Fluid Structure Interactions in Low Aspect Ratio Membrane Wings

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Biological systems have inspired many engineers to investigate the use of flexible membranes in wings for applications involving small flying vehicles. Flexibility in wing surfaces allow for passive shape adaption (adaptive cambering), which has been shown to increase aerodynamic efficiency and flight stability for many small remotely piloted and autonomous vehicles. Recently, many numerical and experimental studies have been conducted to develop a better understanding of the fluid structure interactions and how they affect the aerodynamic performance of the wing. These studies have concentrated on the effects of extensible membranes with both fully rigid boundaries and free trailing edges which have demonstrated some differences. In the current study time dependent velocity and surface deformation measurements are acquired simultaneously for a membrane wing with an aspect ratio of 2. From these measurements the effects of the rubber membranes are shown to highly correlated with the velocity field and significantly alter the flow patterns compared to a rigid wing of the same aspect ratio.

The wings examined here were constructed of an aluminum frame with a pre-tensioned black rubber adhered to it using a methodology presented in Abudaram et al. (2014) and can be seen in the figure below. Each of the membranes cells had a free trailing edges and were scalloped to approximately 25% of the membranes length. For the results reported here pre-tension values of 1% and 4% were investigated.

Fig. 1 Aspect Ratio 2 Membrane wing

Time dependent two component particle image velocimetry (PIV) and digital image correlation measurements (DIC) were acquired with a free stream velocity 10 m/s resulting in a chord based Reynolds number of approximately 50,000. The angles of attack investigated ranged from 4 to 20 degrees. The PIV measurements were acquired one the centerline of the wing in two domains; one directly over the wing, and one in its wake. The digital image correlation measurement extended over a domain which included all three cells allowing to examine phasing in-between them. Both the PIV and DIC were sampled at 800 Hz for a contiguous block of 1024 samples. Synchronization of the measurement systems was accomplished with a pulse generator syncing the DIC camera to the PIV camera’s sync out. The DIC measurements were acquired on the pressure side of the wing and high-pass (>600 nm) optical filters, which offer zero percent transmittance of the 532 nm laser light were used to eliminate the light from the PIV system corrupting the measurements. A photograph of the experimental setup is included in figure above.

Examination of the mean and turbulent flow fields showed significant differences for the membrane wings similar to the larger aspect wing studied by Timpe et al. (2013). From examination of mean streamwise velocity field there is evidence of a slight increase in the stall angle for the membrane wing compared to the rigid counterpart. Additionally the width of the wake, in the center plane of the wing, was significantly narrowed due to the release of the fluid from under the wing and the shrinking of the recirculation bubble on the suction side of the wing. The membrane models also demonstrated a redistribution of both the normal and shear components of the turbulent stresses as compared to the baseline rigid model. This provided further evidence of smaller recirculation bubble and a thinner wake due to increased momentum transport.

Measurements of the membrane’s deflections demonstrated both static and dynamic phenomena. The static phenomenon was an increased cambering of the wing due to the pressure differential across the wing associate with lift. The dynamic phenomenon appears as the time dependent membrane motion appears to consist of the superposition of a standing and traveling wave pattern. The level of pretension applied to the membrane affected these frequencies and wave speeds as expected. Additionally, aerodynamic tensioning, which is a function of angle of attack, had a similar affect as it was increased. Spectral analysis of the velocity membrane fluctuations showed them to be in sync and appear to be driven by the membranes characteristics.

References