On the fluid-structure interaction of flexible membrane wings for MAVs in and out of ground-effect

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Abstract

Wind tunnel experiments are conducted at a Reynolds number 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 with 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. A membrane wing's 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. The dynamic motions of membrane wings help to exploit vortex-shedding dynamics from the leading-edge that ensures time-averaged reattached flow over the wing upper surface, resulting in further lift enhancement. Membrane wings show lag-free fluid-membrane coupling at peak-lift conditions. In post-stall conditions, the membrane is found to lag the flow dynamics, signalling the end of direct fluid-structure coupling.

Keywords: Membrane wings, ground-effect, Micro-Air-Vehicles, compliant wings, shape adaptable wings, low Reynolds number wings

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Nomenclature

α	global angle-of-attack [$^\circ$]	E_{POD}	energy contribution to total energy
Π	aeroelastic parameter $(\frac{Et}{qc})^{1/3}$	h	height above ground
σ	standard deviation	LE/TE	leading/trailing edge
c	chord length	POD	proper orthogonal decomposition
CCF	cross correlation function	PSD	power spectral density
C_D	drag coefficient	q	dynamic pressure $\frac{1}{2}\rho U_\infty^2$
C'_D	drag coefficient fluctuation	Re	Reynolds number $\frac{U_\infty c}{\nu}$
C_L	lift coefficient	St	Strouhal number $\frac{fc}{U_\infty}$
C'_L	lift coefficient fluctuation	U	streamwise flow velocity [m/s]
$C_{M/4}$	pitch coefficient at 1/4 chord	V	vertical flow velocity [m/s]

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 capable to modify the flow around the wing (Swartz et al., 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 et al., 2011).

Nevertheless, the development of lift enhancing vortical structures come at a price of further drag increase (Bleichwitz et al., 2015b; Timpe et al., 2013), resulting in aerodynamic efficiency limitations (Pines and Bohorquez, 2006). Recent attempts focused on active camber adjustment or even modulated membrane vibrations (Curet et al., 2014; Buoso and Palacios, 2016; Barbu et al., 2016). However, this challenging concept comes with electro-mechanic complexity for an implementation in MAVs and probably payload constraints. The usage of MAVs with flexible wings in ground-effect could be one operational option to combine stall related gust (Ifju et al., 2002) and lift (Gordnier, 2009) recovery performance of flexible membranes 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). At the same time, tip vortices are pushed out and reduce in size and strength with the descent into ground-effect (Han and Cho, 2005), resulting ultimately in superior aerodynamic efficiency in comparison to free-flight conditions. However, ground-effect induced stagnation of the flow below the wing results into an upwards diverted flow, causing earlier leading-edge flow separation on the upper side of the wing and therefore earlier wing stall, limiting the range of efficient angles-of-attack in GE (Rozhdestvensky, 2006).

The ability of flexible membrane wings to respond and interact with growing vortical flow structures opens the question how membrane wings perform in the vicinity of ground-effect. Recent work at the University of Southampton acquired time-synchronised load and membrane deformation measurements and focused on the aerodynamic performance and load-to-membrane interaction in and out of ground-effect (Bleichwitz et al., 2015a, 2016a). Fig. 1a and Fig. 1b shows extracted results of the recent study, illustrating lift and aerodynamic performance modifications of membrane wings in comparison to rigid flat-plates, going from free-flight ($h/c = 2$) into ground effect conditions ($h/c = 0.1$). The height, h , is measured from the trailing-edge. Three angles-of-attack at $\alpha = [10, 15, 25]^\circ$ are shown for brevity.

Generally, both wings show lifting (Fig. 1a) and efficiency benefits (Fig. 1b) in GE. However, membrane wings were found to outperform rigid flat-plates not only in free-flight but also GE conditions. The reason of this performance

Fig. 1 Background information extracted from the initial study (Bleischwitz et al., 2016a): (a) Static lift capability (b) and aerodynamic efficiency for rigid flat-plate and membrane wings going from free-flight ($h/c = 2$) into ground-effect conditions ($h/c \leq 1$), measured at three angles-of-attack ($\alpha_R = \alpha_{Rigid}$, $\alpha_M = \alpha_{Membrane}$). Points of interest in the current paper are marked in blue.

benefit relies on a combination in static membrane cambering and membrane oscillations. Specific studies (Gordnier and Attar, 2014; Rojratsirikul et al., 2009) in free-flight conditions were able to separate camber and oscillation related effects (by comparing membrane wings with cambered rigid plates) and found that the gain in static camber is mainly responsible for enhanced lift production and improved aerodynamic efficiency at low to moderate angles-of-attack. However, membrane wings come with superiority in separated (stall related) flow conditions, showing further lift (and drag) enhancement to rigid, similar cambered plates due to their ability to couple membrane dynamics with leading-edge vortex-shedding for further energy entrainment close to the wing surface.

The vortex-shedding related oscillation behaviour of the membrane was suggested to be either triggered by high angles-of-attack in free-flight conditions or by ground-effect conditions (Bleischwitz et al., 2015a, 2016a). However, these first studies on membrane wings in ground-effect focused on pure loads and membrane interaction, but lacked measurements of the flow development and coupling characteristics between the flow and the membrane. The coupling dynamics are key to understand the underlying physics behind the (lift-enhancing) performance benefits of membrane wings in separated (stall-related) flow conditions. Furthermore, the early stall-inducing nature of ground-effect can be used to understand the ways in which flexible wings benefit from separated flow conditions.

Therefore, 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 simultaneous deformation measurements (high-speed digital image correlation, DIC) and force/moment measurements (load-cell). Membrane wings are measured at a selection of angles-of-attack of $\alpha = [10, 15, 25]^\circ$ and three heights-over-ground $h/c = [2, 0.25, 0.1]$, going from free-flight into ground-effect conditions (selected cases are marked in blue in Fig. 1a,b). For integrity reasons to previous studies, rigid flat-plates are used for comparison. Time-series of the flow development are used to extract the mean flow characteristics, the turbulent kinetic energy and vorticity. The spatio-temporal flow dynamics are investigated by using proper orthogonal decomposition. Finally, membrane dynamics are correlated and phase-averaged to flow and load oscillations.

