

Unsteady Flow Structures and Aerodynamic Loads over a Pitching-and-Plunging Flexible Membrane Wing

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ABSTRACT

Structural flexibility offers considerable potential for improving wing performance; however, its influence on the dynamic stall process remains insufficiently understood. In this study, synchronous force and particle image velocimetry measurements are conducted for a flexible membrane wing undergoing prescribed pitching-and-plunging motions. The results show that wing flexibility contributes to lift enhancement and drag reduction during dynamic stall. These aerodynamic benefits are mainly attributed to the favourable camber variations induced by membrane deformation. Furthermore, the lift curve exhibits a distinct double-peak pattern, which is governed by two different mechanisms. Specifically, the first lift peak occurs before the formation of the leading-edge vortex (LEV) and is primarily associated with the increase in circulation lift caused by rapid growth in wing camber. Alternatively, the second lift peak arises from the interaction between the LEV and the flexible membrane, which helps sustain a large positive camber during the downstream development of the LEV. These findings deepen the understanding of fluid–structure interaction during dynamic stall and highlight the important role of flexibility-induced camber variation in modulating unsteady aerodynamic loads.

1. Introduction

Dynamic stall is a fundamental unsteady aerodynamic phenomenon in which wings can sustain high lift at angles of attack that exceed the static stall limit. A deeper understanding of dynamic stall is essential not only to reveal the intricate manoeuvring mechanisms adopted by flying animals, but also to support technological advances in engineering applications. Over the past few decades, extensive efforts have therefore been devoted to understanding dynamic stall on wings subjected to prescribed unsteady motions (Corke & Thomas, 2015; Li, Feng, & Wang, 2020; Li, Feng, Kissing, et al., 2020).

The formation, growth, and subsequent shedding of large-scale leading-edge vortices (LEVs) constitute a salient feature of dynamic stall, as such vortical structures dominate the transient aerodynamic forces acting on the wing (Benton & Visbal, 2019). During the initial stage of dynamic stall,

the emergent LEVs generate low-pressure regions on the suction surface, thereby augmenting lift. Nevertheless, once the LEV grows to a critical state and eventually detaches from the wing surface, the favourable lift enhancement deteriorates rapidly (McCroskey, 1982). The development of LEVs has been shown to be highly sensitive to both wing kinematics (Baik et al., 2012; Karbasian & Kim, 2016) and Reynolds number (Ashraf et al., 2011; Jantzen et al., 2014; Li et al., 2019). Furthermore, Widmann & Tropea (2015) identified two distinct LEV detachment mechanisms, namely ‘boundary-layer eruption detachment mechanism’ and ‘bluff-body detachment mechanism’. The fundamental distinction between these mechanisms lies in whether LEV detachment is triggered by a secondary vortex or by a trailing-edge vortex. Eldredge & Jones (2019) suggested that a hybrid detachment mechanism may also exist, involving the combined effects of the secondary vortex and the trailing-edge vortex. Li, Feng, Kissing, et al. (2020) verified this conjecture and proposed a definition of the vortex Reynolds number based on variations in the leading-edge shear-layer angle, which can be used to distinguish between the boundary-layer eruption detachment mechanism and the secondary-vortex detachment mechanism.

Despite significant progress in understanding dynamic stall physics and the associated LEV dynamics, most existing investigations remain confined to rigid wing geometries. Inspired by bats and other natural flyers, structural flexibility has attracted increasing attention because of its potential aerodynamic benefits (Muijres et al., 2008; Cheney et al., 2014). The passive deformation of a flexible membrane can interact with the flow structures over the wing, modify the pressure distribution, and thereby enhance aerodynamic performance.

Previous studies have primarily emphasized aerodynamic characteristics under static angle-of-attack conditions, whereas the unsteady flow physics of flexible membranes during dynamic stall remains insufficiently understood. In particular, the interaction between the LEV and the flexible membrane, together with its aerodynamic implications, remain open questions. To shed light on these issues, the present study experimentally investigates the unsteady flow structures and aerodynamic characteristics of flexible membrane wings undergoing combined pitching and plunging motions.

2. Experimental Methods

The experiments are conducted in the low-speed water tunnel of Beihang University. The test section has a cross-sectional profile of $1.0\text{ m} \times 1.2\text{ m}$. The freestream velocity is set to $U_\infty = 0.2\text{ m s}^{-1}$, and the turbulence intensity is below 1.0%.

