Pulsed engine powered MAV: Airframe configurations and wing morphing with cross-winds

N. Madhavan & H. Medina

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Abstract

The aerodynamic characteristics present in a Micro Aerial Vehicles (MAV) are of a challenging nature. A low Reynolds number flow coupled with a low aspect ratio wing and size limitations is enough to provoke unfavourable flow physics. Lately, research into MAVs have gained considerable interest due to their complex nature and also due to advancements in Micro-Electro-Mechanical systems (MEMS), making it possible for MAVs’ to endure a stable and efficient flight. However, an MAV has to be light and this presents obvious problems to its flight stability, especially in the presence of cross-winds. This paper reviews the aerodynamics of MAVs, the current technologies aiding them and the computational analysis on effects of cross-winds on MAVs.

Nomenclature

\begin{itemize}
  \item \( C_d \) \hspace{0.5cm} \text{drag coefficient}
  \item \( C_l \) \hspace{0.5cm} \text{lift coefficient}
  \item \( C_l/C_d \) \hspace{0.5cm} \text{lift-to-drag ratio}
  \item \( p \) \hspace{0.5cm} \text{relative pressure (Pascals)}
  \item \( Re \) \hspace{0.5cm} \text{Reynolds number based on streamwise velocity component}
  \item \( Re_t \) \hspace{0.5cm} \text{Reynolds number including cross-wind component}
  \item \( t \) \hspace{0.5cm} \text{time (seconds)}
  \item \( u, v \) \hspace{0.5cm} \text{streamwise, vertical and spanwise instantaneous velocity components}
  \item \( U, V \) \hspace{0.5cm} \text{streamwise, vertical and spanwise mean velocity components}
  \item \( x \) \hspace{0.5cm} \text{streamwise coordinate (metres)}
  \item \( y \) \hspace{0.5cm} \text{vertical coordinate (metres)}
  \item \( z \) \hspace{0.5cm} \text{spanwise coordinate (metres)}
  \item \( \alpha \) \hspace{0.5cm} \text{angle of attach (degrees)}
\end{itemize}

Greek symbols

\begin{itemize}
  \item \( \alpha \) \hspace{0.5cm} \text{angle of attach (degrees)}
\end{itemize}

Abbreviations

\begin{itemize}
  \item \text{cw} \hspace{0.5cm} \text{cross-wind}
  \item MAV \hspace{0.5cm} \text{Micro Aerial Vehicle}
\end{itemize}

1 Introduction

Micro Aerial Vehicles (MAVs) are defined by their restricted size specifications and their low Reynolds number flight envelope. Boundary layer theory dictates that the flow field within this range of Reynolds numbers is principally within the transition from laminar to turbulent flow[1]. The demand for MAVs in recent years comes from the need for a small, inexpensive and expendable platform required for surveillance or measurement situations where a larger vehicle fails. This coupled with technological advances along a multidisciplinary front, be it miniature propulsion systems and high-density power systems or miniaturised computer hardware components with efficient programming, have made the manufacture and application of MAVs possible for a diverse amount of tasks[2][3]. A successful MAV design requires an alliance of understanding between biology and aerodynamics hence the inspiration for designs of MAV comes from studying biological animals as the degree of flexibility that the MAV possesses due to its scale is a deviation from typical modern air-
craft designs\cite{2}. Due to its size and flexibility, the MAV has the advantage of favourable scaling characteristics which includes low inertia and reduced stalling speed. However, from an aerodynamic point of view, there are many outstanding issues present which includes control, stability, and manoeuvrability. The low Reynolds number flight envelope generates unfavourable characteristics that include laminar boundary layer separation and low lift-to-drag ratio\cite{2,4}. The restricted size in MAVs forces the wing to have a low aspect ratio which creates tip vortices through strong vortical flow structures\cite{2,4}. This is sort of a paradox as the vortices that are generated reduce the effective angle of attack directly lowering the lift force but tip vortices also provide supplementary lift force by creating a low pressure zone. The fluctuation in wind speed and cross-winds can highly affect the stability of an MAV's flight and being a low aspect ratio wing causes rolling instabilities for the MAV\cite{2,4}. Two approaches have been followed so far in producing MAVs; flapping flight and fixed wing. Flexible fixed wing MAV is studied in this paper owing to its desirable characteristics of lower cost and simpler design and manufacture which produces satisfactory aerodynamic characteristics\cite{5}. Membrane materials are desirable for the construction of the MAV’s skin as they facilitate passive shape adaptation which produces a favourable delayed stall reaction. Shyy et al., Waszak et al., Smith and Shyy and Jenkins et al., proved in previous research that a more favourable aerodynamic performance in the low Reynolds number regime can be achieved by allowing the lifting surface to fluctuate and deform\cite{6}. A membrane wing has the capability of smoother flight by adapting to the airflow through the passive mechanism of adaptive washout\cite{7}. A membrane wing relatively solves the problems of decrease in lift through gust winds\cite{7}. A decrease in lift efficiency is observed when an MAV wing is hit by a gust wind but due to the speed of the gust wind being higher, the wing preserves nearly the same lift. As the airspeed recovers, the wing returns to its original configuration\cite{7}. A two configuration wing design is desired providing high lift and glide action. In flight adaptive camber to achieve wing configurations coupled with a pulsed engine to save energy is visualised. Adverse pressure gradients are highly influenced by free stream turbulence and wing planform/camber. Adverse pressure gradient causes the laminar boundary layer to separate, especially under low Reynolds number\cite{4}. Adaptive camber is favoured by studying nature intently. Birds and insects are blessed with a large flight envelope and appraisable manoeuvrability due to their ability to adapt to each flying condition with different wing configuration(s)\cite{8}. An economical option to provide adaptive camber is through Shape Memory Alloy.