2. EXPERIMENTAL SETUP

2.1. Wind tunnel and equipment

The experiment was conducted in an open-loop, low-speed blow-down wind tunnel at the University of Southampton. The test section measures 48 cm width by 43 cm height with a free-stream turbulence intensity of less than 0.1%. The turbulence level was measured with hot-wire anemometry. The wind speed could be varied between 2 to 14 m/s and was fixed to 8.4 m/s, reaching a Reynolds number of $Re = 56,000$ for the given experiment. The wind speed is determined by measuring dynamic pressure with a Pitot-static probe together with barometric pressure and ambient temperature, where the latter two are used to determine the air density ρ . The typical uncertainty in the free-stream velocity of the wind tunnel is ± 0.1 m/s and was verified throughout different experiments with flow-field (PIV) and hot-wire measurements (next to pitot-tube recordings).

The experimental setup (Fig. 2) is similar to those used in our previous studies on time-synchronised load and membrane measurements (Bleischwitz et al., 2015a, 2016a) and adds further time-synchronised flow measurements. Key elements of the setup consist of a robotic sting arm for pitch and altitude control of the wings and a rolling road system for ground-effect. Further details of the design process and validation of the ground-effect related hardware can be found via this video-link (Video-Fig.2) and in the above mentioned studies. All time-synchronised load-membrane-flow measurements in the current study are based on one representative wing sample. Spectral content of forces and deformations compared with previous membrane samples showed representative membrane dynamics. In the following, we describe the wing design and the measurement techniques for load, membrane and flow measurements.

Fig. 2 Experimental setup with time-synchronised load (load-cell), deformation (DIC) and flow (PIV) measurements. LED illumination for DIC is illustrated with blue shading, whereas the laser plane is colored in green. Link to video: (Video-Fig.2) (For illustration of the videos, the reader is referred to the web version of this paper.)

2.2. Wing design

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. 3).

The rigid flat plate (Fig. 3a) consists of a 1 mm transparent 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. 3b,c) consists of a flexible latex membrane and a steel frame. The membrane is free-to-rotate around the outer perimeter steel frame to adapt to changes in incoming flow angle, resulting in higher maximum lift and higher stall angles (Bleischwitz et al., 2015b). The latex sheet material has a thickness of $t = 0.2$ mm, density of 1 g/cm^3 and a stiffness of $E = 1.5$ MPa. The aeroelastic parameter $\Pi = (Et/qc)^{1/3}$ (Smith and Shyy, 1996) is found to be $\Pi = 4.27$ for $U_\infty = 8.4 \text{ m}\cdot\text{s}^{-1}$. 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.

Fig. 3 (a) Rigid flat-plate with steel-frame and transparent acrylic window (b,c) Membrane wing with speckle pattern and translucent region for PIV measurements above and below the wing surface at quarter-span. Links to videos: [Video-Fig.3a](#) and [Video-Fig.3b](#) (For illustration of the videos, the reader is referred to the web version of this paper.)

The black membrane has a 10 mm wide translucent latex region at quarter-span to allow laser light for PIV measurements to reach above and below the wing (Fig. 3b,c). This enables access to the flow-field information on the lower side of the wing and dynamic vortex-shedding effects on the upper wing surface. In addition, the translucent membrane region allowed us to run at a higher laser power without cutting through the (light absorbing black) membrane, which improved the PIV correlation values. The translucent latex material strip has the same material properties ($\rho = 1 \text{ g/cm}^3$, $E = 1.5$ MPa, $\Pi = 4.27$) of the surrounding black latex membrane and was bonded to the black membrane with silicon glue (WACKER ELASTOSILTM E41). The bonding had to be done with care, minimising any stiffness differences due to the glue. Both flow-induced static membrane deflections and membrane dynamics were found to be consistent with previous experiments on a continuous black membrane (Bleischwitz et al., 2016a). For the readers interest, Fig. 3 includes two illustrative videos, showing the original camera-acquisition based wing deformations with the speckle pattern (Video-Fig.3a) and post-processed deformations (Video-Fig.3b).

2.3. Load measurement

Forces and moments are measured by a six-axis load-cell (ATI-Nano 17, pre-calibrated following ISO9001 standards) with a load capacity of 25 N. The load-cell is integrated into the sting system (Fig. 2, for further details, please refer to Bleischwitz et al. (2015a, 2016a)). Data is acquired at 10 kHz and over a length of 20 s. The uncertainty in the load cell is ≤ 0.006 N in forces and ≤ 0.03 Nmm in pitching moment. Adjustments of the load-cell calibration-matrix are not possible for the end-user. However, simple static force and moment measurements (using weights and pulleys) validated the calibration that was provided. It should be noted that these ATI load-cells are accepted within the research community as reliable and accurate within its maximum load specifications as evidenced by its wide use (Wahidi et al., 2014; Gardiner et al., 2011; Zhang et al., 2015; Colorado et al., 2012; Timpe et al., 2013).

Fig. 4 shows the mean values in the aerodynamic lift, drag and pitch moment coefficients, accompanied with their uncertainty bounds (errors come mainly from wing sample attachment and the load-cell, errorbars are shown with 68% confidence level). Rigid flat-plates and membrane wings are illustrated in free-flight ($h/c = 2$) and in one

ground-effect case ($h/c = 0.1$) for brevity. Both rigid flat-plates and membrane wings show a very consistent and small uncertainty in their aerodynamic coefficients, even in wing stall conditions. An exemplary membrane wing in free-flight conditions ($h/c = 2$) shows an uncertainty in drag of less than 3% at $\alpha = 0^\circ$ and < 1% for $\alpha \geq 15^\circ$, whereas the flat plate shows a slightly higher uncertainty due to lower drag forces with 5% at $\alpha = 0^\circ$ and < 1% for $\alpha \geq 15^\circ$. Ultimately, the uncertainty levels are found to be sufficient to compare the key parameters of the study (height-over-ground, angle-of-attack, flat-plate vs. membrane wing).

The dynamic behaviour of the experimental setup is separately validated by obtaining the eigenfrequencies 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 eigenfrequencies do not significantly influence the results.

Fig. 4 Uncertainty bounds of aerodynamic coefficients for rigid flat-plate and membrane wings at free-flight ($h/c = 2$) and ground-effect conditions ($h/c = 0.1$)

2.4. Deformation measurement

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. 2, upper). 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 ~ 3 to 5 speckles per mm (~ 2 pixels per speckle).

The patterns (Fig. 3b,c) are illuminated with blue light emitting diodes (LEDs, see blue shading in Fig. 1), allowing to remove the (green) laser light with blue bandpass filters during simultaneous DIC and PIV recordings. The translucent light sheet window 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 image-sequences 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, *LaVision StrainMaster*, is used

to obtain deformations from the stereo images. A subset size of 89×89 pixels with a grid step of 15 pixels is chosen, resulting in an average spatial resolution of $0.03c$. 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.