2.1. Model and Kinematics

The wing models are illustrated in figure 1. The flexible membrane wing has a chord length of $c = 120$ mm and a span of 300 mm, corresponding to a chord-based Reynolds number of $Re_c = 2 \times 10^4$. The wing is fabricated from a highly transparent thermoplastic polyurethane (TPU) sheet with a thickness of $\tau = 0.2$ mm, a Young's modulus of $E = 31.2$ MPa, and a density of $\rho = 1.1$ g/cm³. The aeroelastic parameter is calculated as $\Pi = (E\tau/qc)^{1/3} = 14.6$, where q is the freestream dynamic pressure. The TPU sheet is wrapped around 3 mm round steel leading and trailing edges. For comparison, a rigid wing model made of a 1-mm-thick carbon-fibre plate is also tested.

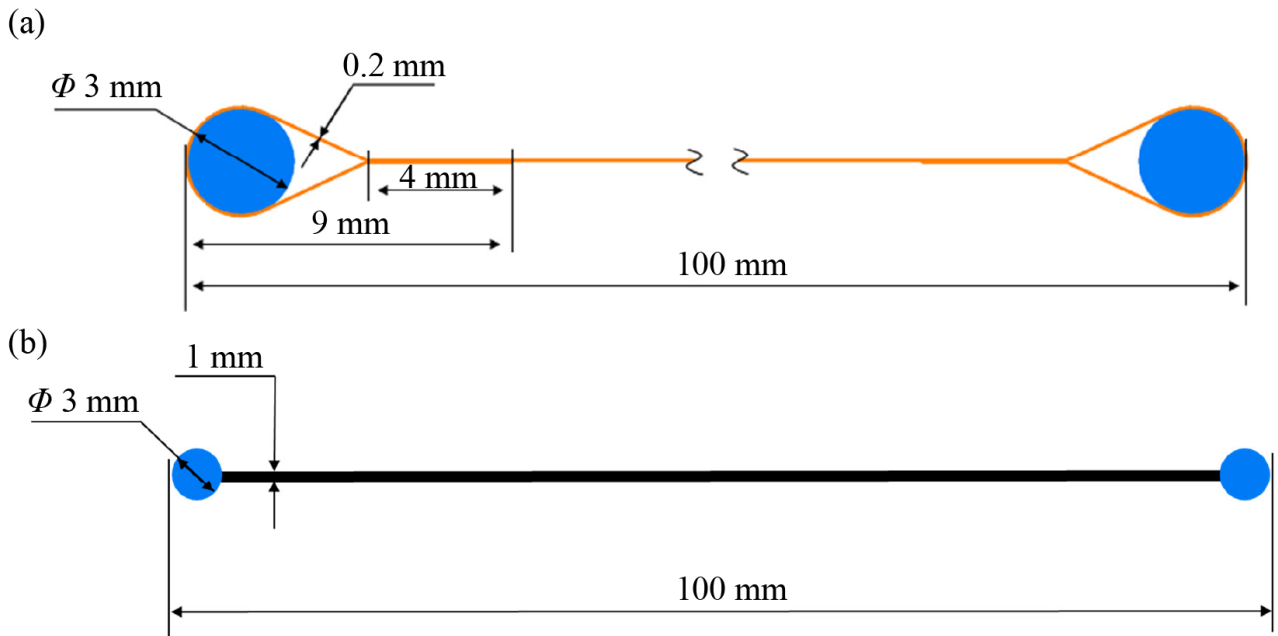


Figure 1. Schematic diagram of the (a) flexible membrane wing and (b) rigid wing models.

A schematic of the experimental set-up is shown in figure 2. One endplate is attached to the wing model to suppress the influence of free-surface waves, while the other endplate is fixed to the bottom of the test section to improve the two-dimensionality of the flow. The wing model is mounted on an experimental platform. This platform consists of two servo motors (Yaskawa SGM7J), a reducer (Kamo JFR90), and a ball-screw actuator (THK LC-EA-030A), enabling the wing to perform combined pitching and plunging motions. A programmable multi-axis controller (Delta Tau Clipper) is used to control the wing motion and synchronize the motion system with the force and flow-field measurement equipment. The pitching pivot is situated at the leading edge. Further details of the experimental set-up can be found in Li, Feng, Kissing, et al. (2020).

The wing models are subjected to combined pitching and plunging motions. The pitching motion

is defined in terms of the geometrical angle of attack as

$$\alpha_{\text{geo}}(t) = \alpha_{\text{geo,max}} \sin(2\pi ft), \quad (1)$$

where f denotes the motion frequency and $\alpha_{\text{geo,max}}$ is the maximum pitching amplitude. The plunging motion is described by the induced angle variation,

$$\alpha_{\text{plunge}}(t) = \tan^{-1} \left(-\frac{U_{\text{plunge}}(t)}{U_{\infty}} \right) \approx \alpha_{\text{plunge,max}} \sin(2\pi ft), \quad (2)$$

where $U_{\text{plunge}}(t)$ is the vertical velocity of the leading edge (i.e., pivot point) resulting from the plunging motion. In the literature, three dimensionless parameters are commonly used to characterize the combined pitching-and-plunging motions: the maximum effective angle of attack $\alpha_{\text{eff,max}}$, the reduced frequency $k = \pi fc/U_{\infty}$ and the Strouhal number $St = 2fh/U_{\infty}$. Here, h denotes half of the maximum plunge height. Since the pitching and plunging motions are prescribed in phase, the effective angle of attack can be expressed as

$$\alpha_{\text{eff}}(t) = \alpha_{\text{geo}}(t) + \alpha_{\text{plunge}}(t) \approx \alpha_{\text{eff,max}} \sin(2\pi ft). \quad (3)$$

