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Can Tip Vortices Enhance Lift of a Flapping Wing?

Wei Shyy,* Pat Trizila,† Chang-kwon Kang,† and Hikaru Aono‡
University of Michigan, Ann Arbor, Michigan 48109

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Tip vortices associated with fixed finite wings are traditionally seen as phenomena that decrease lift and induce drag [1]. Now, however, we have discovered that for a low aspect-ratio flapping wing, tip vortices can increase lift both by creating a low-pressure region near the wing tip and by anchoring the leading-edge vortex (LEV) to delay or even prevent it from shedding. Furthermore, for certain flapping kinematics, the LEV remains attached along the spanwise direction and the tip effects are not prominent; in such situations, the aerodynamics is little affected by the aspect ratio of a wing. Figure 1 illustrates two scenarios of a flapping flat plate with 2% thickness, aspect ratio of 4, hovering at $Re = U_{\mathrm{ref}} c/v = 100$ based upon the maximum translational speed. Two kinematic patterns are shown; the left case depicts qualitatively different time histories in lift between an infinite and a finite wing, whereas the right case demonstrates that the lift history of an infinite wing can closely mimic that of a low aspect-ratio finite wing.

The unsteady three-dimensional fluid physics associated with flapping wing aerodynamics have been probed in a large number of previous studies, for example, [2,3]. Several unsteady 3-D mechanisms that we know as responsible for enhancing the lift of a flapping wing are notably delayed stall of a LEV [4] and recapturing one's own wake [5]. Wake capture depends strongly on the wing kinematics [6], and performance of delayed stall is affected seriously by the stability of the LEV [4,7] as well as the flow parameters such as the Reynolds number [3,8]. For example, the LEV can be stabilized by spanwise flow in its core at high Reynolds number [3] and by induced flow by the tip vortex at low Reynolds number [9]. The previously mentioned studies have focused specifically on the aerodynamic force generation due to the LEV and trailing-edge vortices (TEVs). From our Navier–Stokes simulations, additional physical mechanisms have been identified, including a persistent downward jet found in the wake and the tip vortices. Both flow features are observed to noticeably affect the aerodynamic of a low Reynolds number flapping wing. Figure 2 highlights several flow structures we consider important for determining the flapping wing aerodynamics. In the upper left-hand corner we highlight the starting vortices and wake capturing which occur near the starts of translation. In the upper right corner are vorticity contours demonstrating the LEV, while in the lower right corner are vertical velocity contours showing the strong jet formed in the wake of a hovering wing. The tip vortices are shown in the lower left corner via instantaneous streamlines colored by their vertical velocity component. To see how these features relate to the aerodynamic forces the reader is referred to [10]. Although the jet [10] and the tip vortices [11] have been investigated in the literature, their impact on the lift and thrust associated with a flapping wing have not been adequately established.

In this Letter, we focus on a hovering flapping flat plate [2% thickness, aspect ratio $b^2/(bc) = 4$] at $Re = 100$ based upon maximum translational speed and wing chord, experiencing no freestream. Furthermore, in such a situation, the reduced frequency k is simply a restatement of geometric quantities, specifically $k = c/(2h_a)$ when the maximum translational velocity is used as the reference velocity. At this Reynolds number, turbulence is absent and the issues of numerical resolution can be addressed satisfactorily. The role and implications of changing kinematic parameters on the aerodynamics of such a wing and the associated unsteady fluid physics are our primary interests. As reported in [10], certain combinations of the kinematic parameters can significantly affect lift or drag by manipulating the flow structures, in particular, the interplay between tip vortices and the LEV.