2.5. Flow measurement

High-speed PIV is conducted by capturing frame pairs at 800 Hz, resolving dynamics in the flow up to 400 Hz (Fig. 2, left). A double-cavity Nd:YLF laser (*Litron LDY-300*) is used with a wavelength of 527 nm. The laser sheet thickness measures 1 mm. 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.

The flow measurements are conducted at quarter-span in a streamwise wing-normal plane. 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. Previous studies on finite wings (Tregidgo et al., 2011; Gordnier and Attar, 2014) showed that the tip-vortex influences the flow along the span, showing a reduced recirculation area and flow reattachment towards the wing tip. However, the flow at the quarter-span position was found to be still predominately driven by (continuously rolling-up) leading-edge vortices, allowing us to correlate streamwise flow dynamics with chordwise membrane dynamics.

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 (DIC-related) LEDs. 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. A planar calibration plate of known grid spacing (acrylic plate with printed dot-pattern) is used to transfer pixel based displacements into millimetres. The calibration plate covers the full individual field-of-view of both side-by-side arranged cameras (each spanning 1616×1088 pixels, equal $148 \text{ mm} \times 100 \text{ mm}$ (streamwise $\times$ height)) and both cameras share a 36 mm wide overlapping region with common calibration points for the later vector-stitching process. The image-pair acquisition frequency is set to 800 Hz, acquiring 5000 images over a total time period of 6.25 s.

The time delay between image pairs is set to $\Delta t = 50 \mu\text{s}$, which results in a peak particle image displacement of about 5-7 pixels. Interrogation areas are set 64×64 pixels with 50 % overlap for a first pass and to 16×16 pixels with 75 % overlap 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 the 36 mm wide overlapping region (in which the vectors are averaged) to obtain a $26 \text{ cm} \times 10 \text{ cm}$ 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 as the translucent latex window reduces the laser light intensity significantly. Nevertheless, it is possible to resolve the mean flow below the wings, which is of specific interest with the descent into ground-effect.

The flow is seeded with $1 \mu\text{m}$ droplets generated using glycerine-water mixture in a typical atomiser (smoke machine MartinTM Magnum 1200). Previous studies with similar high-speed PIV and droplet sizes have shown that those particle are sufficient quick ($\sim 30 \text{ kHz}$) to resolve the given (vortex-shedding dominated) flow scales (Timpe et al., 2013).

2.6. Decomposition of flow

Subsequent sections of this paper will present analysis of the flow-field based on proper orthogonal decomposition (POD). The results of such analysis could depend on the number of vector fields included in decomposition process. Fig. 5 shows the sensitivity of the modes to the number of vector fields included in the decomposition process. It is shown that 1000 (Fig. 5a) and 5000 (Fig. 5b) field both exhibit similar dominant POD-mode shapes in the first five POD-modes. In addition, Fig. 5c shows the energy distribution over the first 30 modes, considering 5000, 2500 and 1000 vector fields. The energy content in the modes is found to vary not more than $< 0.5\%$. Therefore, the POD modes of the flow that are presented in subsequent sections are converged and confirm that the ensemble size of 5000 fields is sufficient.

Fig. 5 Sensitivity analysis of POD on the flow-plane, using 1000 to 5000 images. Spatial POD mode shapes (intensity normalised contours $\sqrt{(U_{POD}^2 + V_{POD}^2)}/U_\infty$) are shown for the first five dominant POD modes (a,b). The energy distribution is reflected for the first 30 modes (c). Exemplary case: Extreme ground-effect ($h/c = 0.1$) at $\alpha = 15^\circ$. Ultimately, the ensemble size (between 1000 and 5000 images) does not show any significant impact on the POD mode shapes and their energy content.

3. Results

The results cover time-averaged flow-fields for rigid flat-plates and membrane wings at different angles-of-attack and heights-over-ground. In addition, the flow dynamics are broken down into their spatial and spectral content. Coupling dynamics are shown between the membrane and the flow as well as the load, the membrane and the flow. Finally, cycle-averaging is used to explain load-membrane-flow coupling over one representative cycle.

3.1. Flow-statistics

Fig. 6 shows contours of the time-averaged speed $\sqrt{(U^2 + V^2)}/U_\infty$ together with the mean streamline patterns. Rigid flat-plates and membrane wings are compared at three different angles-of-attack $\alpha = [10, 15, 25]^\circ$, going from free-flight ($h/c = 2$) into moderate ($h/c = 0.25$) and extreme ground-effect conditions ($h/c = 0.1$). The wing position of both rigid flat-plate and membrane wings is represented with a white line (with black outline) and reflects DIC-based time-averaged deformations for the membrane wing cases. The positioning error of the wing sections to the flow plane measures $< 0.03c$ and is probably caused by a slight mounting imperfections of the wing (as wing LE/TE points reference to the wing tips and not quarter-span). Due to the small maximum membrane fluctuations ($\pm 1mm$ from mean), a static PIV mask is used and therefore the flow information within the region of the membrane fluctuation is discarded.

Both rigid flat-plate and membrane wings show large separation regions for increased angles-of-attack and reduced heights. The growth in flow separation within GE is related to a strong flow diversion over the upper wing surface, caused by the flow blockage on the lower side of the wing in GE (Qu et al., 2014). However, the ability to adapt to a mean camber (due to the effect of mean dynamic pressure) allows membrane wings to reduce the size of the separation region for both high α or low height-above-ground. The adaptability has limitations for $\alpha = 25^\circ$ in extreme GE and similar post-stall conditions, where both wings behave similar as a bluff body, as static and dynamic camber movements can not counteract the growing risk of flow detachment from the upper wing surface. Nevertheless, membrane wings show a separation region at $\alpha = 25^\circ$ in free-flight conditions (Fig. 6f, upper) which is similar in size to rigid flat-plates at $\alpha = 15^\circ$ (Fig. 6c, upper). Similarly, membrane wings show a separation region at $\alpha = 25^\circ$ in extreme GE (Fig. 6f, lower) which is comparable in size to the separation region exhibited by rigid flat-plates at the same incidence in free-flight conditions (Fig. 6e, upper).

The vicinity of the ground 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 well known from literature (Rozhdestvensky, 2006; Qu et al., 2014) and is accompanied with predominant lift generation at the lower side of the wing, reducing the aerodynamic impact of the upper wing surface. Membrane wings reflect the ram-effect by extending their maximum membrane camber with descent into GE, even while exhibiting fully separated flow conditions on the upper wing surface (Bleischwitz et al., 2016a).