In this study, particular attention is paid to the influence of the maximum effective angle of attack

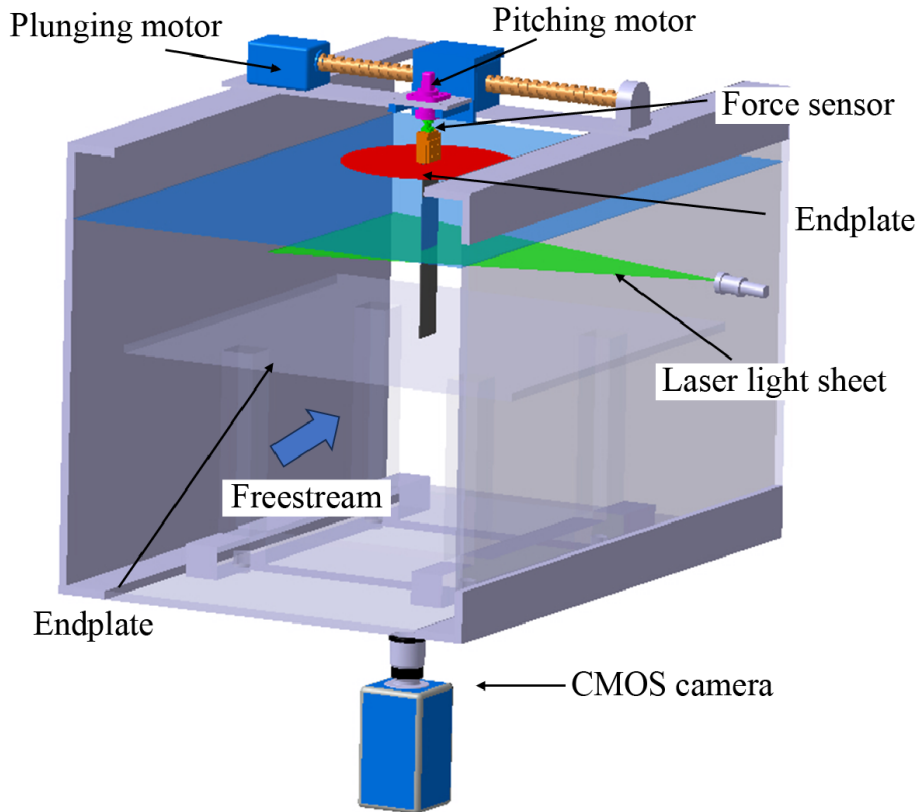


Figure 2. Experimental set-up.

$\alpha_{\text{eff,max}}$ on the flow structures and aerodynamic loads. Accordingly, $\alpha_{\text{eff,max}}$ is varied from 12° to 36° , while the reduced frequency and Strouhal number are fixed at $k = 0.2$ and $St = 0.048$, respectively.

Two coordinate systems are used for data presentation. One is the natural coordinate system $O - xy$, where the origin O is set at the trailing edge at the midspan at $t/T = 0$. The axes (x, y) are along the streamwise and vertical directions, respectively. The other is the wing-based coordinate system $\hat{O} - \hat{x}\hat{y}$, where the origin $\hat{O}$ is set at the leading edge at the midspan, and the axes $(\hat{x}, \hat{y})$ are along the chordwise and wall-normal directions, respectively.

2.2. Force and flow-field measurements

Force and flow-field measurements are performed simultaneously. Aerodynamic forces are measured using an ATI-Mini40 six-component load cell at a sampling frequency of 2×10^3 Hz, with a load range of 20 N and a resolution of 5×10^{-3} N. The recorded force signals are post-processed using a finite impulse response (FIR) low-pass filter and then phase-averaged. The reliability of the force sensor in measuring the unsteady force has been verified in our previous studies (Wang et al., 2021; He et al., 2023).