The simplified kinematic motions are governed by Eq. (1). The translational (plunging) position $h(t)$ is a function of time t and depends further on the plunging amplitude h_a and the flapping frequency f. The rotational (pitching) motion is similarly governed by the flapping frequency and the angular amplitude α_a. The angular amplitude is a measure of how far the airfoil deviates from the yz plane, see Fig. 3. The time average of the pitching motion is $\alpha_0 = 90$ deg. Higher angular amplitudes will yield lower angles of attack and vice versa. The phase lag between the pitching and the plunging motions is denoted as ϕ. In this Letter, we present two cases corresponding to those presented in Fig. 1, namely, a delayed rotation which sees that the pitching motion lags that of the translation (plunging) motion, and a synchronized rotation where the pitching and translation are in phase. As will be seen, the flow structures and the aerodynamics are significantly different between these two cases, largely due to the impact of the tip vortices,

$$h(t) = h_a \sin(2\pi f t) \qquad \alpha(t) = \alpha_0 - \alpha_a \sin(2\pi f t + \phi) \tag{1}$$

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*Clarence L. "Kelly" Johnson Collegiate Professor and Chair, Department of Aerospace Engineering. Fellow AIAA.

†Graduate Student, Department of Aerospace Engineering. Member AIAA.

‡Post Doctoral Research Fellow, Department of Aerospace Engineering. Member AIAA.

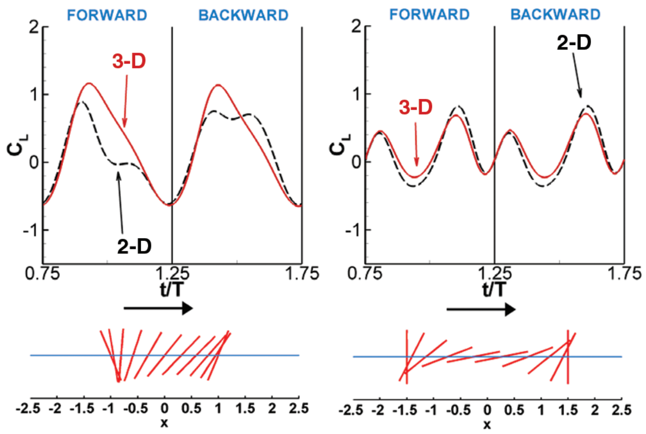

Fig. 1 Instantaneous 2-D and 3-D lift histories. Left panel: delayed rotation, $2h_a/c = 2.0$, $\alpha_a = 45$ deg, and $\phi = 60$ deg. Right panel: synchronized rotation, $2h_a/c = 3.0$, $\alpha_a = 80$ deg, and $\phi = 90$ deg, at $Re = 100$. Here, T denotes a flapping period. The time instant $t/T = 0.75$ corresponds to the start of the forward stroke, that is, $x = -h_a/c$, and $t/T = 1.25$ is the end of the forward stroke, that is, $x = h_a/c$.

1) Delayed Wing Rotation: Figure 4 compares the vorticity contours of the 2-D case with the 3-D simulations at midspan and the tip at various time instants for a delayed rotation case with $2h_a/c = 2.0$, $\alpha_a = 45$ deg, and $\phi = 60$ deg. Of note are the rotational starting vortices (RSVs), a subset of LEVs, so called because of their generation due to the pressure gradients created by the wing rotation, but not generally associated with delayed stall. The difference in the flow physics encountered due to 3-D phenomena is noticeable. Through the entire stroke it is seen that the shed vortices are more dissipative in 3-D. It is also seen that the behavior of the vortices changes as evidenced by the snapshots at $t/T = 0.8$ and 1.1. In 2-D, the stroke starts by running into the previously shed vortices, whereas in 3-D the RSV is shed above the plane of translation. This is seen to occur at $t/T = 1.1$, where not only do the RSV and TEV shed, but in 3-D they convect away from one another due to the influence of the tip vortices.