Lower heights above ground are accompanied by downstream movement of the centroid of the separation bubble. This can be seen specifically for high angles-of-attack of $\alpha = 25^\circ$. Rigid wings (Fig. 6e) exhibit separation bubbles whose centroid appears close to the trailing-edge or even farther downstream. In contrast, membrane wings (Fig. 6f) show separation regions appearing close to the upper membrane surface. The chordwise or height location of the separation bubble becomes specifically important for fluid-structure interactions and resulting lift generation, discussed later on in more detail.

Tab. 1 gives further insight into flow modifications (specifically flow diversion over the upper wing surface), caused by wing flexibility, angle-of-attack and height-over-ground changes. The flow diversion at the leading-edge is of major importance for the separation behaviour (and coupling ability) of the airfoil and is qualitatively estimated by the upwash-angle (α_{UP}), measured from inclination of the streamline at the leading-edge to the horizontal direction (as sketched in Tab. 1). As previously mentioned, membrane wings exhibit camber related smaller separation regions compared to rigid flat-plates, resulting in a reduced incoming upwash-angle (similar to a reduction in effective angle-of-attack). Therefore, a membrane wing in pre-stall flow conditions exhibits a reduced incoming upwash-angle at the leading-edge by $2-5^\circ$. Ground-effect causes an increase in the incoming upwash-angle, caused by the constrained flow at the lower wing surface. For moderate angles-of-attack of $10^\circ \leq \alpha \leq 15^\circ$, both rigid flat-plate and membrane wings show an increase in the upwash-angle by $7-11^\circ$ when moving from free-flight ($h/c = 2$) into extreme ground-effect conditions ($h/c = 0.1$). At $\alpha = 25^\circ$, ground-effect causes a significant incline in the upwash-angle of up to 27° ,

(a) $\alpha = 10^\circ$, rigid flat-plate

(b) $\alpha = 10^\circ$, membrane

(c) $\alpha = 15^\circ$, rigid flat-plate

(d) $\alpha = 15^\circ$, membrane

(e) $\alpha = 25^\circ$, rigid flat-plate

(f) $\alpha = 25^\circ$, membrane

Fig. 6 Freestream normalised velocity magnitude and streamlines for rigid flat-plate and membrane wings at $\alpha = [10, 15, 25]^\circ$, modifying with height-over-ground $h/c = [2, 0.25, 0.1]$. Lift-coefficients C_L are shown for all cases.

Tab. 1 Upwash-angle (α_{UP}) at leading-edge (in reference to horizontal), modifying with angle-of-attack, height-over-ground and wing type(rigid flat-plate/membrane wing).

reflecting the increasing mass-flow which has to be diverted over the upper wing surface. These results are consistent with previous findings obtained for rigid wings in ground-effect at $\alpha = 6^\circ$ (Vogt and Barber, 2012).

Fig. 7 shows contours of turbulent kinetic energy $(U'^2 + V'^2)/U_\infty^2$ that highlights the regions of unsteady flow. Again, rigid flat-plate and membrane wings are compared for three angles-of-attack and three heights-over-ground. Rigid flat-plate wings (Fig. 7a,c,e) have generally strong velocity fluctuations close to the trailing-edge or even further downstream. In comparison, membrane wings exhibit strong velocity fluctuations close to the upper wing surface (Fig. 7b,d,f). Interesting to note, membrane wings at $\alpha = 25^\circ$ in ground-effect (Fig. 7f) show a vertical upwards movement of the highly energetic flow structures from the membrane surface, suggesting a fading influence in fluid-membrane coupling.

Fig. 8 shows contours of the time-averaged vorticity $\bar{\omega}c/U_\infty$ of rigid flat-plate and membrane wings for different angles-of-attack and heights-over-ground. The figures show strong vorticity values with opposite signs at leading and trailing-edges. The vorticity magnitude is in agreement with previous studies at comparable Reynolds numbers (Gordnier, 2009; Timpe et al., 2013). Both rigid flat-plate and membrane wings exhibit strong vorticity at the trailing edge along a line that is parallel to the ground. In comparison, wings in free-flight conditions exhibit a vortex street that is parallel to the wings chord line. This suggests strong TE-vortex interaction within GE and this is consistent with previous ground-effect studies (Prasad and Damodaran, 2013). Additionally, membrane wings are found to relocate the vorticity at the leading-edge. This is primarily due to introduction of small-scale vorticity in to the flow due to the vibrations of the membrane. As a result, membrane wings (Fig. 8b,d,f) show more intense attached vorticity close to the LE than seen for rigid flat-plates (Fig. 8a,c,e).

(a) $\alpha = 10^\circ$, rigid flat-plate

(b) $\alpha = 10^\circ$, membrane

(c) $\alpha = 15^\circ$, rigid flat-plate

(d) $\alpha = 15^\circ$, membrane

(e) $\alpha = 25^\circ$, rigid flat-plate

(f) $\alpha = 25^\circ$, membrane

Fig. 7 Turbulent kinetic energy for rigid flat-plate and membrane wings at $\alpha = [10, 15, 25]^\circ$, modifying with height-over-ground $h/c = [2, 0.25, 0.1]$.

(a) $\alpha = 10^\circ$, rigid flat-plate

(b) $\alpha = 10^\circ$, membrane

(c) $\alpha = 15^\circ$, rigid flat-plate

(d) $\alpha = 15^\circ$, membrane

(e) $\alpha = 25^\circ$, rigid flat-plate

(f) $\alpha = 25^\circ$, membrane

Fig. 8 Time-averaged vorticity for rigid flat-plate and membrane wings at $\alpha = [10, 15, 25]^\circ$, modifying with height-over-ground $h/c = [2, 0.25, 0.1]$.

3.2. Spatial Flow Structures

Leading-edge vortex-shedding and break-down are difficult to observe in instantaneous snapshots since this phenomena is accompanied by other smaller-scale vorticity carrying features, which are known to depend significantly on the given Reynolds number. Studies of [Visbal et al. \(2009\)](#); [Gordnier \(2009\)](#) focused on the Reynolds number effect and found that higher Reynolds numbers ($Re > 10^4$) reduce the coherence of flow structures and interactions with the surface boundary layer, resulting in a higher amount of small scale vortical features. For the given Reynolds number of the current study of $Re = 56,000$, it is found useful to filter out the effects of these smaller flow scales in order to examine the interaction between the leading-edge vortex and the membrane. Proper orthogonal decomposition (POD) offers one way to group the energetic flow structures that are coherent and is often used as a tool within the literature ([Shi et al., 2013](#); [Schmit et al., 2003](#); [Lian et al., 2003](#); [Kostas et al., 2002](#)). For details of POD snapshot method, which is used within this flow related POD study, the reader referred to the previous publications [Lumley \(1967\)](#); [Sirovich \(1987\)](#) and more recently [Pinnau \(2008\)](#).

