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On the dynamics of perching manoeuvres with low-aspect-ratio planforms

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Abstract
The dynamics of a simple perching manoeuvre are investigated using circular and aspect-ratio-two elliptical flat plates, as abstractions of low-aspect-ratio planforms observed in highly-maneuuvrable birds. The perching kinematic investigated in this study involves a pitch-up motion from an angle of attack of 0° to 90°, while simultaneously decelerating. This motion is defined by the shape change number, Ξ, which acts as a measure of the relative contributions of added-mass and circulatory effects. This motion has been observed in natural flyers during controlled landings, and has recently been explored through the use of a nominally two-dimensional airfoil. The parameter space of low-aspect-ratio plates therefore serves to elucidate how realistic free-end conditions affect the timescales of vortex evolution, and therefore the relative contributions between added mass and circulation. The results presented herein suggest that for the low-aspect-ratio plates, the shedding of vortices occurs more rapidly than for equivalent two-dimensional cases, and therefore faster pitching motions are required to compensate for the lower levels of lift and drag. Furthermore, the vortex topology and instantaneous forces that arise during the rapid-area changes show no sensitivity to aspect ratio, and strong collapse is observed between both flat plates. Similar aerodynamic advantages may therefore be exploited during perching manoeuvres by birds of various scale regardless of wing aspect ratio.

1. Introduction

Natural flyers are well-known for their ability to maintain high levels of control while performing complex manoeuvres [1, 2]. In particular, a broad range of birds have been shown to exhibit incredible control during flapping and bounding flight, and during unsteady perching manoeuvres [3, 4]. The abstraction and investigation of such manoeuvres has the potential to inform the implementation of more efficient and precise control strategies in engineered flying vehicles [5, 6]. Perching manoeuvres are particularly interesting in this regard, as they involve the exploitation of simultaneous added-mass effects (due to the rapid area change of wings coupled with the resulting deceleration of the body) and effects due to flow separation. The interplay between the competing added-mass effects has been explored in recent years using nominally two-dimensional test cases; however, the more realistic influence of three-dimensional vortical structures on instantaneous lift and drag forces has not been considered.

Although the exact perching kinematics employed by birds generally vary from species to species, one common motion involves wing pitches from a near-horizontal to near-vertical position, which has been observed of the steppe eagle during perches [7]. This motion is visualized in figure 1 from a front view and side view (for a cross-sectional slice at the approximate midspan) at three points during the motion.

To investigate the role of added-mass forces associated with such a manoeuvre, Polet et al (2015) [8] studied a nominally two-dimensional airfoil pitching from an angle of attack of α = 0° to 90° while simultaneously decelerating. The pitching motion was defined by the shape change number, Ξ, which relates the rate of frontal area increase to the deceleration. Weymouth and Triantafyllou (2013) [9] showed Ξ to be the governing dimensionless group in relating the acceleration imparted to the body and the speed of the shape change. Several shape change numbers were considered by Polet et al [8]. It was shown that at the highest shape change numbers (Ξ = 0.25 and 0.5) added-mass energy transfer between the surrounding fluid and
airfoil plays a primary role in the augmentation of lift and drag forces, both of which are necessary for controlled perching manoeuvres. These forces were attributed to energy lost due to flow separation, and added-mass energy transfer between the fluid and airfoil during the motion. Although more realistic free-end conditions were not considered by Polet et al. [8], it is reasonable to assume that the total lift and drag forces will be sensitive to the spanwise extent of the wing.