The spanwise variation in the 3-D case shows remarkable changes in the aerodynamic loadings. The RSVs stay anchored at the tips. A perspective is given in Fig. 5, where the criterion, see Eq. (2), is used to illustrate the vortical nature of the flow, where R_{ij} is the angular rotation tensor, and S_{ij} is the rate-of-strain tensor, such that the velocity gradient tensor $\partial u_i/\partial x_j = S_{ij} + R_{ij}$. A high value of Q suggests a more coherent vortical flow structure. These plots illustrate the spanwise variation of the flowfield as well as the anchoring of the vortices near the wing tips. Also plotted in Fig. 5 is the nondimensional lift per unit span due to pressure at the selected time instants versus the 2-D equivalent. For these kinematics it is evident that the tip vortices can enhance the lift for the majority of the stroke cycle,

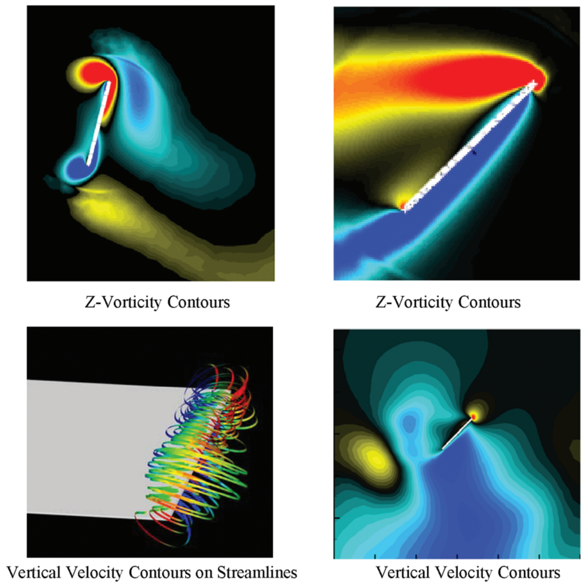

Fig. 2 Illustration of the time-dependent flow structures affecting the aerodynamics of flapping airfoil during the stroke cycle and the corresponding lift coefficient. Upper left panel: Starting vortices and wake capture; lower left panel: tip vortices; upper right panel: delayed stall and leading-edge vortex; lower right panel: jet interaction.

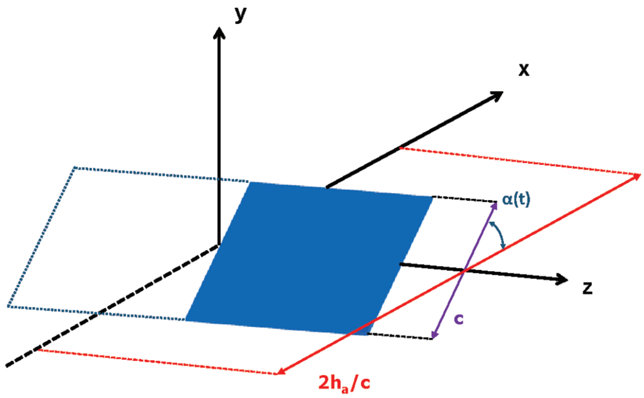

Fig. 3 Illustration of the finite aspect ratio (AR = 4, only half shown) wing plunging in the x direction and pitching about the z axis.

$$Q = \tfrac{1}{2}(R_{ij}R_{ij} - S_{ij}S_{ij}) \quad (2)$$

2) Synchronized Wing Rotation: In contrast to the delayed rotation, a synchronized rotation with low angles of attack can largely negate the effect of the tip vortices. Figure 6 shows the flowfields corresponding to the parameters $2h_a/c = 3.0$, $\alpha_a = 80$ deg, and $\phi = 90$ deg, a synchronized rotation case. The variation along the spanwise direction is weak, and the differences between the 2-D and 3-D simulations are small. Figure 7 shows the lift per unit span from pressure as well as a perspective shot of the Q criterion for these kinematics. Although it is seen that the lift is marginally enhanced near the wing tips at $t/T = 0.9$, the lift response is almost uniform across the rest of the wing. Likewise the flow features, as seen from the plots of Q, do not feature much variation in the spanwise direction compared to the delayed rotation case. The high angular amplitudes lead to low angles of attack, and coupled with the timing of the rotation, lead to a flow that not only lacks a dominant response due to the tip vortices, but also does not experience the delayed stall as the formation of the LEV is not promoted. The timing of the rotation for this example puts the flat plate at its minimum angle of attack at maximum translational velocity, while the translational velocity is zero when the flat plate is vertical.

