FLEXIBLE WING AERODYNAMICS AT LOW REYNOLDS NUMBERS

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Abstract

In this paper, the research performed on flexible-wing Micro Air Vehicle (MAV) is described. Flexible-wing MAV is renowned for improved lift characteristics and smooth flight in gusty conditions than its rigid-wing counterpart. The wind-tunnel experiments are carried out for various configurations to determine the ways of further enhancing lift. The effects of following techniques are quantized: (1) underlying skeleton; (2) wing membrane extension; (3) wing membrane relaxation and (4) wing membrane material. The results are compared with the rigid-wing. The baseline geometric description for all MAVs includes 15 cm box dimension and aspect ratio of 1. Results show that the skeleton layout significantly governs the lift characteristics. Latex sheets are found to be the best choice for membrane material. The effect of membrane extension and relaxation proved to be of little advantage. The aerodynamic assessment at low Reynolds number has demonstrated significant improvement of lift characteristics for flexible wings over rigid wings counterpart.

1 Introduction

Micro Air Vehicles (MAVs) have gained significant attention from defense industry in recent years because of its versatility in multi-faceted mission profiles. These vehicles have an enormous potential for near-area surveillance and close-field battle support. They can be used as a primary information-gathering source in cluttered terrains. However, several challenges need to be addressed by technological protagonists for the successful realization of MAVs flying in urban environment. Some of the challenges are:

- Low Aerodynamic Efficiency: Typical MAVs operate at low Reynolds numbers roughly ranging from 0.07 million to 0.2 million. Such low Reynolds numbers decrease the lift-to-drag ratio that result in poor aerodynamic performance. The increase in lift is of great importance so that surveillance based payload capacity can also be increased. Moreover, because of the size constraints, MAV designs belong to the class of low aspect ratio wings. These factors significantly degrade the aerodynamic efficiency of MAVs.
- Poor Gust Response: The wind gradients vary significantly at low altitudes and especially in urban environments. The gust speed can go up to 6 m/sec at low altitude. On the other hand, the rigid wing MAVs are known for poor gust performance thereby decreasing there maneuver potential and steady flight in such environments. Thus, the need for suppressing the effect of wind gusts becomes increasingly important for such systems.

One of the techniques being explored for mitigation of these problems is the use of flexible wing membranes instead of rigid surfaces. Studies have shown that flexible-wing MAVs perform better than the conventional rigid-wing MAVs in terms of improved aerodynamic efficiency and gust suppression.

Flexible wing MAVs [1-3] have the ability to alleviate gust effects by the mechanism of adaptive washout. The adaptive washout in flexible wings is produced through the deformation of the wing skin. The flexible wing shape change is a function of airspeed and angle of attack. When there is an increase in airspeed, due to a head-on wind gust, there will be a change in the wing shape. This change brings a decrease in lift efficiency. However, the overall lift remains same due to the increase in airspeed. When the wind gust dies, the flexible membrane will revert back to its original shape, thereby maintaining the same lift. In an ideal case, the flexible wing MAV will fly smoothly in a turbulent atmosphere by maintaining constant lift. The flexible membranes however, are not without disadvantages. Studies have shown that flexible wings typically have lower lift-to-drag ratio than the conventional rigid wings. This is attributed to membrane deformation that results in lift reduction and increased drag.

Most of the work jumps from the conceptual design directly to the flying prototype without going through the fundamental evaluation of aerodynamic and flight dynamic behavior of flexible membrane aerodynamics. Flexible membrane centric design philosophy is still pre-mature.

In this work, experiments are performed on various configurations of flexible-wing MAV. Specifically, wind-tunnel testing of low-aspect ratio wings at low Reynolds number is conducted. The test free-stream velocity is 15 m/s. The parameters varied are: batten arrangements for various frame configurations, skin materials, extension and relaxation of materials. The effect of these parameters on lift characteristics are quantized and discussed.

2 Experimental Setup and Procedures

2.1 Model Fabrication

The experiments in the wind tunnel are used as the primary method of evaluation. The baseline wing geometry consists of a square frame of 15 x 15 cm, resulting in aspect ratio of 1 for the wings. A total of six configurations are fabricated to determine the effects of battens on lift. Each configuration differs in terms of number and orientation of the battens. The battens primarily govern the deformation pattern of the wing membrane. The layout of the fabricated six frames are shown in Fig. 1.