PIV measurements are conducted in the midspan plane of the wing models. Hollow glass spheres with a typical diameter of $10 \mu\text{m}$ and a density of 1.05 g/cm^3 are used as seeding particles. The flow is illuminated by a continuous 8 W laser, which generates a 1-mm-thick light sheet. Particle images are recorded using a high-speed CMOS camera (Fastcam Nova R2) equipped with a 75-mm focal-length lens. The camera has a resolution of 2048×2048 pixels, corresponding to a field of view of $235 \text{ mm} \times 235 \text{ mm}$. A phase-locked approach is employed such that velocity fields at 200 phases are acquired in each cycle, and a total of 54 cycles are recorded. The velocity fields are calculated using the Multipass Iterative Lucas-Kanade (MILK) algorithm. The interrogation window size is 32×32 pixels with an overlap of 75%.

3. Results

3.1. Aerodynamic characteristics

To examine the effect of wing flexibility on aerodynamic performance, figure 3 compares the aerodynamic forces of the flexible membrane wing and the rigid wing for the $\alpha_{\text{eff,max}} = 28^\circ$ case. Given the inherent symmetry of the wing motion, this study focuses exclusively on the downstroke, i.e., $t/T = 0 - 0.5$. For the rigid wing, the lift exhibits an approximate sinusoidal variation in response to the prescribed wing motion, with a peak occurring at $t/T = 0.19$. In comparison with the rigid wing, the flexible membrane wing exhibits a significant enhancement in lift, accompanied

by a reduction in drag. During the downstroke, the maximum lift of the flexible membrane wing increases by 11.4%, whereas the drag peak decreases by 23.5%. Moreover, the lift curve of the flexible membrane wing displays a notable double-peak pattern, with two distinct local maxima at $t/T = 0.11$ and $t/T = 0.22$, respectively.

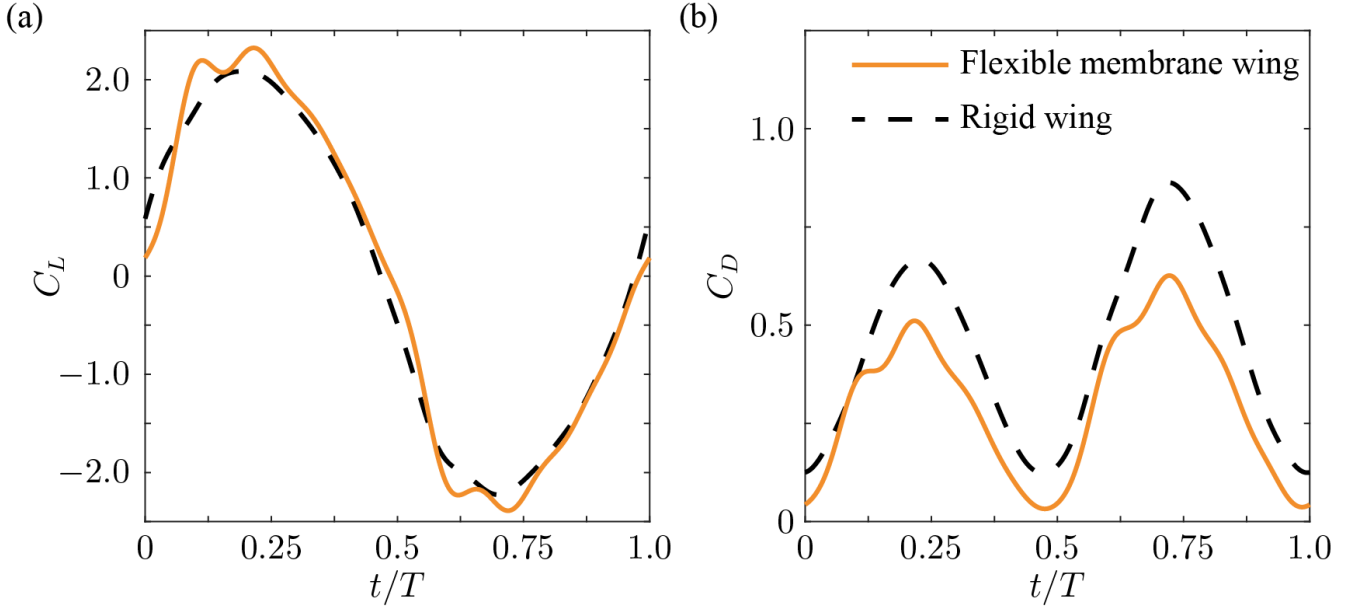


Figure 3. Comparison of the (a) lift and (b) drag coefficients between the flexible membrane wing and the rigid wing for the $\alpha_{\text{eff,max}} = 28^\circ$ case.

