Dynamics of Flexible Wings in and out of Ground Effect

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Keywords: Flexible wings, FSI, DIC, PIV, POD, MAV

Abstract

Wind tunnel experiments are conducted at moderate Reynolds numbers of Re = 56,000 measuring rigid flat-plates and flexible membrane wings from free-flight into ground-effect conditions. Load cell measurements, digital image correlation and particle image velocimetry are applied in high-speed to resolve time-synchronised lift, drag and pitch oscillations simultaneously to membrane and flow dynamics. Proper orthogonal decomposition is applied on flow oscillations to determine their spatiotemporal evolution. Loads, membrane motions and flow dynamics are correlated to each other to investigate their underlying coupling physics. Membrane wings ability of static cambering and dynamic membrane oscillations are found to be beneficial when the wing is in ground-effect, where the descent in height forces premature leading-edge vortex-shedding and drag increase. Measurements show that the ground-effect leads to early stall onset in rigid wings. However, the dynamic motions of membrane wings help to promote (low height, high angle) vortex-shedding from the leading edge that ensures attached flow to the wing upper surface, resulting in even further lift enhancement. The primary effect of the flow on the membrane wing is to force the membrane in to chordwise modes that are essentially responsible for the fluctuations in the forces.

1. Introduction

Demand for expanding the flight capabilities of Micro-Air-Vehicles (MAVs) has lead into increasing interest in biological inspired wings. These wings show strong flow modifications for improved flight performance at low to medium Reynolds numbers of Re = 10,000 to 100,000. For example, bats show with their thin and flexible membrane wings strong fluid-structure interactions, where vibrations in the membrane are cable to modify the flow around the wing (Swartz 2007). The key requirement of such wings is the capability to get energy into the flow, allowing energy entrainment into the boundary layer for lower angles of attack and triggering leading-edge vortex-shedding at higher angles. As a result, wing stall can be suppressed into higher angles of attack and it becomes possible to increase maximum lift (Rojratsirikul 2011). However, the aerodynamic efficiency remains still very limited for wings at such low to moderate Reynolds numbers, constricting fundamental problems such as flight distance and mission time of MAVs. Recent attempts focused on active camber adjustment or even modulated membrane vibrations (Curet 2014).

However, this challenging concept comes with electro-mechanic complexity for an implementation in MAVs and probably payload constrains. The usage of MAVs with flexible wings in ground-effect could be one operational option to combine benefits of flexible membrane wings with additional efficiency enhancement by flying in the vicinity
to the ground. At close ground proximity, the flow starts to interact with the ground, causing stagnation of the flow below the wing surface and as a result pressure increase (ram-pressure). Additionally, tip vortices are pushed out and reduce in size and strength (Han 2005). Earlier flow separation appears at the leading-edge due to suppressed downwash when in ground-effect (Rozhdestvensky 2006).

Most studies focused on rigid wings in ground-effect (GE) at high-Reynolds-numbers (Qu 2014, Qu 2015). The physics of flexible membrane wings in ground-effect are challenging due to coupling effects between membrane vibrations, interacting flow structures and resulting force dynamics. A recent study focused on the ground/membrane/force interaction and found that membrane wings change their vibration behaviour towards larger scales (low modes), when they are closer to the ground (Bleischwitz 2015b, Bleischwitz 2016). The dynamic behaviour of the membrane when in ground effect was found to be similar to an increase in angle-of-attack in free-flight. However, the coupling of specifically the flow structures to membrane oscillations and their ground interference remains still unknown. Therefore, the current study tries to address this by carrying out simultaneous flow, deformation and load measurements. Wind tunnel experiments are conducted at Re = 56,000, applying time-resolved streamwise flow measurement (high-speed particle image velocimetry, PIV) at quarter-span location with simultaneously recorded deformation (high-speed digital image correlation, DIC) and force/moment measurements (load-cell). Rigid flat-plates and membrane wings are compared at an illustrative angle-of-attack of α = 25 ° and for three trailing edge heights-over-ground h/c = [2, 0.25, 0.1].