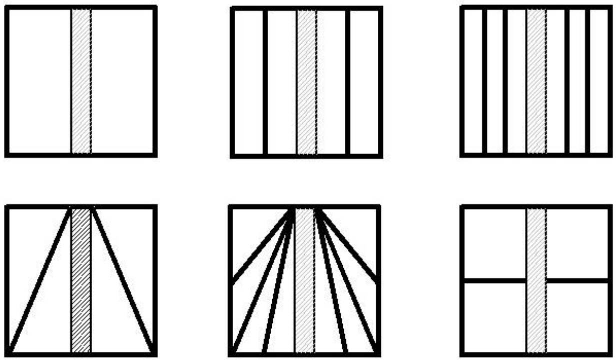

Fig. 1 Wing frame design configurations

The wing frames are fabricated using rigid 3 mm diameter carbon fiber rods and 1 mm thick carbon fiber plate. The carbon fiber plate is used in the centre of the wings so that electronics and battery can be placed on top of it in actual flying prototype. The carbon fiber plate is 2 cm wide and of the same chord length. The rods are joined together using epoxy. The thickness-to-chord ratio of the wings is about 2 %. All wings are fabricated on a custom-designed fixture to hold the rods to provide sufficient time for epoxy to settle down. The tolerance for all wings is within the range of 1 mm. The rigid wing (for benchmark studies) is made from 3 mm thick aluminum sheet cut out to the same external dimension of flexible wing frames. The wing frames are rigid whereas the skin/membrane of the wings is of different flexible materials. Overall four type of materials used in this study are – polyvinyl chloride (PVC sheets, elastic latex, nylon (parachute material) and silk. The materials are shown in Fig. 2.

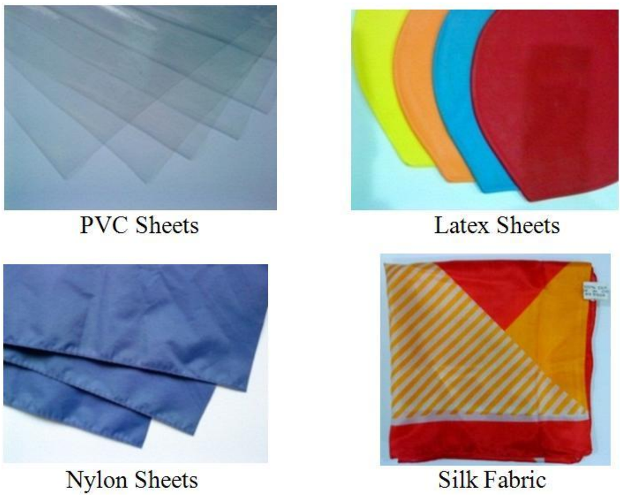

Fig. 2 Materials used for flexible membrane

The schematic of material extension and relaxation is shown in Fig. 3. For extension case, the material is cut in a square dimension. The square dimension of the wing is 15 cm and the material is cut in a dimension less than 15 cm. Then the material is stretched to cover the wing surface area uniformly. For relaxation, as the wing dimension is 15 cm, the material is cut in square dimension greater than 15 cm and subsequently fit onto the wing area. It should be noted that the wing membrane will have some wrinkles for relaxation case. The arrows in Fig. 3 show the direction of extension or relaxation.

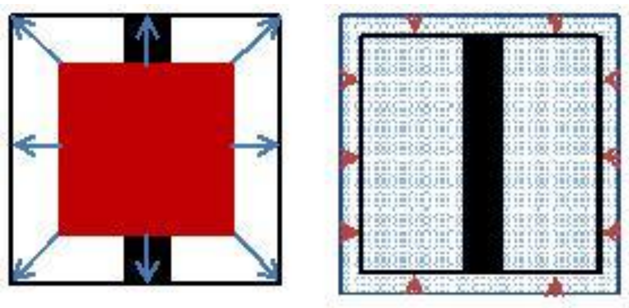

Fig. 3 Membrane extension (left) and relaxation (right) relative to wing frame

The PVC, nylon and silk fabric sheets are attached with the wing frame by stitching. This is done for the sake of easy removal when the wing frame is re-used for other materials. However, the same cannot be done for the latex sheets as the holes created by stitching will propagate when the latex sheets are stretched and end up in tearing them. Therefore, the latex sheets are attached with superglue.

2.2 Wind Tunnel Facility

The wind-tunnel experimentation is carried out at Nanyang Technological University (NTU). The facility is a low speed, low turbulence closed loop wind-tunnel and is used to test the full scale flexible membrane wings for different configurations. The test section is 2 m long and internal cross-section is 0.72 by 0.78 m. A six component internal balance is used to measure all forces and moments. The model positioning system is of quadrant type and is equipped with a sting model support. The data acquisition system is based on National Instruments (NI) platform and Lab-View based software to graphically view and records the data. It is known as Data Acquisition, Reduction and Control System (DARCS). The wind-tunnel test section is shown in Fig. 4.