Figure 4 further presents the aerodynamic forces of the flexible membrane wing at different maximum effective angles of attack $\alpha_{\text{eff,max}}$. Across the range of wing kinematics considered, the lift curves consistently exhibit the double-peak pattern. In particular, the phases of both lift peaks shift earlier as $\alpha_{\text{eff,max}}$ increases. Moreover, the aerodynamic response of the flexible membrane wing shows trends similar to those observed for the rigid wing. Specifically, the magnitudes of both lift and drag increase with increasing $\alpha_{\text{eff,max}}$, while no evident phase shift is observed in the drag curves. These results indicate that wing flexibility plays a critical role in dynamic stall, modifying the temporal evolution of the aerodynamic forces.

3.2. Interaction between the leading-edge vortex and the flexible membrane

This section aims to elucidate the physical mechanisms underlying the double-peak lift response of the flexible membrane wing. To this end, the temporal evolution of the membrane deformation is first characterized in detail. Subsequently, the LEV dynamics are analysed to clarify how the interaction between the LEV and the flexible membrane contributes to the observed aerodynamic response.

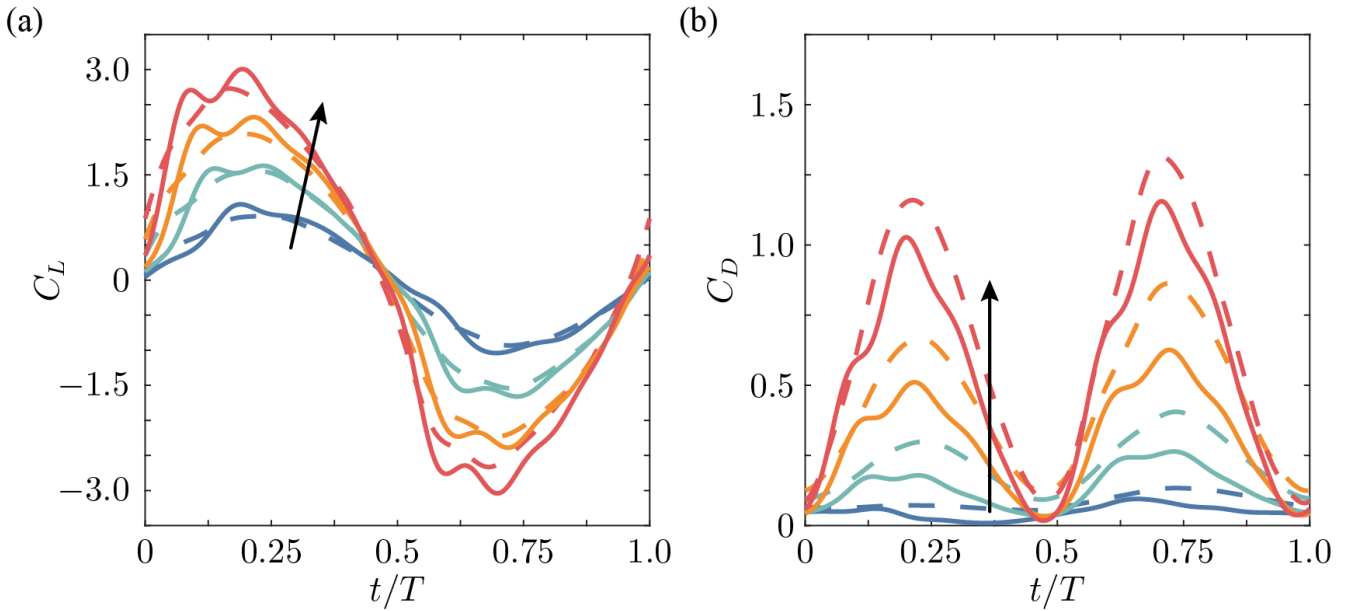


Figure 4. Influence of the maximum effective angle of attack $\alpha_{\text{eff,max}}$ on the aerodynamic forces of the flexible membrane wing. The solid and dashed lines represent the flexible membrane and rigid wings, respectively. The solid lines correspond to $\alpha_{\text{eff,max}} = 12^\circ, 20^\circ, 28^\circ$ and 36° in the direction of the arrows.

Figure 5(a) presents the evolution of the membrane deformation during the downstroke for the $\alpha_{\text{eff,max}} = 28^\circ$ case. The black dash-dotted line denotes the corresponding position of the rigid wing at each phase. It is shown that the membrane deflects relative to the rigid wing in the positive Y -direction as it plunges in the negative Y -direction, thereby giving rise to a positive camber. To further quantify the spatiotemporal evolution of the membrane deformation, the membrane displacement relative to the rigid wing at each chordwise location is extracted at a given phase, as indicated by the magenta line segment in figure 5(a). This displacement is denoted as $\Delta\hat{y}(\hat{x})$. It should be noted that the maximum value of $\Delta\hat{y}$ corresponds to the camber of the membrane wing at the given phase.