2. Experimental Setup

2.1 Wing design

Fig. 1 (a) Rigid flat plate with steel-frame and transparent acrylic window (b,c) Membrane wing with speckle pattern and translucent strip for PIV measurements above and below the wing surface
The full wing models have a rectangular planform with a chord length of 100 mm and a wingspan of 200 mm, resulting in an aspect-ratio of AR = 2 (Fig.1). The wingspan to tunnel width ratio is 0.47, which is well below a maximum of 0.8 suggested by (Barlow 1999) to avoid significant wall effects. The rigid flat plate (Fig.1a) consists of a 1 mm thin acrylic plate which is surrounded by a 3 mm diameter perimeter steel frame. The transition between steel frame and the acrylic plate is covered to be comparable with the edge design of the membrane wing models. The perimeter reinforced membrane wing (Fig.1b,c) consists of a flexible latex membrane and a steel frame. The latex sheet material has a thickness of \( t = 0.2 \text{ mm} \), density of \( 1 \text{ g/cm}^3 \) and a stiffness of \( E = 1.5 \text{ MPa} \). The aeroelastic parameter \( \Pi = (Et/qc)^{1/3} \) (Smith 1996) is found to be \( \Pi = 4.27 \) for \( U_\infty = 8.4 \text{ m/s} \). The membrane was wrapped around the 3 mm perimeter steel frame and attached to itself with a 5 mm wide and 0.05 mm thin double sided tape. The membrane has a 10 mm wide translucent window at quarter-span to allow laser light for PIV measurements to reach above and below the wing (Fig.1b,c). All time-synchronised load/membrane/flow measurements in this study are based on one representative wing sample which was selected from previously conducted experiments (Bleischwitz 2016). Spectral content of forces and deformations compared with previous membrane samples showed comparable membrane dynamics.

### 2.2 Load measurements

Forces and moments are measured by a six-axis load cell (ATI-Nano 17) with a load capacity of 25 N. The load cell is integrated into a sting as shown in Fig.2. Data is acquired at 10 kHz over a length of 20 s was used. The uncertainty in the load cell is \( \leq 0.006 \text{ N} \) in forces and \( \leq 0.03 \text{ [Nmm]} \) in pitching moment (ATI calibration, ISO 9001 certified).

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**Fig. 2** Load-cell integration in sting nose
However, this accuracy is found to hold only if the measurements were made within an overall time frame of 60s due to electrical drift of the load cell. In order to ensure reliable measurements, a wind-off tare point is obtained as a baseline just prior to each measurement for all combinations of angle-of-attack and ground height. As a result, an individual membrane wing shows an uncertainty in drag of less than 3% at $\alpha = 0^\circ$ and less than 1% for $\alpha \geq 15^\circ$, whereas the flat plate shows a higher uncertainty due to lower drag forces with 5% at $\alpha = 0^\circ$ and less than 1% for $\alpha \geq 15^\circ$. The dynamic behaviour of the experimental setup is separately validated to obtain the eigen frequencies and damping characteristics of all its electro-mechanical components. The spectral content of the rolling road/sting, wind tunnel fan and the attached wings appears remarkably constant for all angles-of-attack and had significantly lower amplitude levels (20 dB) compared with membrane wing induced force and membrane fluctuations. Clear changes in spectra of membrane wing force/moment coefficients with modifying angle-of-attack and height-over-ground show that the setup eigen frequencies do not significantly influence the results.

2.3 Deformation measurements

Stereoscopic DIC is carried out to measure instantaneous membrane deformations using two high-speed cameras (Phantom V341) with 50 mm focal length lenses (Nikon AF Nikkor 50mm f/1.8D) with aperture set to f/8 (Fig.3). The field-of-view is 1312 x 1000 pixels, capturing the entire membrane wing surface. Volumetric calibration is conducted using a calibration plate. The black parts of the membrane are sprayed with a white random speckle pattern with $\sim$ 3 to 5 speckles per mm ($\sim$ 2 pixels per speckle).