In the current study, we endeavour to gain an understanding of the three-dimensional effects that may be expected during rapid-area-change problems, and in particular, how the shape change number (as a metric for the interplay between added-mass and circulatory contributions) is affected by the timescales of vortex formation when realistic end conditions are considered. To this end, circular and aspect-ratio-two elliptical flat plates are investigated as abstractions of wing planforms observed in nature. Similar flat-plate abstractions are frequently made in the study of biological propulsion [10–13]. Since at the onset of the rapid-area change the flow will immediately separate along the edges of the body, the salient features of the flow can be assumed to be preserved, despite the geometric simplification. The two flat-plate geometries were selected to determine the sensitivity of the added-mass and circulatory forces to planform shape. Convergence of general planform aspect ratio (AR) of natural propulsors used during drag-based swimming towards a narrow range of values has previously been documented [14]; however, no such clear convergence has been observed in the wing aspect ratios of birds with high manoeuvrability, beyond the general trend towards aspect ratios less than five [15]. This apparent lack of collapse is also explored in this work through the investigation of two planform shapes with varying aspect ratios. Although the relevance of the shape change numbers investigated by Polet et al. [8] to birds of varying scale is unclear, a follow-up study looking at chickadees concluded that the shape change number can be finely tuned to meet the energetic requirements of perching manoeuvres [16]. However, as the shape change number increases, so do the structural demands required to perform the manoeuvre. Therefore, faster motions are likely to be coopted by a bird while perching only if there are significant aerodynamic advantages. As such, a broad shape-change-number parameter space is investigated in this study at a constant Reynolds number of Re = 50,000 (based on the initial velocity and body length scale), which is representative of a broad range of bird species that exhibit high levels of manoeuvrability [17].

The remainder of this manuscript is presented as follows. In section 2, a description of the motion prescribed in this study is detailed, along with discussions of the added-mass and circulatory forces expected in this study. Specifications for the flat-plate geometries, the test facility, and the force and velocimetry measurements are provided in section 3. The instantaneous lift and drag force data are then presented and discussed in sections 4 and 5, along with the vorticity-field data derived from the velocimetry measurements. Finally, the main findings from this study are summarized in section 6.

2. Background

2.1. Added-mass forces during rapid area change

A brief discussion of the expected added-mass effects is provided for readers not familiar with the subject. When an acceleration is imposed on a fluid via the motion of a body through it, additional forces will act on the body. These forces arise from the necessary work done to change the kinetic energy of the fluid in response to the energy added as the body accelerates [18]. For the case of a steadily-translating body the kinetic energy will remain constant. However, if the body accelerates, the kinetic energy will increase, and additional work must therefore be done on the fluid to increase its kinetic energy as well. This additional work can be expressed in terms of the rate of change of kinetic energy, which

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Figure 1. Perching kinematic observed of steppe eagles involving pitches from near-horizontal to near-vertical positions. Shown from a front view (left) and side view (right).
can be formulated as the product of the time rate-of-change of velocity (i.e. the acceleration) and the mass of the fluid being accelerated with the body, known as the ‘added mass’ [18]. The added-mass force, which exerts additional drag on a body, can be expressed in terms of the following two-part decomposition:

\[
F_{\text{lag}} = \frac{\partial}{\partial t}(m_a U) = \frac{\partial m_a}{\partial t} U + m_a \frac{\partial U}{\partial t},
\]

where \( m_a \) is the instantaneous added mass. The first term represents the rate of change of added mass, and the second represents the acceleration of the added mass. In other words, a body that expands in time while traveling at a non-zero velocity will experience a drag force (separate from the quasi-steady drag force arising from the instantaneous shape and velocity of the body), in much the same way as a body with unchanging shape will experience an increase in drag if accelerated. Note, however, that if the body decelerates \(-\partial U/\partial t\), then added-mass energy is instead recovered in the form of thrust. Therefore, by rotating a body and decelerating it at the same time, added-mass forces resulting from the rate of change of added mass and the deceleration simultaneously act on the body.

2.2. Circulatory effects during rapid area change

Von Karman and Sears (1938) [19] demonstrated that the circulatory forces on an airfoil can be modeled through the superposition of equal-strength counter-rotating vortices. In particular, the circulatory force can be expressed as:

\[
F_{\text{circ.}} = \rho \left[ \frac{d\Gamma}{dr} + \Gamma \frac{dr}{dr} \right],
\]

where \( \Gamma \) is the vortex circulation, and \( r \) is the relative spacing between the two vortices. Therefore, the circulatory forces can be altered through vortex growth \( (d\Gamma/dr) \), and the convection of the vortices relative to one another \( (dr/dr) \).