The instantaneous lift coefficient for the two cases examined is illustrated in Fig. 1. In the first case, that is, delayed rotation, it was seen that the tip vortices played a dominant role in the aerodynamic loading, and, in particular, the lift was enhanced significantly near the wing tips because of the presence of strong tip vortices as well as their secondary influence of anchoring the RSVs. Compared to an infinite wing, the tip vortices caused added mass flux across the span of a low aspect-ratio wing, which helps push the shed RSV and TEV at midspan away from one another. Furthermore, there is a spanwise variation in the effective angle of attack induced by the downwash, stronger near the tip. Overall, the tip vortices allowed the RSV in their neighborhood to be anchored near the wing surface, which promotes a low-pressure region and enhances lift.

On the opposite side of the spectrum, Fig. 1 shows that for the present synchronized rotation case, the aerodynamic loading of a low aspect-ratio wing is well approximated by the analogous 2-D calculations.

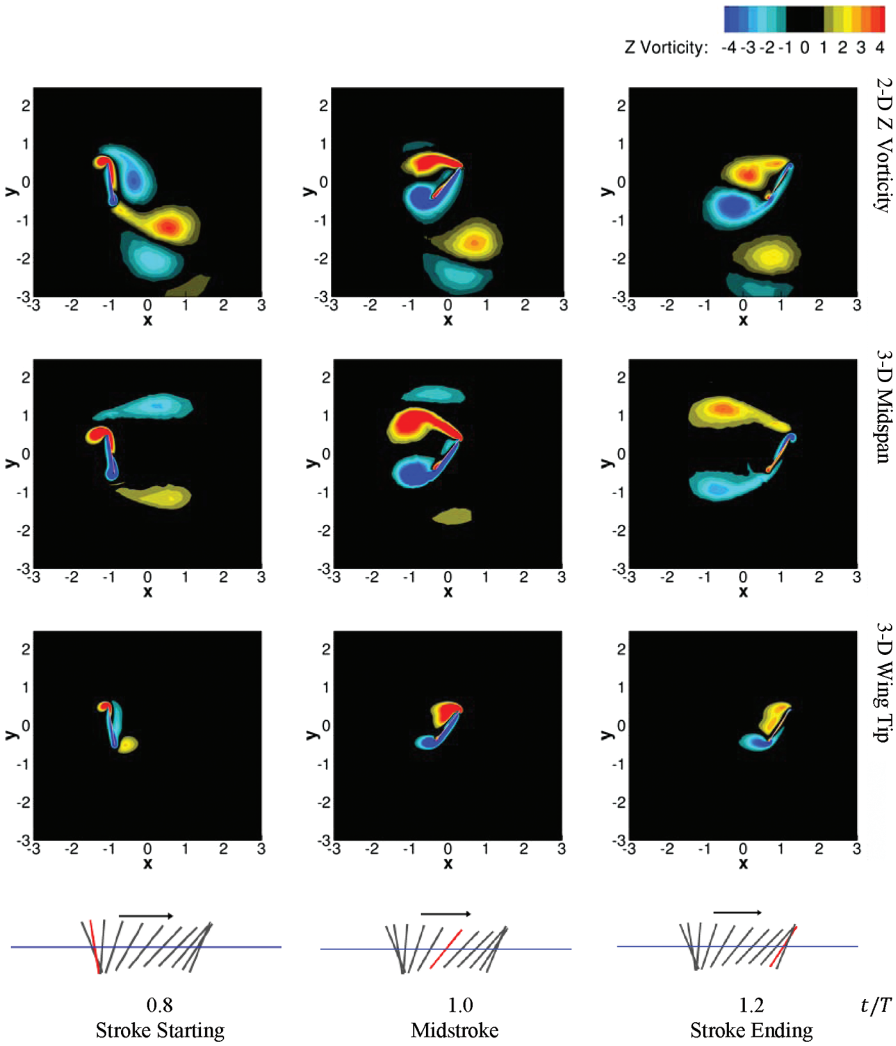

Fig. 4 ***Z*-vorticity contours at selected time instants during the forward stroke using the kinematic parameters $2h_a/c = 2.0$, $\alpha_a = 45$ deg, and $\phi = 60$ deg at $Re = 100$. There is a noticeable difference in the shed vortex strength between the 2-D and 3-D simulations as well as the nature of the vortex behavior. For this combination of kinematic parameters, there is also a large variation of the flow physics in the spanwise direction.**