Fig. 3 Stereo-DIC setup with speckle pattern on membrane
The patterns are illuminated with blue light emitting diodes (LEDs), allowing to remove the (green) laser induced interference with blue bandpass filters during simultaneous DIC and PIV recordings. The light sheet window, a 10 mm wide translucent region in the membrane, did not cause major problems for the DIC measurements as the translucent surface even allowed DIC-correlation based on its natural texture. High-speed images are captured at a sampling-rate of 800 Hz over a sampling-time of 6.25 s. The sampling frequency allows resolving dynamics in the membrane below 400 Hz. A total of 5000 images are obtained. A commercial software package, LaVision StrainMaster, is used to obtain deformations from the stereo images. A subset size of 89 x 89 pixels with a grid step of 15 pixels is chosen, resulting in an average spatial resolution of 0.03 c. The uncertainty of the membrane deformation is estimated to be no worse than 0.1 % of the chord length and is measured by recording two images in still position while comparing the displacement between them. The DIC-technique is widely used in experimental mechanics, allowing sub-pixel accuracy due to grey value interpolation schemes over the interrogation grid (Schreier 2000). The results agree with previous studies, applying DIC on membrane wings (Rojratsirikul 2011, Galvao 2006, Stanford 2014). Out-of-plane displacements of the membrane are referenced with respect to the plane coinciding with the wing’s rigid frame.

2.4 Flow measurements

High-speed PIV is conducted by capturing frame pairs at 800 Hz, resolving dynamics in the flow up to 400 Hz. A double-cavity Nd: YLF laser (Litron LDY-300) is used with a wavelength of 527 nm. The synchronisation between all cameras (DIC + PIV) and the laser is ensured with a LaVision high-speed controller, which is triggered via Matlab. The commercial software LaVision Flowmaster is used for image acquisition and post-processing of particle images into vector fields.

Fig. 4 Planar side-by-side PIV setup to capture streamwise flow futures at ¼-span position
The flow measurements are conducted at quarter-span in a streamwise–wing-normal plane (Fig.4a). The quarter-span position is chosen for these measurements as it has the least interference from the sting system while ensuring that we capture the representative flow dynamics that are correlated to the membrane deformations. An exemplary flow snapshot can be seen in Fig.4b. Two Phantom V341 cameras (same type as used for DIC) are equipped with a set of two 105 mm focal length lenses (Sigma 105mm f/2.8 EX DG Macro) with aperture set to f/2.8 (fully open). Green bandpass filters are added on the PIV-lenses to increase the signal-to-noise ratio for the cameras by filtering out the background light from the LEDs. The image-pair acquisition frequency of 800 Hz is achieved by reducing the resolution to 1616 x 1088 pixels, allowing an individual PIV-camera to capture a field-of-view of 14.8 cm x 10 cm (streamwise x height). A total number of 5000 images are recorded over a time of 6.25 s. The time delay between image pairs is set to Δt = 50 μs, which results in a peak particle image displacement of about 5-7 pixels. The cameras are aligned perpendicular to the flow field in a side-by-side arrangement, allowing typical 2D flow measurements above/below the wing and in the near wake. Interrogation areas are set 64 x 64 pixels with 50 % overlap for a first pass and to 16 x 16 pixels with 75 % for the second pass. This results in a spatial resolution of 0.68 vectors/mm with a grid resolution of ~ 1.6 % of chord. The resulting instantaneous vector fields of each of the two planar cameras are stitched using a 3.6 cm wide overlapping region (in which the vectors are averaged) to obtain a 26 cm x 10 cm spanning vector field. The PIV-based freestream velocity is verified against a pitot tube system and they stay within 2 % of each other. The particle image correlation values in the flow reach 0.6 to 0.9 on the top side of the wing and reduce to 0.3 to 0.4 below the wing due to light reductions caused by the milky appearance of translucent latex. Nevertheless, it is possible to resolve the mean flow below the wings, becoming specifically important with the descent into ground-effect. The flow is seeded with 1 μm droplets generated using glycerine-water mixture in a typical atomiser. Previous studies with similar high-speed PIV and droplet sizes have shown that those particle are sufficient quick (~ 30 kHz) to resolve the given (vortex-shedding dominated) flow scales (Timpe2013). The POD analysis on flow dynamics shows that the same analysis with half the number of PIV-images exhibited similar dominant POD-mode shapes. Therefore, the POD modes of the flow are converged and confirm that the ensemble size is sufficient.