The pitching motion undertaken by Polet et al [8] is visualized in figure 2(a) for the airfoil at the beginning \( (\alpha = 0^\circ) \), middle \( (\alpha = 45^\circ) \), and end \( (\alpha = 90^\circ) \) of the manoeuvre. As the airfoil begins to rotate and decelerate, the flow separates at the edges resulting in the formation of a (nominally two-dimensional) leading-edge vortex (LEV) and trailing-edge vortex (TEV), shown at \( \alpha = 45^\circ \) in figure 2(a). For extremely fast manoeuvres, the flow will not have time to convect significantly, and the second term in \( 2 \) will be negligible. Similarly, for slow motions, or in cases where the TEV is quickly destabilized, the average circulation value will tend to zero, and the second term is once again negligible. Consider the aspect-ratio-two-elliptical flat plate now, shown in figure 2(b) at \( \alpha = 45^\circ \). Vorticity is produced at the plate boundaries, and the LEV and TEV are continuously connected by two tip vortices (TV) that form along the sides of the plate. In this case, the curved leading edge encourages spanwise transport of vorticity towards the tip vortices [20]. Fernando and Rival (2016) [12] showed that for low-aspect-ratio flat plates (with aspect ratios other than one), vortex destabilization occurs over short timescales due to non-uniform induced velocities that distort the vortex at the onset of growth. Therefore, when three-dimensional effects are considered, larger vortex convection and destabilization are to be expected. As such, higher values of \( \Xi \) may be required to achieve the same levels of peak lift and drag as the nominally two-dimensional case.

2.3. Shape change number and prescribed motion

As previously mentioned, the motion considered in this study involved the deceleration of flat-plate geometries from a steady translation velocity, \( U_0 \), to rest, while simultaneously rotating from an angle of attack of \( 0^\circ \) to \( 90^\circ \) over the same time interval. The time interval is non-dimensionalized using the definition:

\[
t' = \frac{t U_0}{L},
\]

where \( t \) is the physical time of the motion, and \( L \) is the body length scale. The normalized motion is illustrated in figure 3(a), which shows the inline deceleration and angular position of the plate as a function of normalized time. Note that both components of the motion take place over the same normalized time period. Figure 3(b) shows a schematic representation of the information provided in figure 3(a) for one of the flat plates. The normalized representation of the kinematics provided in these figures is applicable to all of the motions undertaken in this study, which were defined using the
shape change number, $\Xi$. This dimensionless parameter can be expressed as:

$$\Xi = \frac{V}{U_0},$$

where $V$ is the velocity of the rotation, and $U_0$ is the translational speed of the body when the deceleration begins. The shape change number can be viewed as a measure of the relative importance of the added-mass and circulatory effects. For an infinitely fast rotation, the added-mass effects will dominate the forces, while for an infinitely slow acceleration, the forces will primarily be due to the quasi-steady separation (circulatory) effects. Four shape change numbers were investigated: $\Xi = 0.25, 0.5, 1,$ and $2$ (from slowest to fastest). These numbers are therefore representative of values where both added-mass and circulatory effects are expected to play an important role. Interestingly, studies have begun to show that these range of values have biological relevance; shape change numbers of around $\Xi = 0.5$ have been observed during perching manoeuvres employed by small black-capped chickadees [16], for instance.

By definition, the motion for each shape change number will take place over a different physical time. In fact, by combining equations (3) and (4) it can be shown that $\tau^* = 1/\Xi$, such that the motions (from slowest to fastest) occur over $\tau^*$ values of 4, 2, 1, and 0.5. These dimensionless times are then normalized a second time, to collapse the four motions to the single normalized kinematic shown in figure 3, which occurs over $\Delta \tau^* = 1$.

3. Experimental methods

An optical towing tank at Queen’s University was used to perform the experiments. The towing tank has a cross-section of $1m \times 1m$ and an overall length of $15m$. Since the water in the tank is initially quiescent, the tank is free of boundary-layer development along the side-walls, and model blockage effects are minimized. To prevent free-surface effects (sloshing), a fibreglass roof is located along the entire length of the towing tank. Three-sided optical access facilitates the acquisition of velocimetry measurements.