In conclusion it was seen that tip vortices can either promote or make little impact on the aerodynamics of a low aspect-ratio flapping wing. Consequently, interpretation of the low Reynolds number flapping wing aerodynamics needs to be qualitatively modified in contrast to that of a fixed wing. The relationships between kinematic motions and unsteady fluid physics, as well as the effects of Reynolds number and reduced frequency, will be further investigated in an upcoming work, which uses combined

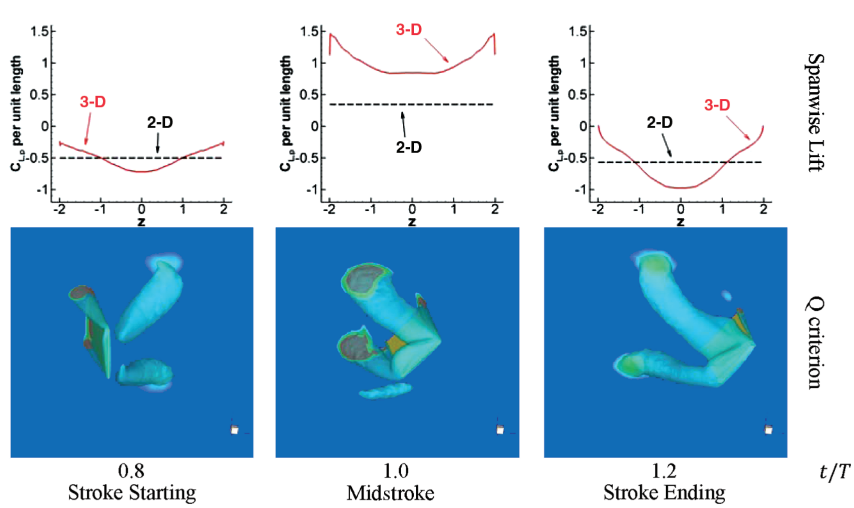

Fig. 5 **The lift per unit span and iso-Q surfaces ($Q = 0.75$) snapshots over half of the wing using the kinematic parameters $2h_a/c = 2.0$, $\alpha_a = 45$ deg, and $\phi = 60$ deg at $Re = 100$. The spanwise variation in forces is examined with the 2-D equivalent marked for reference. The tip vortices lead to increased lift in their immediate region as well as anchor the RSV. Time averaged lift coefficient for 1) 2-D: 0.13; 2) 3-D: 0.22.**