3. Results

The results concentrate on rigid and membrane wings at high angle-of-attack of α = 25°, going from free-flight into ground-effect. These cases are specifically selected since the ground-effect induces strong fluid-structure interactions. Prior studies on the same setup (Bleischwitz 2016) showed peak-lift for membrane wings at α = 25° in free-flight conditions, whereas rigid wings showed already a drop in lift and typical post-stall aerodynamics. We are exploiting the flow modifying (stall-inducing) nature of ground-effect to understand the ways in which flexible wings benefit from separated flow conditions.
3.1 Results: Flow-statistics

Fig. 5 shows contours of the time-averaged velocity $(U^2 + V^2)^{0.5}/U_{\infty}$ together with the mean streamline patterns. Rigid and membrane wings are compared at $\alpha = 25^\circ$, going from free-flight ($h/c = 2$) to moderate ($h/c = 0.25$) and into extreme ground-effect conditions ($h/c = 0.1$). Both rigid and membrane wings show at the given high angle-of-attack a fully developed separation bubble in free-flight conditions. However, the ability to adapt to a mean camber (due to the effect of mean dynamic pressure) allows membrane wings to reduce the separation region. As a result, membrane wings show a separation region in extreme GE (Fig.5b, lower) which is similar in size to rigid wings in free-flight conditions (Fig.5a, upper). The descent into ground-effect shows for both wings a clear reduction in speed at the lower side of the wing, slowing down to 50% of the freestream value. This “ram-effect” in GE is accompanied with predominant lift generation at the lower side of the wing, reducing the aerodynamic impact of the upper wing surface. The vicinity of the ground enlarges the separation bubbles and is accompanied by a downstream movement of the centroid of the bubble. Rigid wings (Fig.5a) exhibit separation bubbles whose centroid appears close to the trailing-edge or even farther downstream.

![Fig. 5 Freestream normalised velocity magnitude and streamlines for rigid and membrane wings at extreme angle-of-attack of $\alpha = 25^\circ$, modifying from free-flight into ground-effect ($h/c = [2, 0.25, 0.1]$)](image)

In contrast, membrane wings (Fig.5b) show separation regions appearing close to the upper membrane surface. The location of the separation bubble becomes specifically important for fluid-structure interactions and resulting lift generation, discussed later in more detail.
Fig. 6 Turbulent kinetic energy for rigid and membrane wings at extreme angle-of-attack of $\alpha = 25°$, modifying from free-flight into ground-effect ($h/c = [2, 0.25, 0.1]$)

Fig.6 shows contours of turbulent kinetic energy that highlights the regions of unsteady flow features. Rigid wings (Fig.6a) have strong velocity fluctuations downstream of their trailing edge. In comparison, membrane wings exhibit strong velocity fluctuations close to the upper wing surface (Fig.6b, upper). The descent of membrane wings into ground-effect (Fig.6b, mid) shows an increasing vertical detachment of the highly energetic flow structures from the membrane surface, suggesting a fading influence in fluid-membrane coupling.