The geometric characteristics of the two plates investigated in this study are provided in table 1. In order to appropriately scale the two plates —since aspect ratio alone is not sufficient to fully define the geometries—the hydraulic diameter, $D_h$, was used to constrain the free parameter. The hydraulic diameter is defined as a scaled ratio of planform area to perimeter ($D_h = 4A/P$), and has previously been shown to be the relevant length scale in highly unsteady, separated flows [12]. Included in table 1 is the nomenclature for each plate used throughout the remainder of the manuscript, the plate height ($a$), width ($b$), thickness ($t$), aspect ratio, area, and percent blockage relative to the tank cross-section.

3.1. Pitching actuation

The desired pitching motions were achieved with a stepper motor that was mounted on a platform situated above the fibreglass roof, and rigidly attached to the main sting support. The rotational motion of the stepper motor was transmitted to the plates via a series of couplings and sprockets, and a chain. Figure 4(a) shows a schematic view of the lower portion of the assembly. A horizontal sting $2D_h$ in length was used to connect the main vertical sting to a streamlined body (known as a ‘yoke’), which houses a sprocket and chain and smoothly adapts the circular cross-sectional profile of the horizontal sting. The chain is not shown in the rendering; instead, an annotation has been included to indicate the relative angle of the chain toward the sprockets mounted on the upper platform. A flanged adapter is rigidly attached to the sprocket, on which a submersible force sensor is attached (the specifications of which are provided in the following section). Also included in the schematic is the aspect-ratio-two elliptical flat plate, shown at the starting position of the motion ($\alpha = 0^\circ$). Figure 4(b) contains a schematic
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of the upper portion of the assembly. The uppermost sprocket is mounted colinear with the stepper motor, and an intermediate sprocket assembly functions as an idler to tension the chain.

The stepper motor used in this study (PK296–03AA from Orientalmotor) has a resolution of $0.9^\circ/$step and radial accuracy of $\pm 0.05^\circ$. The motor is controlled by a VXM–1 Velmex motor controller, which interfaces to a computer through COSMOS utility software and is used to specify the speed of the motor. The pitching motions were initiated in a repeatable manner by syncing the motor controller with an output voltage signal from the traverse. At the desired position along the motion, the motor was triggered via a low-high-low voltage transition. To accurately reset the flat plates to an angle of attack of $0^\circ$ between each run, a high-precision mechanical stop was machined, which provided a run-to-run angular accuracy of $\pm 0.01^\circ$. The plates were secured at $\alpha = 90^\circ$ at the end of the motions using a spring plunger, which slotted into a high-precision hole that was machined into a circular disk. These components are illustrated in figure 4(b).

Table 1. Relevant nomenclature and geometric characteristics of the flat plates. The aspect ratios of the plates are varied, while maintaining a constant hydraulic diameter.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Aspect ratio</th>
<th>$D_h$ (m)</th>
<th>$a$ (m)</th>
<th>$b$ (m)</th>
<th>$t$ (mm)</th>
<th>Area ($m^2$)</th>
<th>Blockage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1</td>
<td>0.3</td>
<td>0.300</td>
<td>0.300</td>
<td>3</td>
<td>0.0707</td>
<td>7.07</td>
</tr>
<tr>
<td>E</td>
<td>2</td>
<td>0.3</td>
<td>0.474</td>
<td>0.237</td>
<td>3</td>
<td>0.0884</td>
<td>8.84</td>
</tr>
</tbody>
</table>

Figure 4. (a) Schematic of the lower assembly depicting the streamlined body that houses the sprocket and chain used to facilitate the pitching motion. A submersible force sensor is mounted to a flanged adapter that is rigidly attached to the sprocket. (b) Schematic of the upper assembly indicating the location of the stepper motor and the two additional sprockets used to guide the chain mechanism.

