^5$ was selected along with enforced turbulent boundary layers. The range of reduced frequencies found in nature vary substantially even within a single species, for instance Tobalske and Dial (1996) observed that magpies fly with an approximately constant wingbeat frequency across their entire flight envelope, resulting in a range of reduced frequencies $0.1 \leq k \leq 0.5$. Furthermore, Baik et al. (2012) found that only reduced frequencies lower than approximately $k \leq 0.5$ resulted in LEV detachment before the aerofoil reached the bottom of the motion, due to the timescale of LEV development relative to profile motion. Therefore, as we are interested specifically in the timescales of LEV detachment, a reduced frequency of $k = 0.4$ was selected in order to produce a highly unsteady motion where LEV detachment was nevertheless expected.

As the modelled tip kinematics can be imposed arbitrarily, it was decided to match the flexion observed by Lucas et al. (2014), equivalent to a flexion angle of $\pm 25^\circ$ at the 60% span location. Lastly, a ‘rigid’ two-dimensional case with no physical flapping motion was included as a reference. The modelled effective incidence for each of these three cases is shown in Fig. 3, along with the corresponding physical pitching and flapping programmes of each case. The average effective angle-of-attack $\alpha_{\text{eff}}$ at the root for all three cases (black). Meanwhile, the modelled deformation resulted in a common pitching angle $\alpha_{\text{geo}}$ (black) for all three cases, and flapping angles $\theta$ for the tip-leading (red) and tip lagging (blue) cases as shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

All experiments were performed in the optical towing-tank facility at Queen’s University, which has a 15 m long test section, and a 1 m × 1 m cross-section with three-sided optical access, as shown in Fig. 4. The towing tank is enclosed by a roof along its length to minimize free-surface effects, with a 50 mm opening through which test articles can be mounted and towed. The test article chosen was a NACA0012 aerofoil with 0.3 m chord and 1 m span, which spanned from the roof to the floor in order to minimize tip effects. The effectiveness of turbulators has been shown by Lissaman (1983) to diminish towards Reynolds numbers of $10^5$, suggesting that the occurrence of laminar separation is rare after this point. However, as the efficiency of the aerofoil is not critical in this study a z-type turbulator was nevertheless included at the 20% chord position in order to fully ensure attached boundary layers prior to the pitching–flapping manoeuvre. Wall gaps at both the root and tip were kept as small as possible in order to minimize free-end effects while accommodating the profile motion. In the two-dimensional case, the tip gap was approximately 2% of chord, increasing with flapping angle to a maximum of 6% at a flap angle of 15°. The NACA0012 profile was mounted to a robotic pitching–flapping system (labelled I in Fig. 4) through the root opening in order to prescribe the motions described above. This pitching–flapping system was integrated into a rack–and–pinion traverse that provided a convective velocity of $U_{\infty} = 0.3$ m/s.

A 527 nm Photonics Industries 40 mJ per pulse Nd:YLF laser was used to illuminate the flow-field at the mid-span of the NACA0012 profile during a pitching–flapping cycle, after approximately 20-chords of steady-state travel. The flow was seeded with 100 μm hollow glass micro-spheres, which were tracked using four-dimensional Particle Tracking Velocimetry (4D-PTV), a state-of-the-art Lagrangian measurement technique described by Schanz et al. (2016). The use of 4D-PTV allows the reconstruction of the entire velocity gradient tensor and therefore every component of the vorticity transport equation, thus enabling the direct testing of the hypothesis laid out in Section 1. The 4D-PTV system was comprised of four Photron
Fig. 4. (a) A pitching–flapping mechanism (I) was use to actuate the NACA0012 profile (II) as it was towed along the 15 m-long optical towing tank (b). Pitching and flapping axes are labelled $\phi$ and $\theta$, respectively. The flow-field around the profile was illuminated from the side-wall with a high-speed laser, and was subsequently captured with a four-camera 4D-PTV setup (III), which was located below the glass floor.