3.2. Results: Flow-dynamics

Leading-edge vortex-shedding and break-down are difficult to observe in instantaneous snap shots. POD offers one option to group the energetic flow structures that are coherent (Shi 2013, Schmit 2003, Lian 2003, Kostas 2002). Fig.7 shows the five most energetic POD modes (a1, ..., a5) of the velocity fluctuations. Additionally, the energy contribution of individual POD coefficients ($E_{POD}$) is illustrated on the top right corner of each contour plot. Contours in each individual subplot are normalised such that the peak value is 1. Both rigid and membrane wings show coherent flow structures related to leading-edge vortex-shedding. The rigid wings mostly show POD structures which are mainly located downstream of the trailing. Membrane wings show (Fig.7b) closely attached vortex structures within free-flight conditions which roll down the chord along the membrane. Those structures remain apparent in extreme GE (Fig.7d), but are lifted up vertically from the membrane surface. This suggests that membrane oscillations still influence dynamic flow structures passing over the wing, but the resulting entrainment is not sufficient to
overcome the strong adverse pressure gradient. Nevertheless, membrane wing oscillations are found to actively excite leading-edge vortex roll-up by locking-into vortex-shedding frequencies of similar value. As a result, the flow dynamics get further excited close to the moving wing surface.

**Fig. 7** Five most energetic POD mode shapes (a1,...,a5) of velocity fluctuations \((U^{2}_{\text{POD}} + V^{2}_{\text{POD}})^{0.5}/U_{\infty}\). Comparison of rigid and membrane wings at \(\alpha = 25^\circ\), modifying from free-flight \((h/c = 2)\) into extreme ground-effect \((h/c = 0.1)\). Rigid wings show shedding dynamics happening downstream of trailing edge, whereas membrane wings close to and above the wing surface.
Rigid wings can also exhibit vortex-shedding and attached vortex roll-down close to the wings surface, however at much lower angles-of-attack of $\alpha \sim 10^\circ$ and therefore much lower lift capability (not shown). In addition, their performance envelope (i.e. range of angle of attack and heights above ground) is narrow since they are unable to take advantage of the attached shedding dynamics.

3.3 Results: Membrane-Flow coupling

A recent study on batten-reinforced membrane wings correlated membrane dynamics with simultaneously recorded flow dynamics (Timpe 2013). Vibrations at the trailing-edge of batten-reinforced membrane wings were shown to correlate well to the flow dynamics close to the trailing-edge. This result opens the question of how perimeter reinforced membrane wings couple with the flow dynamics. Fig. 8a shows the cross-correlation, at zero time-lag, between vertical flow fluctuations ($V'$) and the vertical membrane fluctuations at a listener point (M), placed 0.4c downstream of the leading-edge. Exemplary membrane fluctuations are shown amplified above their mean by factor 7 for clarity. Contours of cross-correlation at zero time-lag are illustrated for free-flight (Fig.8a, upper), moderate ground-effect (Fig.8a, middle) and for extreme ground-effect conditions (Fig.8a, lower).

**Fig. 8** Cross-correlation (CCF) between vertical membrane fluctuations at point M (x/c=0.4) and vertical flow fluctuation velocity ($V'$) at listener point P illustrated cases are at $\alpha = 25^\circ$, modifying from free-flight (h/c = 2) over moderate (h/c = 0.25) into extreme ground-effect (h/c = 0.1). (a) Contour plots base on zero time-lag. The descent into ground-effect causes decoupling of the flow with the membrane dynamics, noticeable by a phase-shift between each other. (b) Time-shifted (phase shifted) CCF between M and P1, P2, and P3.
Perimeter reinforced membrane wings (Fig.8a) show similar flow-membrane coupling as found for batten-reinforced (BR) membrane wings (Timpe 2013). However, perimeter-reinforced membrane wings show extended coupling due to the membrane vibrations occurring all along the chord length between leading- and trailing-edge (with two chordwise peaks), rather than only concentrating close to the unsupported trailing-edge. In addition, membrane vibrations show strong correlations close to the leading-edge, initiating and promoting vortex-shedding from the beginning. The free-to-rotate membrane attachment likely helps the exploitation of coupling dynamics (Bleischwitz 2015a, Bleischwitz 2016). Overall, the results suggest that constraining the trailing-edge of the membrane could provide more options for flow control. Further studies are required to understand the impact of chordwise vibration locations on flow interactions. It is important to mention that the vertical membrane fluctuations are often no more than 1mm in peak regions but significantly influence the flow dynamics.