3.2. Force and PIV measurements

A six-component, submersible ATI Nano force transducer was mounted to the flat plates to record instantaneous force data, as depicted in figure 4(a) for the elliptical plate. The transducer was attached to the geometric center of each plate to minimize interference effects from the yoke on vortex formation at the plate edges. The transducer has a static resolution of 0.125 N and was operated at a sampling rate of 1000 Hz. All data sets were averaged over 20 runs. In addition, all experiments were repeated with the water emptied from the tank to measure the non-hydrodynamic inertia of the system, which was later found to be negligible. The measured data was transformed from a plate-fixed to lab-fixed frame of reference to extract the instantaneous lift and drag forces. The constant Reynolds number of $Re = 50,000$ was calculated using the initial translational velocity, $U_0$, and the hydraulic diameter.

Time-resolved planar particle image velocimetry (PIV) was used to measure vortex growth during the pitching manoeuvre. A right-hand coordinate system was adopted such that the $x$-, $y$-, and $z$-axes are oriented in the streamwise, wall-normal, and spanwise directions, respectively. PIV measurements were conducted for the cases $\Xi = 0.25$ and 2, for which the largest differences were observed in the instantaneous lift and drag forces. The constant Reynolds number of $Re = 50,000$ was calculated using the initial translational velocity, $U_0$, and the hydraulic diameter.

The flow field was captured using a Phoptron SA4 high-speed camera, which has a resolution of $1024 \times 1024$ pixels, and was operated at a frame rate
200 Hz. A 40 mJ pulse$^{-1}$ Photonics high-speed laser was used to create a laser sheet approximately 1.5 mm thick. The field of view (FoV) used for all measurements was approximately $1.7D_h \times 1.7D_h$ in size and was situated at the horizontal midspan of the plates (i.e. in the $xy$-plane), as shown in figure 5. The circular plate is depicted here during the pitching manoeuvre. The towing motions were repeated and recorded 20 times for each FoV, to produce the phase-averaged vorticity fields presented in section 4. The PIV uncertainty in non-dimensional vorticity is estimated as $\delta \omega^* = \pm 0.3$ based on error-propagation estimates from Raffel et al [21]. Since the laser was situated below the tank, a region behind the plates was obstructed during the motions, as depicted in figure 5. However, the primary features of the wake are cleanly imaged as the plate completes the pitching motion.

To determine the effect of the chain on the force production, measurements were conducted with the chain assembly enforcing a fixed angle of $\alpha = 90^\circ$. These measurements were compared to existing data obtained using a rigid (not rotating) version of the sting assembly shown in figure 4(a) [13]. During the periods of acceleration and deceleration, where the interplay between the added-mass and circulatory effects is of relevance to the current study, less than 1% error was calculated in the force histories between the ‘baseline’ cases, and those with the chain in place. The chain was therefore shown to have minimal influence on the vortex dynamics.

4. Results

In the following section, PIV data is first presented for the highest and lowest shape change numbers to understand the development of the vorticity field during the fastest and slowest manoeuvres, respectively. The vorticity field for the highest shape change number is found to show topological similarities to existing data for a two-dimensional case at comparatively lower shape change numbers. The instantaneous lift and drag forces measured in this study are then compared to data for the peak forces from the two-dimensional case.

4.1. Vorticity-field results

The vorticity fields derived from the measured velocity data are presented in figures 6 and 7 for the highest and lowest shape change numbers, respectively. In each sequence, timesteps of $t^* = 0.5$ and 1 are shown, which represent the middle and end of the manoeuvre. The large grey-shaded areas in the first timestep of each subplot represent the region of the field of view that was obstructed from laser light. Vorticity is normalized by $\omega^* = \omega D_h/U_c$.

The vorticity fields for the circular flat plate at $\Xi = 2$ are shown in figure 6(a). At the first timestep, positive boundary-layer vorticity has shed from the plate and rolled up into a strong leading-edge vortex (LEV) and trailing-edge vortex (TEV). As the plate approaches the end of the manoeuvre, the TEV convects away from the plate, and when the plate comes to rest, two stopping vortices with negative vorticity form at the leading and trailing edges. At the end of the manoeuvre, the TEV has convected a distance of approximately $0.8D_h$ from the plate, as annotated in the figure. Polet et al [8] observed identical levels of TEV convection at $\Xi = 0.5$ for the nominally two-dimensional case, suggesting that the development of the wake behind
planforms with realistic free-end conditions occurs more rapidly. In addition, contrary to the expected topology shown in figure 2(b), the LEV forms on the front side of the plate, due to plate velocities that largely exceed the oncoming flow velocities. This LEV topology will produce a plate-normal force on the front surface, and instantaneous thrust and downforce will be exerted on the plate, which can be expected to lower the magnitude of the force peaks. Therefore, the circulatory forces may be lower than expected in the current study for higher values of $\Xi$. Nearly identical topological development is observed for the aspect-ratio-two elliptical plate, shown in figure 6(b).