SA-4 cameras operating at 1500 Hz with a resolution of 1024 $\times$ 1024 px$^2$, capturing particle tracks over a 130 $\times$ 130 $\times$ 10 mm$^3$ measurement volume, with the short-axis of the domain parallel to the profile span to capture the LEV cross-section. Utilizing two adjacent fields of view, just under one convective time of data was obtained, and measurements were repeated for ten individual runs per test case. At the mid-point of the measurement, each of the three cases had an identical angle-of-attack ($\alpha = 32^\circ$). Raw pre-processed images were also used to verify the repeatability of the motion, which had a maximum variation of 5 pixels (0.2% of chord) at the half-span location where measurements were conducted. These pre-processed images were also used to determine the geometric angle of attack and flapping velocity in order to estimate the error in the motion reproduction. The RMS error observed in geometric angle of attack across all cases and all runs was $\Delta \alpha = 0.2^\circ$. Meanwhile, the deviation in the flapping velocity resulted in an RMS error in effective incidence of $\Delta \alpha_{\text{eff}} = 0.4^\circ$. Processing of the 4D-PTV data was accomplished with LaVision Davis 8.3.0 software.

3. Results

Fig. 5 shows the evolution of the flow-field captured for an individual run of each of the three test-cases considered, with the final snapshot corresponding to the maximum geometric angle of attack. Tracked particles of high rotation have been coloured by gamma criterion to highlight the LEVs formed, as defined by Graftieaux et al. (2001), and low-rotation particles have been removed for clarity. At this point in the motion, streamwise position of the vortex does not vary significantly between the three cases as the vortex detachment process has not yet started. However, at this point it can already be observed that the tip-lagging case (blue), which replicates the passive bending kinematics found in nature, has a much more compact and less coherent vortex structure, closer to the surface of the profile than the tip-leading case (red) or the two-dimensional case (grey). In turn, the LEV in the tip-leading case has a larger cross-sectional area than the two-dimensional case. These observations are already intuitively in agreement with the hypothesis laid out in Section 1 that the tip-leading case would exhibit a stronger, larger vortex while the tip-lagging case would have a weaker, more compact vortex. These hypothesis are further supported in the time-resolved, quantitative measurements. Circulation histories are shown in Fig. 6, where the circulation value presented is the ensemble average of ten runs per case. Along with its smaller vortex size shown previously, the tip-lagging case (blue) has a smaller circulation, and a lower rate of circulation growth relative to the tip-leading (red) and two-dimensional (grey) cases. The tip-leading case has a larger circulation and a higher circulation growth rate than the two-dimensional case, but does not deviate as far from the two-dimensional case as that of the tip-lagging case.

Spanwise vorticity convection is shown in Fig. 7(a), next to spanwise vortex stretching in Fig. 7(b). Vorticity transport in the two-dimensional case will not be discussed here, as it is nearly zero for the entire measurement duration. However, values are nevertheless presented in Fig. 7 as an indicator of the run-to-run variation present in the current experiments. For each of these two parameters, the spatial average was taken across the vortex area as defined by a gamma criterion of $\gamma = 0.64$, and once again the ensemble average from ten runs is presented here. Based on Eq. (1), the large negative vorticity convection seen in the tip-leading case should serve to increase the circulation at this spanwise location, explaining its higher circulation relative to the two-dimensional case. Meanwhile, the tip-lagging case exhibits a positive vorticity convection, matching its correspondingly reduced circulation relative to the two-dimensional case. Vortex stretching meanwhile is non-negligible and positive in both cases. The spanwise flow set up due to rotation is similar in magnitude for both flexible cases, however the tip-lagging case has a lower centre line vorticity. Nevertheless, it does not appear that vortex stretching can be used to differentiate the tip-leading and tip-lagging cases, as it is the same sign for both flexible cases.
Fig. 5. Three snapshots centred about $s/c = 1.5$ of highly-rotational tracked particles are highlighted here with the gamma criterion for the tip-leading case (red, left), two-dimensional reference case (grey, centre), and tip-lagging case (blue, right), respectively. All low-vorticity particles are removed for clarity. The tip-lagging case, similar to kinematics found in nature, exhibits a compact LEV closer to the profile surface than either of the other cases. As a faster-growing LEV is likely to reach the limiting $1c$ length-scale earlier, this indicates that it will not remain attached for as long into the motion. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 6. Vortex circulation is highest for the tip-leading case, and lowest for the tip-lagging case, similar to the results seen for the cross-sectional vortex area.