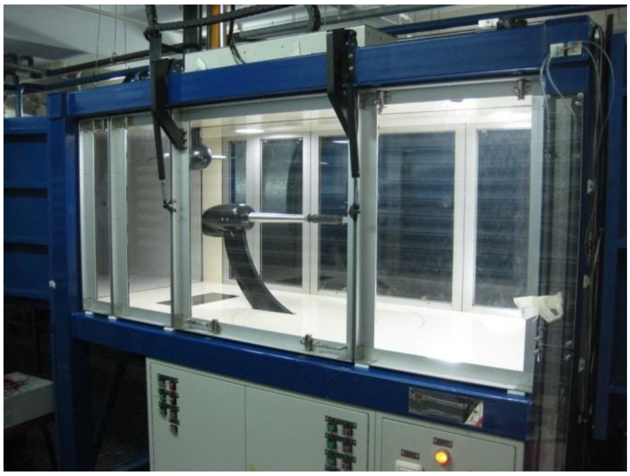

Fig. 4 Closed-circuit wind-tunnel test section with sting balance

3 Results and Discussion

The experimental results presented in this paper have all been corrected for wind-tunnel blockage effects (solid blockage, wake blockage and streamline curvature) from Barlow et. al. [4]. The magnitude of blockage corrections increases with the increase in angle of attack. However, the maximum blockage correction for most of the scenarios is less than 10%. Support interference studies show little effect on the aerodynamic forces. Moreover, no hysteresis was observed for all the wings during the experiments.

3.1 Effects of Skeleton Structure

In order to observe specific peculiarities associated with different wing skeletons, PVC sheets are used as flexible membrane on entire six wing frame configurations. The sheets are stretched and woven with the skeleton. The flexible and rigid wings are shown in Fig. 5. Moreover, all six wing skeletons are numbered from Planform 1 to Planform 6. Planform 1 is without any battens. Planform 2 and 3 are with axial battens. Planform 4 and 5 are with diagonally spaced battens whereas Planform 6 has a batten normal to the flow direction.

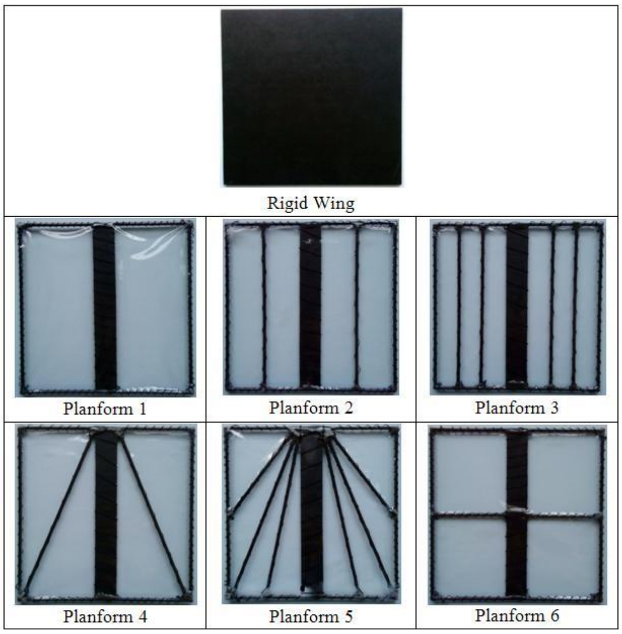

Fig. 5 Rigid and flexible wings with PVC membrane

After applying the necessary wind tunnel corrections, the experimental data is tabulated. The objective is to find the flexible wing frame configuration giving rise to the best overall lift over a wide range of angle of attack. The coefficient of lift for all wing skeletons as well as rigid wing is plotted in Fig. 6. The legend naming follows the format: [Skin Material] [Skeleton number]. It can be clearly seen that the flexible wings generally have higher lift than the rigid wing. Flexible wings with diagonal battens (PVC 4 and PVC 5) generally have higher lift than those with axially arranged battens (PVC 2 and PVC 3) and normally arranged batten (PVC 6). Moreover, normal and axial battens exhibit similar lift trends. For axially arranged battens, the number of battens does not seem to have an effect on lift. However, the diagonally arranged battens (PVC 4 and PVC 5) are better than others. It can be noted that the PVC 5 reaches to the maximum lift attainable at high angle of attack.

Overall, PVC 1, representing the flexible wing without any battens, exhibits the highest lift but shows signs of stalling in the vicinity of 18^{o} angle of attack. This is due to the flexible membrane able to deform more than other wings, giving the wing some camber which in turn results in higher lift. The more camber however results in earlier flow separation. Based on the results shown in Fig. 6, Planform 1 is used for subsequent testing to study the effect of other parameters.