At the lower shape change number ($\Xi = 0.25$), the development of the vorticity fields is topologically more similar to the prediction in figure 2(b), and those observed by Polet et al [8]. For the circular plate, shown in figure 7(a), at $t^* = 0.5$ vorticity is continuously fed into the wake at the trailing edge. Due to the smaller plate velocities with decreasing $\Xi$, and comparatively larger oncoming flow velocities, the LEV forms on the back side of the plate rather than the front side, and is obstructed in the first timestep. The relatively weak LEV that forms is visible in the second timestep. LEV formation on the back side of the plate will produce a positive contribution to both the lift and drag forces. The vorticity shed at the trailing edge is weak and diffuse since the deceleration occurs gradually, and both the plate and flow velocities are small near the end of the motion. Very similar topology is observed for the aspect-ratio-two plate in figure 7(b).

4.2. Instantaneous and time-averaged lift and drag forces during perching manoeuvre

Based on the measured similarities in the vorticity fields between the two flat plates, it is reasonable to expect a similar collapse in the plate forces, relative to one another, as well. The instantaneous lift and drag data for all four shape change numbers are plotted in figure 8 as the lift and drag coefficients against normalized time. The data is shown for the circular plate at all shape change numbers in figure 8(a). The peak lift and drag forces have a low magnitude for the smallest shape change numbers ($\Xi = 0.25$ and 0.5), as expected, due to the gradual rate-of-change of added mass. The larger added-mass forces produced with increasing shape change number are manifested in the larger peaks for $\Xi = 1$ and 2. For the highest shape change number, negative lift and drag values are measured late in the manoeuvre, between $t^* \approx 0.6$. These force troughs are caused by the recovery of added mass near the end of the manoeuvre through $\frac{d}{dt} m_a$, and are more pronounced in the drag history because near the end of the motion the plate approaches a ‘pure-drag’ orientation. Instantaneous lift and drag data measured by Polet et al [8] for the nominally two-dimensional wing at $\Xi = 0.25$ have also been superimposed on figure 8(a) as the dashed black line. Direct comparison of the forces between both $\Xi = 0.25$ cases reveals significantly lower lift and drag forces in the current study, which suggests that the circulatory forces may not be as large, as proposed in section 2.3.
Furthermore, the peak forces for $\Xi = 2$ are likely lower than expected due to the LEV formation on the front side of the plate, which is detrimental to lift- and drag-force augmentation. The forces are essentially identical for the elliptical flat plate (both lift and drag), as shown in figure 8(b).

The net forces produced during a pitching cycle ultimately determine the efficacy of the perching manoeuvre, i.e. sufficient levels of (net) lift and drag are required to overcome body weight and reduce speed in a controlled manner. The time-averaged lift and drag forces over one pitching cycle are provided in figures 9(a) and (b), respectively, as the time-averaged force coefficients plotted against the shape-change number. As expected from figure 8, the time averages for both the circular plate (hollow orange circles) and aspect-ratio-two elliptical plate (hollow blue circles) show strong collapse. The time-averaged drag coefficient grows monotonically only until $\Xi = 1$—see figure 9(b)—due to the recovered added-mass energy in the form of thrust late in the manoeuvre for high shape-change numbers. The time-averaged coefficients reported by Polet et al [8] for $\Xi = 0.25$ have also been superimposed on both figures as hollow black circles. Direct comparison of the time-averages between Polet et al [8] and the current study provides additional support of the disparity (i.e. reduction) in overall forces at equivalent $\Xi$ values when realistic free-end conditions are considered.