Figure 5(b) presents the evolution of the wing camber for different $\alpha_{\text{eff,max}}$ conditions. For all tested cases, the membrane initially undergoes a rapid increase in camber until it reaches the first peak, accompanied by the rapid pitch-down motion of the flexible wing. Interestingly, the phase of this camber peak is consistent with that of the first lift peak shown in figure 4, and both shift to earlier phases as $\alpha_{\text{eff,max}}$ increases. Subsequently, except for the $\alpha_{\text{eff,max}} = 12^\circ$ case, an evident secondary increase in camber is observed, after which the wing camber remains nearly constant for a certain period. The appearance of this plateau is related to the second lift peak in figure 4.

To elucidate the formation of the camber plateau, the evolution of LEVs and their interplay with the flexible membrane are then investigated. Figure 6 compares the LEV evolution for the flexible membrane wing and the rigid wing. It is evident that the LEV development over the flexible membrane wing is phase-delayed relative to that over the rigid wing. More importantly, the membrane

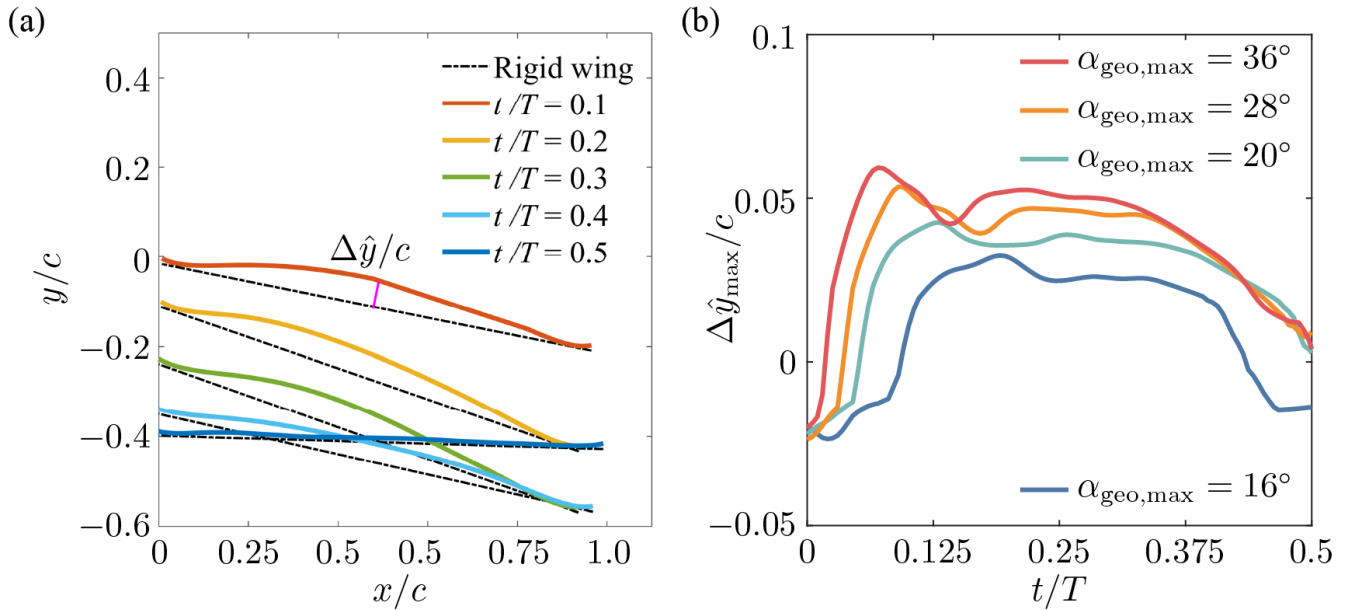


Figure 5. Evolution of the (a) membrane deformation during the downstroke for the $\alpha_{\text{eff,max}} = 28^\circ$ case and (b) wing camber for different $\alpha_{\text{eff,max}}$ conditions.

deformation is modulated by the LEVs. To quantitatively characterize the interaction between the LEV and the flexible membrane, the LEV centre is identified using the Γ_1 criterion (Graftieaux et al., 2001). Specifically, Γ_1 at a given point is calculated as $\Gamma_1 = \sum \sin(\theta_M)/N$. Here, θ_M is the angle between the velocity vector and the radius vector starting from the given point, and N is the number of neighbouring points used in the calculation. The maximum absolute value of Γ_1 within the LEV is taken as the vortex centre.