Some studies ([Lengani et al., 2014](#); [Wee et al., 2004](#)) have shown that the first two most energetic POD modes shapes often appear coupled as pairs and with a defined spatial shift of $1/4$ of the total spatial shedding cycle (wavelength defined between two POD-peaks), allowing to describe the convecting (rolling-down) nature of vortex-shedding and its coherence in velocity fluctuations.

Fig. 9 Instantaneous snapshot of horizontal (U'), vertical (V') velocity and vorticity (ω') fluctuations. Additionally, streamlines are illustrated, based on velocity fluctuation components (U' , V'). Effect of POD as filter technique on highly dynamic flow components and streamlines (using the first five modes). Exemplary case: Extreme GE ($h/c = 0.1$) at $\alpha = 15^\circ$. (For illustration of the videos, the reader is referred to the web version of this paper.)

[Fig. 9a](#) shows a snapshot of velocity components U' (upper), V' (mid) and vorticity ω' (lower) together with the instantaneous streamline patterns (U' , V'). Additionally, instantaneous membrane fluctuations are shown around their mean (dotted). Flow structures and streamlines are hard to identify at a given time-snapshot and come often without distinct coherent structures ([Fig. 9a](#)). [Fig. 9b](#) represents the same snapshot of the flow, reconstructed using the first five most energetic POD modes. The POD reconstructed flow ([Fig. 9b](#)) contains only $\sim 35\%$ of the total flow fluctuation energy (not shown) due a wide range of energetic scales in the flow (and a selection of only the first five POD-modes). As a result, the peak values of the POD-related color-bars in the POD reconstructed flow [Fig. 9b](#) are reduced accordingly to account for the energy loss and allow better illustration of filter. The filtered fields reveal coherent leading-edge vortex-shedding with distinct streamlines ([Fig. 9b](#)). It is interesting to note that the vertical

flow fluctuations (Fig. 9b, mid) seem to correlate well with vertical membrane motions. For the readers interest, Fig. 9 includes two illustrative videos, showing the time-series of the original (Video-Fig.9a) and POD-reconstructed flow (Video-Fig.9b).

Figures Fig. 10 and Fig. 11 show for $\alpha = 15^\circ$ and 25° , the five most energetic POD modes (a1,...,a5) of the kinetic energy ($\sqrt{(U_{POD}^2 + V_{POD}^2)}/U_\infty$). Rigid flat-plates and membrane wings are compared for free-flight ($h/c = 2$) and extreme ground-effect conditions ($h/c = 0.1$). Contours in each individual subplot are normalised such that the peak value is 1 (colored black). Additionally, the energy contribution of individual POD coefficients (E_{POD} in %), relative to the total fluctuation energy, is illustrated on the top right corner of each contour plot. For clarity, a high energy contribution of a POD mode shape (E_{POD}) relates to predominant, highly energetic and coherent flow features within the overall flow surrounding. As previously mentioned, predominant leading-edge vortex-shedding structures and their roll-down behaviour can already be described with the first two highest POD mode shapes. POD coefficients of lower order (and lower energy content) have to be seen with care, as they do not necessarily describe a physical phenomenon since they are projections of the flow-field on to orthogonal basis functions.

Both rigid flat-plates and membrane wings show coherent flow structures which can be related to leading-edge vortex-shedding. The dynamics of rigid flat-plates in free-flight at $\alpha = 15^\circ$ (Fig. 10a) show comparable shedding structures to membrane wings at $\alpha = 25^\circ$ (Fig. 11b). This implies that membrane cambering and dynamic motions help to retain similar flow conditions at drastically higher angles-of-attack ($\Delta\alpha = 10^\circ$), providing superior lifting capabilities to typical rigid flat-plates (up to 75%, see Fig. 1a). Similarly, membrane wings benefit within ground-effect due to their ability to use growing separated flow dynamics to their own benefit, enlarging the overall performance window compared to rigid wings (Fig. 1b).

The narrow performance window for rigid flat-plates (Fig. 1a,b) can be clearly related to the flow structures that are mainly located close to the trailing-edge or even further downstream (as identified by POD modes, see Fig. 10a,c and Fig. 11a,c). In addition, the lack of wing vibrations with rigid flat-plates results in a relatively steady recirculation bubble over the upper wing surface at high angles-of-attack / low ground-heights, avoiding further lift production. This steady recirculation bubble is known from previous studies on rigid cambered wings (Rojratsirikul et al., 2009) and its formation appears independent of the mean camber. In contrast, membrane wings show mostly closely attached vortical structures of the flow which roll down (if the first two POD modes are combined within a time-series) the chord along the membrane (Fig. 10b,d and Fig. 11b). These energetic (and lift producing) structures remain apparent under GE conditions, but are lifted up vertically from the membrane surface (Fig. 11d) rather than moving downstream towards the TE as seen for rigid flat-plates (Fig. 11c). This suggests that membrane oscillations still influence the flow structures passing over the wing, but the resulting energy entrainment is not sufficient to keep the flow structures closely attached to the upper wing surface. Nevertheless, membrane wing dynamics are found to actively enhance leading-edge vortex roll-up close to the upper (oscillating) wing surface. For the readers interest, all cases of Fig. 10 and Fig. 11 are shown with illustrative videos, which can be found in their individual sub-caption (Video-Fig.10a to Video-Fig.11d).

(a) Rigid flat-plate, Free-flight, [Video-Fig.10a](#)

(b) Membrane, Free-flight, [Video-Fig.10b](#)

(c) Rigid flat-plate, Extreme GE, [Video-Fig.10c](#)

(d) Membrane, Extreme GE, [Video-Fig.10d](#)

Fig. 10 Five most energetic POD mode shapes of averaged velocity fluctuations $\sqrt{(U_{POD}^2 + V_{POD}^2)}/U_\infty$. Comparison of rigid flat-plate and membrane wings at moderate angle-of-attack of $\alpha = 15^\circ$, changing from free-flight ($h/c = 2$) into extreme GE ($h/c = 0.1$). Rigid flat-plates show mid-wing to TE located dynamics in vortex-shedding, moving downstream with GE. Membrane wings show with their usage in GE flow dynamics happening close to membranes surface. (For illustration of the videos, the reader is referred to the web version of this paper.)