In free-flight conditions (Fig.8a, upper), perimeter-reinforced membrane wings exhibit strong (CCF > 0.6, Fig.8b, upper) and a lag-free coupling between membrane dynamics (with two chordwise mode shapes) and vertical flow fluctuations. This strong interaction confirms previous results in Fig.7b, showing POD modes shapes appearing close to the wing surface all along the chord. Ultimately, a leading-edge localised upwards camber movement comes with a vertical upwards directed flow and vice versa. The up/downwards directing flow structures base on vortical shedding structures initiated from the leading-edge.

The coupling between membrane and flow dynamics is found to change for different flow conditions, such as changes in angle-of-attack or height-over-ground. The descent into extreme ground-effect (Fig.8a, lower) forces the flow to detach from the wing surface, resulting in a phase lead of the flow to the membrane with 60° phase-shift (Fig.8b, lower). Previous studies showed that this decoupling is accompanied with a loss in lift and gain in drag (Bleischwitz 2016). Therefore, it is shown that direct (lag-free) fluid-structure coupling of membrane wings, accompanied with lifting benefits, is only possible for specific flow conditions, at which the dominant eigen frequency of the membrane or its higher harmonics get close enough to the vortex-shedding frequency. Additionally, the adverse pressure gradient has still to remain weak enough to enable close-to-surface energy transfer between the flow and the membrane surface. Nevertheless, the membrane wings have an enlarged performance windows compared with rigid wings.

3.4. Results: Load-Membrane-Flow coupling

Fig.9 gives an extended overview into the coupling mechanics of membrane wings, considering aerodynamic loads, membrane oscillations and dynamic flow structures, illustrated for brevity at one representative case at \( \alpha = 25^\circ \) in free-flight conditions. Fig.9a shows free-stream normalised vertical flow fluctuations \( V'(t) \) for three time-snapshots (t1, t2, t3), representing one membrane oscillation cycle at a Strouhal number of \( St = 0.78 \). Also
shown are streamlines computed from low-pass filtered (using the first five POD modes) velocity fields. Finally, instantaneous membrane cross-sections (at the quarter-span PIV-plane) are illustrated by overlaying the time-averaged membrane shape (dotted-line) with the membrane fluctuation (where the fluctuation is amplified by a factor of 7 in order to higher the vertical displacement better).

Fig. 9 Load-membrane-flow interactions at $\alpha = 25^\circ$ in free-flight conditions of $h/c = 2$. (a) Time-snapshots (t1, t2, t3) for vertical flow and membrane fluctuations during one membrane cycle. Streamlines based on POD-filtered flow fluctuations. (b) Time-corrresponding development in lift, drag and pitch moment fluctuations. (c) Spectral signature of load-membrane-flow dynamics and their (d) cross-correlation between each other.
At time-step t1 (Fig.9a, upper), the instantaneous positive vertical velocity close to the leading edge (red) appears to be accompanied with upward membrane deformation. Half a membrane cycle further in time (Fig.9a, mid), the rolling down vortex structure has travelled down to the trailing-edge (core at x/c = 1) and results in an upwards deformation of the membrane close to the trailing-edge. This cycle repeats where at time-step t3 (Fig.9a, lower), the situation is the similar to that of time-step t1.

Dynamics in flow/membrane oscillations are also transferred into aerodynamic load fluctuations, which are shown in Fig.9b. At time step t1, the wing shows reduced total lift, increased drag and a pitch-up moment. This relation flips at a later stage t2, showing gain in lift, decline in drag and increasing pitch-down moment.