Figure 7 presents the streamwise locations of the LEV centre as a function of phase. To clarify the relationship between LEV evolution and membrane deformation, the contour map illustrates the temporal variation of the membrane deformation $\Delta\hat{y}/c$, while the black dots denote the locations of maximum membrane deformation $\Delta\hat{y}_{\max}$ at each phase. For $t/T = 0.10$, the flexible membrane is located at approximately $\hat{x}/c = 0.5$, whereas no distinct LEV has yet been identified. After the LEV emerges at $t/T \approx 0.15$, a camber plateau develops, as highlighted by the region enclosed by the black line. During the downstream convection of the LEV, the $\Delta\hat{y}_{\max}$ location remains close to $\hat{x}/c = 0.45$. Around $t/T = 0.30$, this $\Delta\hat{y}_{\max}$ location moves slowly downstream together with the LEV, indicating a pronounced interaction between the LEV and the flexible membrane. This suggests that the suction induced by the LEV helps the flexible membrane sustain a relatively large positive camber, although the LEV strength over the flexible wing is weaker than that over the rigid wing.

To further explain the fluid–structure interaction mechanism responsible for the double-peak lift pattern, the temporal variation of lift is also included in figure 7. The two lift peaks both occur at

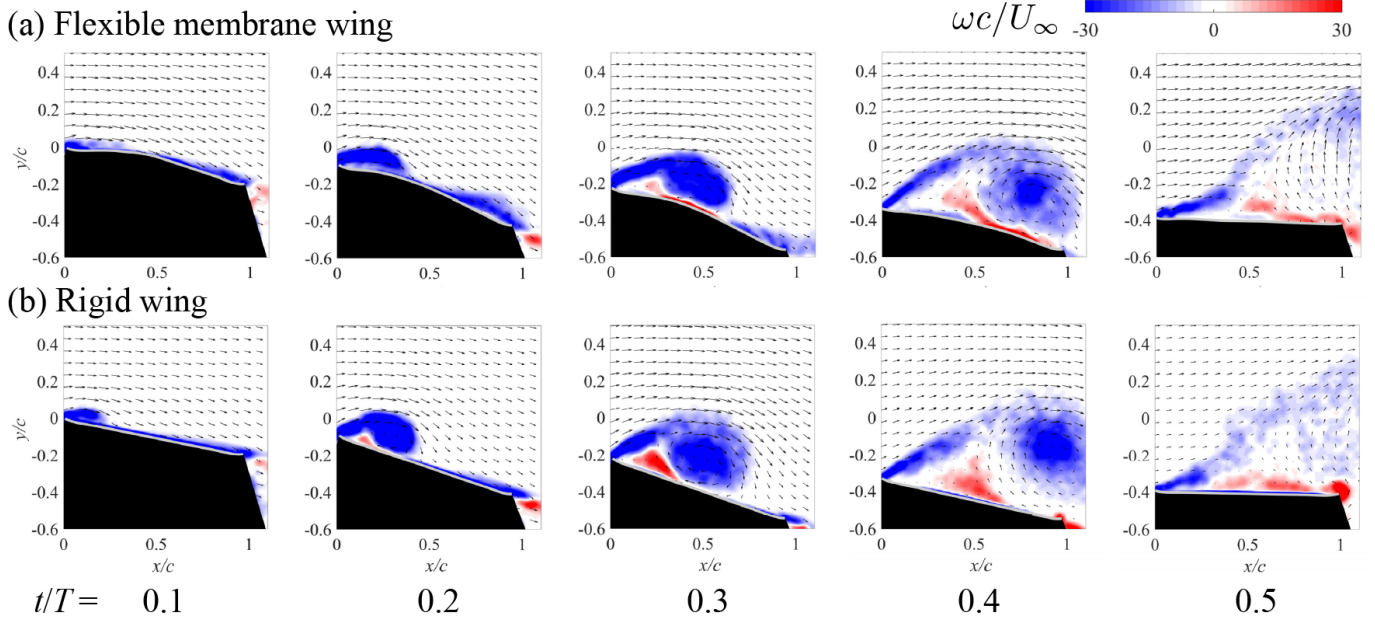


Figure 6. Comparison of the leading-edge vortices (LEVs) between the (a) flexible membrane wing and (b) rigid wing for the $\alpha_{\text{eff,max}} = 28^\circ$ case.

phases where the flexible membrane exhibits relatively large deformation. This indicates that the flexible membrane wing can enhance lift by generating positive camber. In particular, at $t/T \approx 0.10$, the LEV has not yet formed; therefore, the increased lift at this stage is mainly attributed to the circulation lift. By contrast, around $t/T \approx 0.20$, the fluid–structure interaction sustains a large membrane camber, which is primarily responsible for the second lift peak.

4. Conclusions

This study investigates the effects of structural flexibility on dynamic stall. Synchronous force and PIV measurements are conducted at $Re_c = 2 \times 10^4$. The maximum effective angle of attack varies from 12° to 36° , while the reduced frequency and Strouhal number are fixed at $k = 0.2$ and $St = 0.048$, respectively. The main conclusions are summarized as follows.