(a) Rigid flat-plate, Free-flight, [Video-Fig.11a](#)

(b) Membrane, Free-flight, [Video-Fig.11b](#)

(c) Rigid flat-plate, Extreme GE, [Video-Fig.11c](#)

(d) Membrane, Extreme GE, [Video-Fig.11d](#)

Fig. 11 Five most energetic POD mode shapes of averaged velocity fluctuations $\sqrt{(U_{POD}^2 + V_{POD}^2)}/U_\infty$. Comparison of rigid flat-plate and membrane wings in post-stall conditions of $\alpha = 25^\circ$, changing from free-flight ($h/c = 2$) into extreme GE ($h/c = 0.1$). Rigid flat-plates show vortex-shedding happening downstream of TE. Membrane wings show in free-stream conditions strong dynamics close to membrane surface (b), which remain but detach from the wing surface within GE conditions (d). (For illustration of the videos, the reader is referred to the web version of this paper.)

3.3. Spectral Flow Content

Fig. 12 shows the spectral content of vertical flow fluctuations $PSD(V')$ at a selection of flow-listener points (L1–L5). Rigid flat-plate and membrane wings are compared for the case of $\alpha = 15^\circ$ and $h/c = 0.1$. Vertical flow dynamics are chosen as they are clearer in showing correlation to the membrane dynamics (compared to horizontal fluctuations that have more broadband information). The listener points are illustrated within the contour plots of vertical velocity fluctuations $\sigma(V)$. The flow frequency is shown normalised by the chord length c and free-stream velocity U_∞ and is depicted as a Strouhal-number $St = \frac{fc}{U_\infty}$. This type of frequency normalisation is commonly used in the literature (Molkia and Breuerb, 2010; Rojratsirikul et al., 2011; Prasad and Damodaran, 2013; Bleischwitz et al., 2016b).

Fig. 12 Spectral content of flow fluctuations V' for rigid flat-plate and membrane wings, illustrated at a selection of listener points (L1,...,L5) in the wake. Exemplary case at $\alpha = 15^\circ$ and $h/c = 0.1$.

The shear layer energy as shown in Fig. 12 appears to be similar for rigid flat-plate and membrane wing. The relatively weak shedding energy for the rigid flat-plate (Fig. 12a, lower) is saturated by the broadband energy of the shear layer. In comparison, membrane wings show a clear peak in dominant shedding frequency of $St = 0.74$, suggesting membrane vibrations driven and enhanced vortex-shedding. Consequently, the energy values appear highest for listener points placed closer to the wings surface (L1) and immediately behind the trailing-edge (L4). Details of fluid-membrane coupling are discussed later in Section 3.4.

Since the frequency spectra is more broadband for rigid flat-plates (Fig. 12a), a POD-based filtering was first applied to the original flow signal, enabling identification of the dominant vortex-shedding frequency in the wake of the wing. Fig. 13 shows an example of the original and POD-filtered spectra for a rigid flat-plate at $\alpha = 15^\circ$ and $h/c = 0.1$. As mentioned previously, the raw vector-fields (Fig. 13a, upper) consist of diverse flow scales with similar energy content (Fig. 13a, lower). The POD-filtered flow-field (Fig. 13b, upper) removes less energetic background scales and enables to focus on the spectral content of the structures of interest (here leading-edge vortex). As a result, the interpretation of the spectra becomes easier and allows resolution of the dominant shedding frequency of the rigid flat-plate with $St = 0.64$ (Fig. 13b, lower).

Fig. 14 illustrates the dominant vortex-shedding frequencies St_{wake} for rigid (red) and membrane (black) wings for different angles-of-attack (x-axis) and heights-above-ground (marker-shape). Generally, the wake shedding frequency of rigid flat-plates is found to match well with the observations of previous studies on flat/cambered plates, where the Strouhal number was found to be in the range $0.17 \leq St_{wake} \sin \alpha \leq 0.23$ (Rojratsirikul et al., 2011). The shedding frequencies of membrane wings (black markers) are significantly higher than the natural shedding frequencies

Fig. 13 Usage of POD-filtering (using first five modes) to gain easier access to the vortex-shedding frequency in highly unsteady flow conditions. The contour plots show time-instant snapshots in vertical velocity fluctuations. The spectra bases on vertical flow fluctuations at the listener points L1(1.25, 0.2) and L2(2, 0.2). Exemplary case of a rigid flat-plate at $\alpha = 15^\circ$ and $h/c = 0.1$.

of (flat/cambered) rigid wings, suggesting modifications of the flow dynamics due to fluid-structure interactions. The flow provides the energy required for fluid-structure coupling, but the inherent membrane eigenfrequencies (and harmonics) dictate the shedding frequency of the flow (depending on membrane pre-tension and flow induced membrane tensioning, see [Song et al. \(2008\)](#)). Similar wing driven flow modifications are known from the literature by other membrane wing related studies ([Timpe et al., 2013](#)) or wings with active flow control ([Miranda et al., 2005](#)). Detailed spectral comparisons and coupling between the membrane and the flow will be further discussed in the following section of this paper.

It should be noted that membrane wings at $\alpha = 10^\circ$ (all heights) and $\alpha = 15^\circ$ (free-flight, see [Fig. 10b](#)) show attached flow conditions and therefore no dominant (or hardly resolvable) shedding frequencies. As a result, those cases are discarded from the spectral summary in [Fig. 14](#).

Fig. 14 Summary of vortex-shedding frequency, comparing rigid flat-plates (red markers) and membrane wings (black markers) at different angle-of-attack and height-over-ground. The dominant Strouhal number of rigid flat plates (red markers) matches well to literature based flat/cambered plates (blue-shaded $d/\sin \alpha$ rule, where $0.17 \leq d \leq 0.23$, see [Rojratsirikul et al. \(2011\)](#)).

3.4. Coupling: Membrane-Flow

A recent study on batten-reinforced membrane wings correlated membrane dynamics with simultaneously recorded flow dynamics ([Timpe et al., 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.