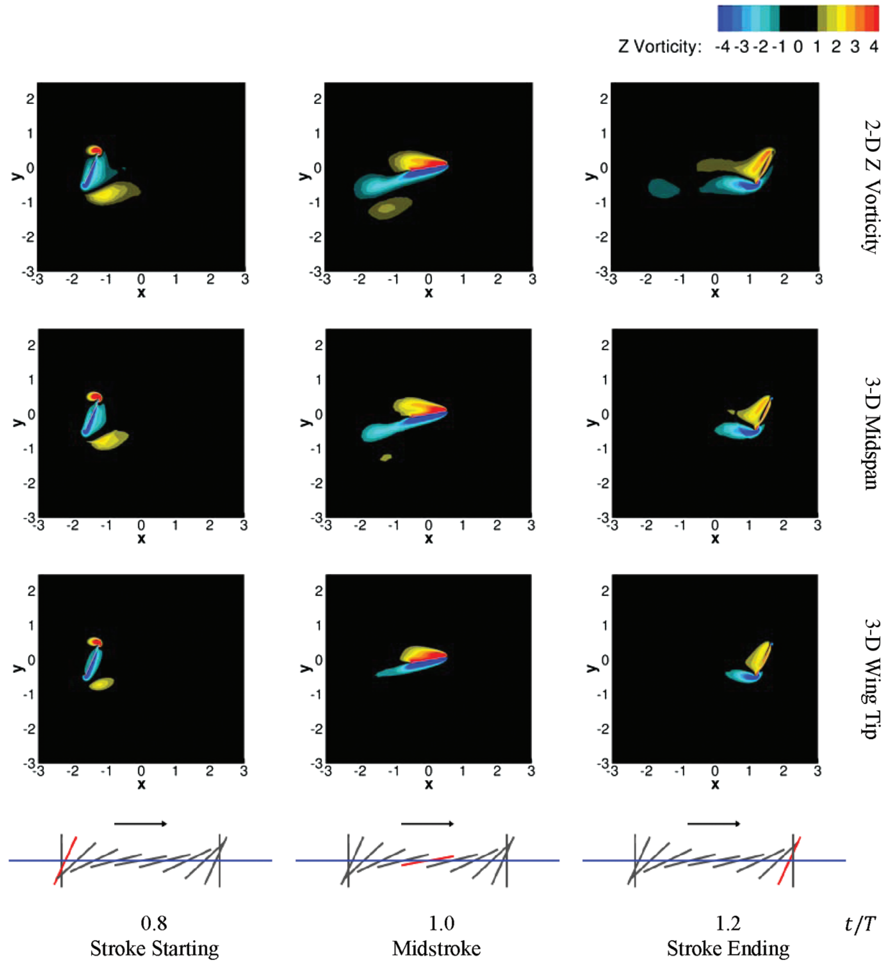

Fig. 6 ***Z*-vorticity contours at selected time instants for 2-D , 3-D midspan, and 3-D wing tip planes for kinematic parameters $2h_a/c = 3.0, \alpha_a = 80$ deg, and $\phi = 90$ deg at *Re* = 100. The high angular amplitude corresponds to high angular velocities near the end of translation and low angles of attack for most of the stroke. The spanwise variation of the 3-D computations is relatively small, and the 2-D and 3-D simulations are in good agreement.**

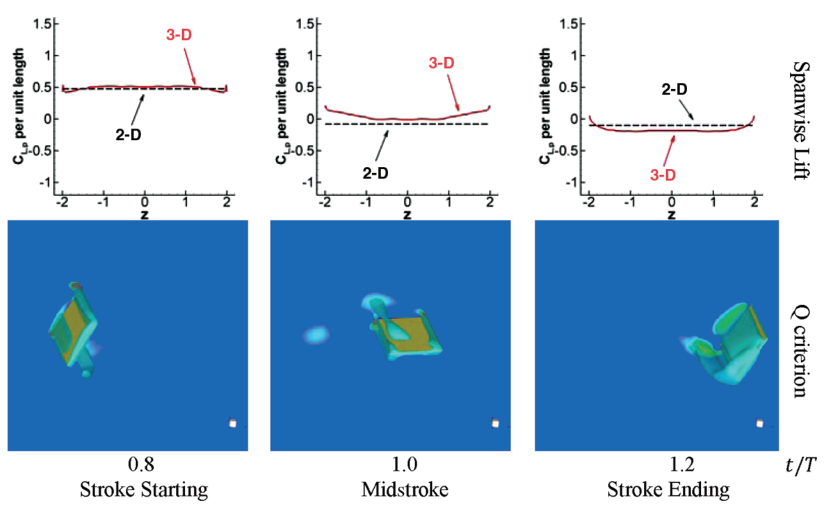

Fig. 7 **The lift per unit span and iso-*Q* surface ($Q = 0.75$) snapshots for flowfields over half of the wing associated with the kinematic parameters $2h_a/c = 3.0, \alpha_a = 80$ deg, and $\phi = 90$ deg, at *Re* = 100. The spanwise variation is limited. Time averaged lift coefficient for 1) 2-D: 0.14; 2) 3-D: 0.17.**

surrogate modeling techniques [12,13] and probing of the associated fluid physics [10].

Acknowledgments

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E. Oran
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