4. Discussion

In Section 1 it was hypothesized that spanwise profile flexibility could be used to control LEV circulation, and thereby also LEV stability. For both flexible cases studied here, the spanwise flow produced by spanwise profile bending was able to convect circulation along the span and thus manipulate LEV circulation. This circulation control would allow the tip-leading case to increase instantaneous lift production, as needed for manoeuvres. However, this increase in circulation is likely to reduce LEV stability such that a manoeuvring animal would only be able to exploit this lift over a shorter period of time. This reduced vortex stability is directly related to the relative growth rate of the vortex; based on the topological detachment criteria laid out by Rival et al. (2014), a faster-growing LEV would detach earlier in its growth as it would quickly reach a limiting length-scale on the order of one chord-length. Moreover, Wong and Rival (2015) found that this specific mechanism of LEV detachment resulted in a correlation between spanwise vorticity convection and relative LEV stability. This argumentation is of course in line with the observation of increased vortex size in the tip-leading case, and decreased vortex size in the tip-lagging case, respectively.
Fig. 7. Vorticity convection is large and negative for tip-leading kinematics. Meanwhile, vortex stretching has the same sign for both tip-leading and tip-lagging kinematics. Therefore, as the flexible cases differ from the two-dimensional case in opposite ways, the two cases cannot be differentiated through vortex stretching.

Due to the use of spanwise profile bending as a method of flow control, it is unlikely that an evolutionary convergence similar to that observed by Lucas et al. (2014) in cruising flight would also be observed in manoeuvring flight, as rapid force generation may be valued higher than efficiency. By analogy, in jet-like propulsion, Dabiri (2009) noted that squid maximized impulse instead of efficiency during escape manoeuvres since survival was prioritized above all else, and therefore the squid deviated from the more universal behaviour seen in cruise. Additionally, Cleaver et al. (2016) only observed large differences in force histories between rigid and flexible profiles for much larger Strouhal numbers than those investigated here. Indeed, Cleaver et al. (2016) observed much less profile deflection at the Strouhal numbers we investigate, implying the above results may only be achieved by an animal actively bending its wing. However, the current study nevertheless echoes the general conclusion of Lucas et al. (2014) that spanwise bending is not determined by wing material or physical structure, but rather by constraints on aerodynamic performance.

5. Conclusions

The first conclusion of this study is that spanwise profile bending can indeed be used to control LEV growth and stability. This conclusion comes from the observation that tip-lagging kinematics, like the passive bending found in the natural world, produced a more compact LEV with reduced circulation relative to the two-dimensional reference case. Meanwhile, tip-leading kinematics produced a much stronger LEV relative to the two-dimensional case.

The second conclusion is that the differences in vortex strength could not be attributed to vortex stretching, as both the tip-leading and tip-lagging cases had positive vortex stretching, while the resulting circulation and vortex sizes differed from two-dimensional case each in an opposite sense. Rather, we conclude instead that flexibility modulates the circulation transport along the span of a profile following Eq. (1). These conclusions together explain one role that spanwise profile bending plays in natural swimming and flying.

Acknowledgement

The authors gratefully acknowledge the support of the US Air Force Office of Scientific Research under grant number FA9550-13-1-0117, monitored by Dr. Douglas Smith.

References