Compared with the rigid wing, the flexible membrane wing produces higher lift and lower drag. This aerodynamic enhancement is attributed to the favourable camber variations induced by the membrane flexibility during dynamic stall.

The flexible membrane wing exhibits a distinct double-peak pattern in its lift curve, which is associated with two different lift enhancement mechanisms. The first lift peak occurs before LEV formation and is accompanied by a rapid increase in membrane camber induced by the prescribed wing motion. This peak is mainly attributed to the increase in circulation lift. The second lift peak appears as the LEV convects downstream, during which the fluid–structure interaction helps

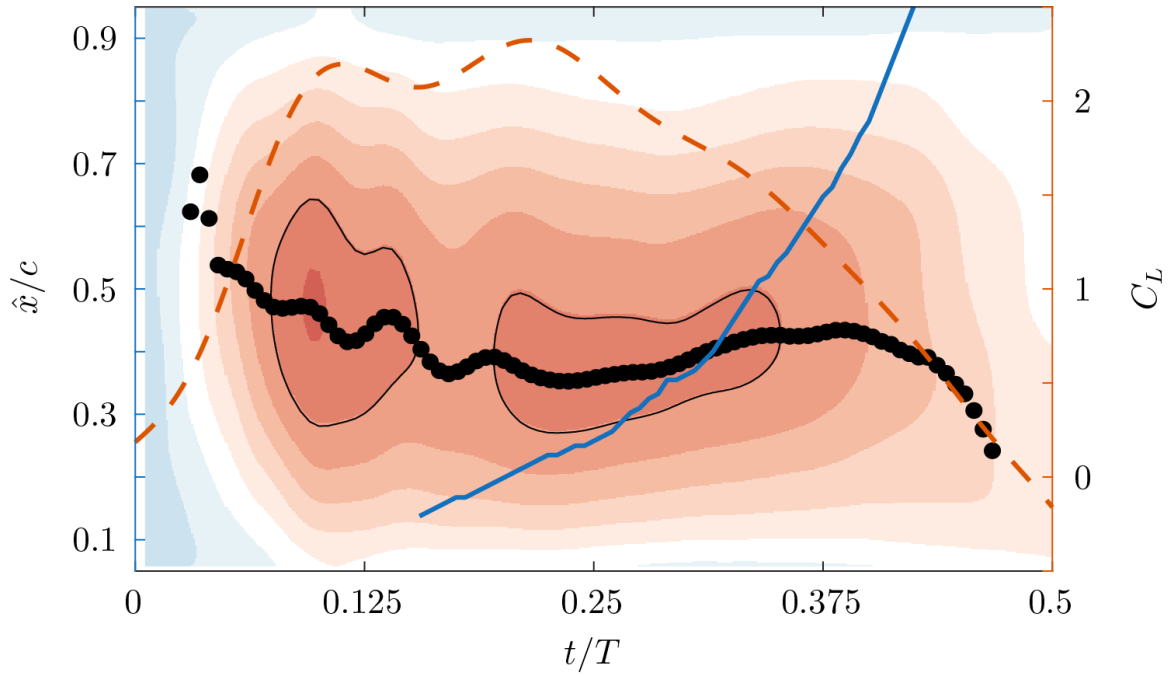


Figure 7. Interaction between the LEV and the flexible membrane. The blue solid line represents the streamwise trajectory of the LEV centre, and the black dots mark the locations of maximum membrane deformation $\Delta\hat{y}_{\max}$.

sustain a large positive camber and further augments the lift.

Acknowledgements

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Nomenclature

c	Chord length [m]
τ	Thickness [m]
U_{∞}	Free-stream velocity [m s^{-1}]
Re_c	Reynolds number [–]
E	Young's modulus [Pa]
ρ	Density [kg m^{-3}]
q	Dynamic pressure [Pa]
Π	Aeroelastic parameter [–]
α_{geo}	Geometric angle of attack [deg]
α_{plunge}	Plunge angle [deg]

α_{eff}	Effective angle of attack [deg]
$\alpha_{\text{geo,max}}$	Maximum geometric angle of attack [deg]
$\alpha_{\text{plunge,max}}$	Maximum plunge angle [deg]
$\alpha_{\text{eff,max}}$	Maximum effective angle of attack [deg]
St	Strouhal number [–]
k	Reduced frequency [–]
$O - xy$	Natural coordinate system [–]
$\hat{O} - \hat{x}\hat{y}$	Wing-based coordinate system [–]
C_L	Lift coefficient [–]
C_D	Drag coefficient [–]
$\Delta\hat{y}$	Membrane deformation [m]
$\Delta\hat{y}_{\text{max}}$	Maximum membrane deformation [m]

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