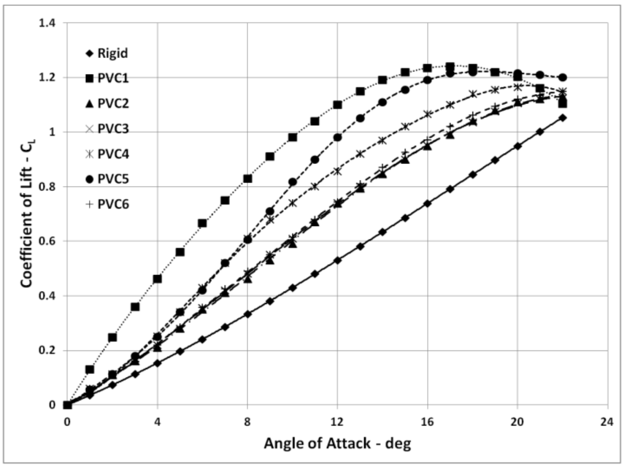

Fig. 6 Coefficient of lift comparison for different wing skeletons

3.2 Effect of Membrane Extension

To study the effect of membrane extension, elastic latex sheets are used. This is done by stretching 8, 10, 12.5 and 15 cm square dimension latex sheets over wing skeleton. Results are compared with the rigid wing case and plotted in Fig. 7.

The latex wings exhibit higher lift values than the rigid wing. Latex 15 cm wing shows the maximum improvement in lift characteristics. It is observed that the magnitude of lift decreases with the increase in extension. This can attributed to the fact that by extension the elasticity of the material is reduced, thereby reducing its flexibility. If we assume that the latex sheets will not tear on extension, it is conjectured that the lift curve slope of the flexible wing will approach to that of rigid wing. Therefore, increasing the extension tends to direct the aerodynamic properties of the latex wings towards that of the rigid wing. At this point, it appears that giving zero initial extension generates maximum possible lift.

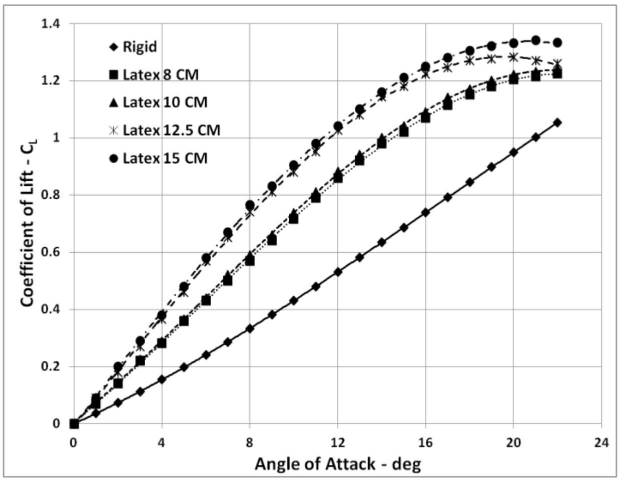

Fig. 7 Coefficient of lift comparison for different membrane extensions

3.3 Effect of Membrane Relaxation

Initially, PVC was decided to study the effect of membrane relaxation. However, it was found that after giving some relaxation to the PVC sheet, the wing membrane showed resistance to deformation under aerodynamic loading. After some tests at typical free-stream velocities, it was found that there was little visible change to the shape of wing membranes. Therefore, a more flexible material option such as nylon is used to accurately investigate the effects of membrane relaxation. The relaxation to the material is given of 0.5 and 1 cm. Results are compared against the rigid wing, as well as for the case of nylon with no membrane relaxation.

Fig. 8 shows coefficient of lift versus angle of attack for wings of varying amount of relaxation. The nylon wings have higher lift coefficients than rigid wing and generally showed nonlinear lift response. This is attributed to the cambered effect brought about by the wing flexibility and the camber varies with angle of attack, thereby contributing to nonlinear behavior. Comparing Nylon 15 cm and Nylon 15.5 cm, the latter has about 4% higher lift for all angles of attack tested. For the Nylon 16 cm case, there is an average of 34% improvement in lift at low angles of attack but suffers significant loss at high angles of attack. Moreover, the stall behavior of Nylon 16 cm is not apparent and it shows are very benign pattern in the vicinity of stall.

It might be worthy to take note that it appears that giving a slight relaxation instead of extension to the wing skin will enhance lift. Further aerodynamic testing is planned to decipher the phenomena for relaxation between 0 and 1 cm as part of future work.