The vorticity-field and force results suggest that the vortex dynamics observed in the current study occur over faster timescales than the two-dimensional case at equivalent $\Xi$ values. Furthermore, no variation is observed between the circular and aspect-ratio-two elliptical flat plate, suggesting that the results are insensitive to moderate changes in aspect ratio/leading-edge curvature. This claim is examined more rigorously in the following section.

5. Discussion

The collapse between the vortex topology and instantaneous force histories for the circular and aspect-ratio-two plates is indeed surprising, in light of previous work that has shown disparate vortex evolution between planforms with circular and elliptical leading edges [12, 20]. As such, an additional pitching program was undertaken with the current experimental apparatus, to gain further insight into the sensitivity of instantaneous force production.
to planform aspect ratio. The additional motion involved pitching manoeuvres from 0° to 90° over \( t^* \) values of 0.5, 1, 2, and 4 while traveling at a constant speed. The purpose of this motion was to determine whether aspect ratio has a more dominant impact on the instantaneous plate forces when large levels of shear-layer feeding (and therefore stronger circulatory effects) are maintained throughout the entire pitching motion. Lift and drag force histories for this case are shown in figures 10(a) and (b), respectively. The force histories are plotted against the dimensionless time periods over which the motions occur, rather than using the additional normalization to collapse each motion to a range of \( t^* \). The lift and drag data for the circular and aspect-ratio-two elliptical flat plate are plotted side-by-side in each subfigure to aid with visual comparisons. The lift histories in figure 10(a) show nearly indiscernible trends between the two geometries once again. The lift is a maximum mid-way through manoeuvres, and then decays to zero near the final position at 90°. Since during the constant velocity pitches there is no force reduction due to the deceleration of added-mass \((-m_a\dot{u}/\dot{m})\), the lift and drag peaks are higher than during the deceleration cases. The drag forces, shown in figure 10(b), remain particular high during the pitch as the plate-normal added-mass forces resulting from \( \partial m_a/\partial t \) are tilted towards a pure-drag orientation near the end of the motion. The drag data shows strongly collapsed trends in peak magnitudes once again between the two plates.

The vorticity fields for the constant velocity cases exhibit qualitatively similar trends relative to the deceleration cases, and (as expected based on the forces) the flow-field development is nearly identical between the two geometries. The vorticity fields are shown in figure 11 for a pitching rate that takes place over \( t^* = 0.5 \), which exemplifies the topological collapse. This case is analogous to a shape change number of \( \Xi = 2 \). At the middle of the pitch, shown in figure 11(a) for the circular plate, positive vorticity rolls up into the LEV and TEV. Once the plate reaches 90°, the TEV has convected a larger distance downstream than for the equivalent deceleration case, due to larger convective velocities, since the plate is traveling at a constant speed. The same timesteps during the motion are shown in figure 11(b) for the aspect-ratio-two elliptical plate.

Despite the clear similarities between the circular and aspect-ratio-two elliptical plates for the two pitching programs, previous studies have shown that the two geometries exhibit dissimilar vortex evolution timescales and instantaneous forces when the plates are rectilinearly accelerated from rest at a fixed angle of attack of 90° [12, 13]. Fernando and Rival (2016) [13] investigated this motion for a single acceleration value and demonstrated vortex evolution timescales that were nearly five times longer for the circular plate relative to the aspect-ratio-two elliptical plate. The much longer growth timescales are due to the formation of an axisymmetric vortex ring that develops behind the circular plate at 90° and remains stable as it continues to grow uniformly in the wake. At 90° the aspect-ratio-two elliptical plate produces elliptical vortex rings in the wake that are inherently unstable due to curvature that changes locally along the entire perimeter of the vortex. The curvature induces non-uniform velocities...
along the vortex ring, which act to deform and destabilize the vortex [22].