Fig.9c compares the spectra of all three load components, vertical membrane dynamics and vertical flow oscillations (both at 40%-chord from leading-edge). The spectra reveal that the membrane motions, loads, and flow are clearly linked. The membrane (Fig.9c, mid) exhibits an oscillation frequency of St = 0.78 (1st harmonic) and St = 1.66 (2nd harmonic). Those two most energetic membrane frequencies are also detected in the loads and the flow spectra, suggesting strong coupling of membrane dynamics with the flow and loads. The membrane eigen frequency of St = 0.78 is significantly different from the natural shedding frequencies of (flat/cambered) rigid wings which measure around St = 0.4 to 0.5 for the given case (this is consistent with the d/sina rule, where 0.17<d<0.23, see Rojratsirikul 2011).

The cross-correlation between the flow and the membrane (Fig.9d, upper), the loads and the membrane (Fig.9d, mid) and the loads and the flow (Fig.9d, lower) underlines strong coupling between each other. The aerodynamic coefficients show a slight delay to membrane motions by 30 to 60°. This result corroborates previous experiments, suggesting membrane inertia cause this shift (Bleischwitz 2016).

Direct flow-to-membrane coupling can not only be initiated by high angles-of-attack (Fig.9), but also with moderate angles-of-attack (α = 15°) in liaison with ground-effect (h/c = 0.1). Therefore, ground-effect acts only as a flow modifying parameter, and its results can also be accomplished with an increase in angle-of-attack in free-flight conditions, allowing to couple/decouple membranes-flow dynamics. Both options rely on LE-vortex-shedding close to the membranes upper surface, encouraging lift enhancing dynamics by entraining fluid to promote flow re-attachment in areas affected by adverse pressure gradients. However, ground-effect dynamics show generally lower strength in comparison to free-flight dynamics, suggesting the increased importance of the lower (static) wing side in the vicinity of the ground, reducing the importance and the significance of flow dynamics occurring on the upper side of the wing. Therefore, the flexibility of membrane wings can only be fully exploited outside of ground-effect conditions.
4. Conclusion

Wind tunnel experiments were conducted at moderate Reynolds numbers of Re = 56,000 by using rectangular rigid and membrane wings. Time-synchronised high-speed recordings of aerodynamic loads, membrane and flow dynamics reveal underlying coupling physics for free-flight and ground-effect conditions. Static cambering and dynamic membrane oscillations become an advantage when membrane wings are used in ground-effect, where the descent in height forces premature flow separation, accompanied with an early onset of leading-edge vortex-shedding and drag increase. Dynamic motions of membrane wings help to promote vortex-shedding and maintain attached flow over the wing surface, resulting in enhanced lift capability. The membrane of a perimeter wing frame is found to benefit specifically from its leading and trailing edge constraints as these boundary conditions enable motions along the entire chord that enhance flow-membrane interaction. Additionally, membrane dynamics with large amplitudes appear close to the leading edge, promoting the growth of leading-edge vortices and their importance to the dynamics. In contrast, other membrane wing types such as batten-reinforced membrane wings exhibit limited flow-structure coupling since the interaction is mostly localised near the free trailing-edge. Therefore, enhancing membrane-flow coupling along the entire chord is found to play a major role in improved lift performance.

The coupling of the membrane with the flow continues even in post-stall flow conditions. The spectral signature of membrane dynamics is clearly apparent in the flow where the membrane motions are strongly coupled with the vertical flow motions in the vicinity of the membrane. This relationship remains mostly in-phase (i.e. the membrane-flow coupling is almost always instantaneous). Under certain conditions, especially in extreme ground-effect, the phase difference between the flow and membrane increases signally an end to the direct coupling between the two dynamics. This change is also accompanied by loss in lift and increase in drag. The exploitation of the dynamics of flexible wings is reduced within ground-effect, because the influence of the lower surface of the wing grows with respect to that of the upper surface.

Acknowledgements

The work was gratefully financial supported by the Engineering and Physical Sciences Research Council (EPSRC, grant EP/J001465/1) and the European Office of Aerospace Research and Development (EOARD, grant FA8655-12-1-2046). Roeland de Kat is supported by a Leverhulme Early Career Fellowship.

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