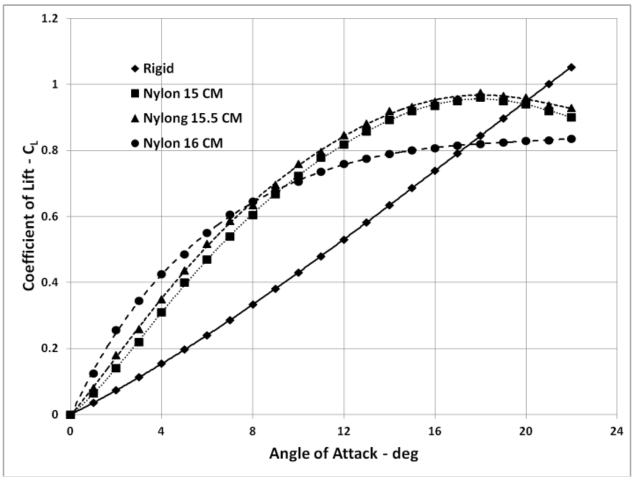

Fig. 8 Coefficient of lift comparison for different membrane relaxations

3.4 Effect of Membrane Material

In order to compare the effect of different materials, PVC, nylon, latex and silk fabric are compared with the rigid wing case. The wing skeleton is same as earlier without battens (Planform 1). The coefficient of lift variation for different membrane materials is shown in Fig. 9. It should be noted that the silk-membrane is perforated and it is expected that the air will pass through the skin.

It is observed that the silk-membrane wing has significantly lower lift than the other flexible wings. The silk wing has higher lift over the range of angle of attack from 0^{o} to 16^{o}, but starts to drop below that of the rigid wing. This is expected since at high angles of attack, the airflow starts to pass through the perforated silk wing. Now comparing the PVC, nylon and latex wing, the PVC wing has slightly higher lift at low angles of attack than the latex wings. However, at high angles of attack, the latex wing has higher lift and also appears to have higher stall angle.

For maximum lift coefficient value, the silk wing has the lowest value whereas the latex has the highest. This phase of testing suggests that perforated materials are not suitable for use on MAVs. Comparing inextensible materials, harder plastic-like materials like PVC result in higher lift than that of softer fabrics like nylon. However, extensible materials like latex is much preferred over the inextensible ones for exhibiting higher stall angles and maximum lift coefficients.

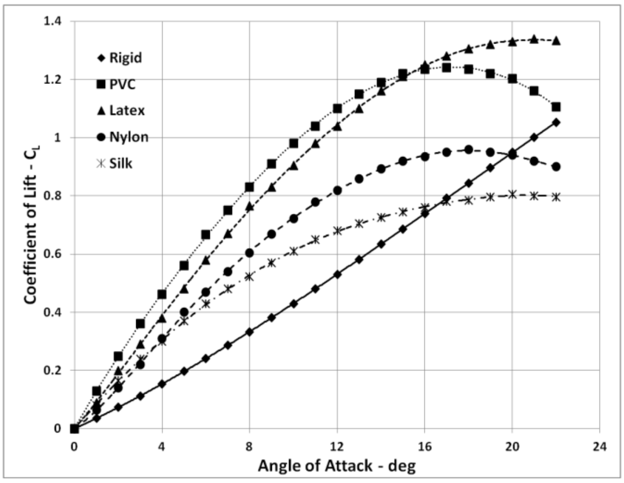

Fig. 9 Coefficient of lift comparison for different membrane materials

4 Conclusion and Future Work

Experiments are performed on various configurations of flexible-wing Micro Air Vehicle. Specifically, wind-tunnel testing of low-aspect ratio wings at low Reynolds number is conducted. The design parameters varied are: batten arrangement, skin material and flexibility. During the investigations of the wing skeleton, it is observed that all flexible wings show higher lift than the rigid wing. The wing skeleton without battens (Planform 1) generates maximum lift. It is also observed that frames with diagonal battens show higher values of lift relative to horizontal and vertical battens. Planform 1 is used for further testing.

For membrane relaxation study, it is observed that applying relaxation degraded the lift and resulted in increased skin-friction drag. Moreover, undesirable nonlinear lift variation with angle of attack is observed for membrane relaxation case. For the membrane extension study, it is observed that applying more extensions to the latex sheets tends to direct the aerodynamic properties towards that of the rigid wing due to increase in plastic behavior of skin membranes. During the comparison of different materials of membranes, it is observed that silk wing has minimum lift at high angles of attack. Planform 1 with latex membrane without extension and relaxation results in maximum lift.

For the future work, effect of exclusion of trailing edge and/or side edges on the aerodynamics of MAV will be investigated.

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