The individual contour plots of [Fig. 15a](#) show the cross-correlation, at zero time-lag, between the vertical membrane fluctuations at a listener point (M), placed $0.4c$ downstream of the leading-edge, and the vertical flow fluctuations (V') at different listener points across the flow. Three different heights-over-ground from free-flight ($h/c = 2$) into GE conditions ($h/c = 0.25$ and 0.1) are compared for a fixed angle-of-attack of $\alpha = 25^\circ$. Instantaneous membrane fluctuations are shown amplified by factor of 7 for clarity. [Fig. 15b](#) shows the normalised cross-correlation function (CCF) between the membrane and specific flow listener points (P1, P2 and P3 as shown in the figure) at a given height.

In free-flight conditions ([Fig. 15a](#), upper), perimeter reinforced membrane wings show with $\text{CCF} > 0.5$ ([Fig. 15b](#), upper) similar in-phase flow-membrane coupling as found for batten-reinforced membrane wings ([Timpe et al., 2013](#)). An exemplary leading-edge localised upwards camber movement comes with a instantaneous vertically upwards directed flow and vice versa ([Fig. 15a,b](#), upper). The vertically directed flow structures originate at the leading-edge and are shed due to the vertical motion of the membrane. The given perimeter reinforced membrane wing type shows strong correlations close to the leading-edge, initiating and promoting vortex-shedding from the beginning. In addition, the free-to-rotate membrane attachment likely helps the exploitation of coupling dynamics ([Bleischwitz et al., 2015b](#)). Overall, the results suggest that wing flexibility, especially close to the leading-edge could enhance 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 1% of the chord (roughly 1 mm) in peak regions ([Bleischwitz et al., 2016a](#)) but can significantly influence the flow dynamics.

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. [Fig. 15](#) demonstrates this by moving a membrane wing at $\alpha = 25^\circ$ from free-flight ($h/c = 2$, [Fig. 15a](#), upper) into GE conditions ($h/c = 0.25$ and 0.1 , [Fig. 15a](#), mid and lower). The

Fig. 15 Cross-correlation (CCF) between vertical membrane fluctuation (amplified by a factor of 7 for clarity) at point M ($x/c = 0.4$) and vertical flow fluctuation velocity (V') at listener point (P_n), changing with height-over-ground at a fixed angle $\alpha = 25^\circ$. The contour plots base on zero time lag.

vicinity of the ground forces the flow to detach from the wing surface (Fig. 15a, lower), resulting in a phase lead of the flow to the membrane with 60° phase-shift (Fig. 15b, lower). Previous force results show that this decoupling is accompanied with a loss in lift (Fig. 1a) and an increase in drag (Bleischwitz et al., 2016a). Therefore, it is shown that lifting benefits of membrane wings can be related to a phase-free coupling between the membrane and the flow. In addition, the coupling has its limitations, which can be seen by a phase-shift between membrane and flow dynamics (Fig. 15b). For the given study, the case $\alpha = 25^\circ$ for $h/c = 2$ and $\alpha = 15^\circ$ for $h/c = 0.1$ show both lag-free fluid-structure coupling (resonance conditions). The case in free-flight conditions ($h/c = 2$) appears comparable to findings in the literature (Rojratsirikul et al., 2011). The discovery of both (lag-free) cases bases on an intensive prior parametric study with pure load and membrane deformation measurements (Bleischwitz et al., 2016b), which allowed to identify (angle-of-attack and height) conditions, where the membrane changes its vibration behaviour from three to two chordwise mode shapes (known to be key for intensive fluid-structure coupling, see Rojratsirikul et al. (2009)). The resonance points, at which a membrane wing engages/promotes lag-free coupling with the vortical flow structures, may vary by different membrane properties, boundary and flow conditions (not considered in detail within this study). Ultimately, stimulated fluid-membrane coupling of membrane wings is found to result in enlarged performance windows compared with rigid wings, allowing larger ranges of efficient angles-of-attack and heights-over-ground.

3.5. Coupling: Load-Membrane-Flow

Fig. 16 gives an extended overview of the coupling of aerodynamic loads, membrane oscillations and dynamic flow structures, measured at $\alpha = 25^\circ$ in free-flight conditions. Fig. 16a shows free-stream normalised vertical flow fluctuations $V'(t/T)/U_\infty$ at three instances (t/T) over one membrane oscillation cycle at a dominant Strouhal number of $St = 0.81$. The time-steps t are normalised with the fundamental period of the membrane vibration ($T = 1/f$, where $f = 68\text{Hz}$). Also shown are streamlines computed from low-pass filtered velocity fields (using the first five POD modes). 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. Note that the fluctuation is amplified

by a factor of 7 in order to display the vertical displacement of the membrane better. Flow fluctuations below the wing surface are removed due to resolution limitations of the setup (low correlation values < 0.4 below the wing surface).

At time-step $t/T = 0$ (Fig. 16a, 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. 16a, 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 at time-step $t/T = 1$ (Fig. 16a, lower), where the situation is the similar to that of time-step $t/T = 0$.

Dynamics in flow and membrane oscillations are also transferred into aerodynamic load fluctuations, which are shown in Fig. 16b. At t/T near zero, the wing shows a reducing total lift (blue-shaded), increasing drag (red-shaded) and a trend towards a pitch-up moment (green-shaded). This relation flips at a later stage $t/T \geq 0.5$, showing gain in lift, decrease in drag and increasing pitch-down moment.

Fig. 16c compares the spectra of all three load components (lift, drag and pitch), membrane deformation (at 40%-chord from leading-edge) and vertical velocity fluctuation (at Listener point L1 as shown in the lower right edge of the figure). The spectra reveals that the membrane motions, loads and flow are clearly linked. The membrane (Fig. 16c, mid) exhibits dominant oscillation frequencies of $St = 0.81$ (1st harmonic) and $St = 1.62$ (2nd harmonic). Both membrane frequencies are also detected in the loads and the flow spectra, suggesting strong coupling of membrane dynamics with the flow and loads. The most dominant membrane oscillation frequency of $St = 0.81$ is significantly different from the typical natural shedding frequencies of (flat/cambered) rigid wings which is around $St = 0.40$ to 0.54 for the given case (Fig. 14). This result confirms the ability of flexible membrane wings to modify the frequency of vortex shedding by the vibration eigenfrequency of the membrane.

The cross-correlation between the flow and the membrane (Fig. 16d, upper), the loads and the membrane (Fig. 16d, mid) and the loads and the flow (Fig. 16d, lower) underlines strong coupling between each other. The aerodynamic coefficients in lift and drag show a slight delay to membrane motions with a phase shift of $\sim 30^\circ$. This phase-shift is likely caused by membrane inertia effects, however, further studies are required to examine this in more detail.