The rectilinear motion described above involving accelerations from rest \((U_0 = 0)\) was conducted with the current experimental apparatus over \(r^*\) values of 0.5, 1, 2, and 4 at constant plate angles of 90°. The results for the circular plate are shown on the left in figure 12 for each of the \(r^*\) values. The initial force peaks are attributed to the acceleration of fluid around the plate, which is impulsively started from rest in each case. The steady-state drag of the plate is achieved by approximately \(t^* = 24\), which represents the time required for the stable vortex ring that forms in the wake to detach from the plate and completely break down. This evolution period is insensitive to the initial acceleration period, and the steady-state plate drag is achieved at the same dimensionless time in all cases. The results for the aspect-ratio-two elliptical flat plate illustrate the much shorter evolution timescales, regardless of the length of the acceleration period. For this motion, Fernando and Rival (2016) [12] observed a strong collapse in evolution timescales between elliptical flat plates with aspect ratios of two, three, and four. The steady plate drag of the aspect-ratio-two elliptical plate is achieved by approximately \(t^* = 6\). Note that the approach to this steady-state value occurs in almost an identical fashion for the pitches while at constant velocity, shown in figure 10(b). This suggests that in both cases, the vortex structures that form have short evolution timescales, and shed from the plate soon after the angular and in-line accelerations are over.

The results for the rectilinear acceleration and the pitching experiments suggest that the circular flat plate only produces stable vortex rings when towed at 90°. When the plate is perturbed from this stable angular configuration, the velocities induced locally by segments of the vortex ring on neighbouring elements are strong enough that the vortex ring destabilizes and sheds sooner. Although the non-uniform induced velocities may be negligible for shallow angular perturbations, at angles of attack representative of bird flight the deviations will be large enough to destabilize the vortex ring quickly, which explains the insensitivity of the vortex dynamics and instantaneous forces to aspect ratio for the biologically-relevant kinematic investigated in this study.

6. Conclusions

In this study, the dynamics of simple perching manoeuvres were investigated using circular and elliptical flat plates, as abstractions of the low-aspect-ratio wings observed in highly-maneovrable natural flyers. The primary motion considered here consisted of a pitching motion from an angle of attack of 0° to 90°, thereby increasing the frontal area of the plate, while simultaneously decelerating. The motion was defined by the shape change number, \(\Xi\), which relates the rate of frontal area increase to the in-line deceleration. The shape change number therefore represents a measure of the relative significance of the added-mass forces relative to the circulatory forces. Shape change numbers \(\Xi = 0.25, 0.5, 1, 2\) were investigated in this study. Shape change numbers past \(\Xi = 2\) represent extremely fast motions, which would likely subject the muscles and skeletal structure of the birds to large strain. Similarly, shape change numbers much slower than \(\Xi = 0.5\) represent very gradual motions that would not produce any significant aerodynamic advantage during perches.

The pitching motion investigated in this work has previously been studied using a nominally two-dimensional airfoil. The results presented in this study suggest that when realistic free-end effects are considered, the relative circulatory contribution for equivalent shape change numbers is less. This is due to rapid vortex destabilization that results in short evolution timescales. As such, the peak lift and drag forces at \(\Xi = 2\) are similar in magnitude to the peaks observed for the nominally two-dimensional airfoil at a lower value of \(\Xi = 0.5\).

For rectilinear motions, it has previously been shown that the vortex dynamics associated with circular and aspect-ratio-two flat plates occur over significantly different timescales [12]. In contrast, it can be concluded from this work that during dynamic pitching motions, the timescales of vortex evolution are insensitive to general planform shape. This is the case not only for pitches.
while simultaneously decelerating to rest, but also during pitches when at constant velocity, with stronger levels of shear-layer feeding throughout the entire pitching motion.

The results summarized above have interesting biological implications. Since the peak and time-averaged lift and drag forces measured in this study are lower than the equivalent nominally two-dimensional cases, birds may be required to coopt higher shape change numbers than initially suspected to achieve levels of lift and drag suitable for controlled perches. In addition, unlike certain forms of biological locomotion that have been shown to exhibit strong preferences towards specific propulsor/appendage aspect ratios, no apparent convergence has been observed among the wings of highly-maneuvrable birds, aside from general trends towards aspect ratios of less than five. The measurements for the circular and aspect-ratio-two elliptical plates therefore provide an explanation for the lack of convergence towards specific aspect ratios, since similar aerodynamic advantages may be achieved by a wide range of wing aspect ratios.

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