Fluid-membrane coupling has its limitations and (lag-free) fluid-membrane coupling cannot always been sustained. Comparing the wing in (highly in-phase coupled) free-flight conditions at $\alpha = 25^\circ$ (Fig. 16) to extreme GE ($h/c = 0.1$), the ground-effect case shows a growing flow diversion over the upper wing surface (reflected by a high upwash-angle, see Tab. 1) which enforces flow detachment from the wing surface (Fig. 17a). The vertical detachment of the vortex-street starts from the trailing-edge and grows towards the leading-edge. As a result, the coupling between membrane dynamics (fundamental period of the membrane vibration $f = 64\text{Hz}$ or $St = 0.76$) and the vortex-street reduces in streamwise extent and is limited to the an area close to the leading-edge. This also results in a phase shift of 60° between the membrane and the flow (Fig. 17d, upper) which is accompanied with a declining and phase-shifted correlations between the loads and the flow (Fig. 17d, lower). The increasing phase-difference reflects a delayed response between the signals, resulting in a degrading overall wing performance (Fig. 1b). For the readers interest, both cases of Fig. 16 and Fig. 17 are available with illustrative videos, which can be found in their figure-caption or directly here (Video-Fig.16 and Video-Fig.17).

Fig. 16 Load-membrane-flow interactions at $\alpha = 25^\circ$ in free-flight conditions of $h/c = 2$. (a) Time-snapshots show vertical flow and membrane fluctuations (latter amplified by a factor of 7 for clarity) during one membrane cycle. Streamlines based on POD-filtered flow fluctuations. (b) Time-corresponding development in lift, drag and pitch moment fluctuations. (c) Spectral signature of load-membrane-flow dynamics and their (d) phase relation between each other. Membrane dynamics show strong coupling with LE-vortex-shedding, allowing improvements in overall wing performance (Fig. 1b). Link to video: [Video-Fig.16](#) (For illustration of the video, the reader is referred to the web version of this paper.) .

(a) Vertical flow + membrane motions

(b) Load time-series

(c) Spectra of loads/membrane/flow

(d) Cross-correlation

Fig. 17 Load-membrane-flow interactions at $\alpha = 25^\circ$ in extreme GE of $h/c = 0.1$. (a) Time-snapshots show vertical flow and membrane fluctuations (latter amplified by a factor of 7 for clarity) during one membrane cycle. Streamlines based on POD-filtered flow fluctuations. (b) Time-corresponding development in lift, drag and pitch moment fluctuations. (c) Spectral signature of load-membrane-flow dynamics and their (d) phase relation between each other. Within GE, flow and membrane dynamics get out of phase. Coupling between lift, membrane and flow dynamics reduces. Link to video: [Video-Fig.17](#) (For illustration of the video, the reader is referred to the web version of this paper.)

3.6. Coupling: Cycle-averaging

[Fig. 18](#) summarises the flow-structure interaction by showing cycle-averaged load fluctuations (mean-value subtracted), membrane and flow dynamics for the highly coupled case at $\alpha = 25^\circ$ in free-flight conditions ($h/c = 2$). The cycle-average comprises of over 420 individual cycles at the dominant frequency of $St = 0.81$, ranging over a recording period of 6.25s. The resulting cycle measures 12 phase points per cycle. The cycle averaged loads show lift, drag and pitch moment fluctuations which are normalised such that the peak value is 1. Vertical velocity fluctuations are shown for different phases ($[0, 65, 130, 229, 294, 360]^\circ$) and are low-pass filtered using the first five POD-modes. Vertical upwards motions of the membrane and the flow-field are coloured in red, whereas downwards motions are shown in blue. Coherent LE-vortices are initiated at the LE and convect downstream over the wing surface into the wake.

[Fig. 18](#) shows at the beginning of the cycle at $0^\circ \leq Phase \leq 65^\circ$ an instantaneous upwards velocity fluctuation (red) close to the LE which comes with an upwards deflected membrane at the same chordwise position, resulting in low lift, high drag and a pitch-up moment fluctuations. The streamwise convection of LE-vortex structures to $130^\circ \leq Phase \leq 229^\circ$ results into a downwards facing flow and membrane motion (blue) close to the LE which results in increasing lift, reduced drag and inclining pitch-down moment fluctuations. The results reveal the strong link between enhanced dynamics of the wing structure and its impact on flow and load dynamics, providing superior aerodynamic properties for wings with enhanced fluid-to-membrane coupling.

For the readers interest, [Video-Fig.18](#) shows an illustrative video interpretation of [Fig. 18](#).

Fig. 18 Membrane based cycle-averaged load fluctuations (left, mean-values subtracted) and vertical flow dynamics, illustrated for $h/c = 2$ and $\alpha = 25^\circ$. Vertical membrane and flow fluctuations are colored red for upwards and blue for downwards motions. Link to video: [Video-Fig.18](#) (For illustration of the video, the reader is referred to the web version of this paper.)

4. Conclusion

Wind tunnel experiments were conducted at a Reynolds number of $Re = 56,000$ by using rectangular rigid flat-plate 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 lower ground-clearance forces premature flow separation, accompanied with an early onset of leading-edge vortex-shedding and drag increase. Generally, membrane motions are found to be able to couple with (either high angle-of-attack or GE-induced) flow separation, which allow to retain time-averaged attached flow conditions by promoting coherent vortex-shedding close to the upper wing surface, resulting in enhanced lift capability and a larger performance window to non-flexible wings. An in-phase coupling between the membrane and the flow reveals to be a major key to improve the aerodynamic performance under separated flow conditions.

Under extreme conditions such as extreme ground-effect or post-stall angles-of-attack, the phase difference between the flow and membrane increases signalling an end to the direct flow-membrane coupling. Even under this extreme conditions, the dynamics of membrane motions are capable to retain the development of leading-edge vortex-shedding, but the vortical flow structures appear lifted up vertically from the membrane surface. This results in loss in lift and increase in drag. This behaviour is different to rigid flat-plate wings which show generally a smaller aerodynamic performance window due to the early development of a steady recirculation zone above the wing surface, accompanied with vortical shedding structures happening rather downstream from the trailing-edge.

Acknowledgements

We gratefully acknowledge the support from the In addition, we gratefully acknowledge *LaVision*, and in specific Dr. Alex Nila for their/his individual and always timely support. We are also grateful to the editor and two anonymous referees for their comments that enabled us to improve this manuscript. Data published in this paper are available from the University of Southampton repository at: <http://dx.doi.org/10.5258/SOTON/401925>.

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