2 Technological advancement and challenges

2.1 Materials

Due to its size and limitations, MAVs are constructed of lightweight yet durable and strong materials. Of the most common materials that are used to construct MAVs, taking into consideration the demand for high quality, low weight, exceptional durability and high strength; bi-directional graphite/epoxy plain weave or uni-directional plies which compose the basic structure of the vehicle that is built around a composite laminate skeleton and then reinforced with Kevlar for added safety of equipment and durability of machine\cite{3}. This carbon fibre skeleton, which acts as the bone of the structure, is attached to an extensible flexible skin which acts as the membrane material usually composed of latex, silicone, plastic sheets, polyester or cloth\cite{3}. These materials can be coated by a layer of polytetrafluoroethylene (PTFE) for added resistance from water or oil.

2.2 Propulsion systems

A fixed wing MAV will require a dedicated propulsion system that will power it whereas a flapping wing MAV would obtain its propulsion power from the flapping action of the wings. A plethora of miniature propulsion systems are available due to advancements on Micro-Electro Mechanical Systems which includes internal-combustion engines, pulse jets, micro turbines, micro-turbojets, gaseous propellant, solid pro-
pellet rockets and electric motors[8]. An MAV is intended to be inexpensive therefore electric motors are generally favoured but tailored needs of missions that are tailored to a certain criterion have the option of various propellant systems. The propellant system best suited for a two configuration wing would be a pulsed jet engine which would be activated automatically when the MAV is in its 'climb' mode and would turn off while the MAV is gliding.

2.3 Actuating mechanisms and control

Simple and efficient actuating mechanisms are significant in ensuring an MAV has a smooth and stable flight. An MAV is futile if it cannot be controlled as per the users wish. Technological advancements have provided miniaturised actuators that are lightweight yet effective. Shyy et al., Waszak et al., Smith and Shyy and Jenkins et al., proved in previous research that a more favourable aerodynamic performance in the low Reynolds number regime can be achieved by allowing the lifting surface to fluctuate and deform[6]. Flapping wing MAVs have been successful by using actuators and servos. Fenelon and Furukawa designed an active flapping wing mechanism using rotary actuators[9]. Chung et al. has used coupled piezoelectric fans as an application for flapping wings[10]. Pawlowski et al. has had success with electro spinning of micro air vehicle wing skin[11]. Shape Memory Alloy provides the simplest and most economical approach to membrane actuation and adaptive camber. Yang and Seelecke studied SMA-Based adaptive structures with respect to MAVs and applied SMA in two different ways; SMA wire a martensite phase and SMA beam in a austenite phase[9]. SMA produces a great potential in the role of actuation in the membrane wing. Another advantage of active membrane actuation is roll control[12]. Ursache et al. studied on morphing airfoils using spinal structures by using a carefully pre-loaded inner spinal structure that moves under control of a single actuator but this is more suited for UAVs or wings without a size limit[13].

2.4 Aerodynamics

The low Reynolds number nature of MAVs presents a strenuous aerodynamic challenge due to its affiliated vulnerability of separation bubbles caused by a probable turbulent transition of the separated shear layer in the separation of the laminar boundary layer which then reattaches to the surface[4]. The low aspect ratio wing displays strong vertical structures through tip vortices. This allows the wing a higher angle of attack as the tip vortices forms low-pressure zones thus generating supplementary lift forces. However, the effective angle of attack is reduced as the low aspect ratio raises the induced drag component[14]. Besides that, the magnitude of the vortical flow causes rolling instabilities for the MAV due to its size and weight. This further complexes the situation when the tip vortices at both sides are not equal in strength[4]. Pelletier and Mueller have done some experimental work regarding on this subject and numerical investigations were reported by Lian and Shyy and Vieru et al[4, 15, 16]. Membrane materials have received considerable attention due to its unique capabilities to alleviate some of the issues present in low Reynolds number flow and low aspect ratio associated with MAVs. Not only does it save weight compared to a rigid wing, a membrane wing is sturdy enough to maintain the relatively low flight loads of an MAV[4]. Besides that, active wing morphing is easier to achieve due to the flexible nature of the membrane wing allowing a relatively low level of torque/power needed to morph the wing to a desired shape for any desired configuration[4]. A flexible surface may spell disaster for much larger vehicles due to instabilities but the aeroelastic design in MAVs is favourable for passive shape adaptation and less emphasis is placed on the trade-off between flexibility and weight[12]. Small operating dynamic pressures and low aspect ratio of the wing lessen typical problems which exist in larger vehicles such as torsional divergence and flutter[4]. Then again, too much flexibility can be detrimental as the lift slope of the wing nearing infinity, excessive drag penalties resulting from a poorly constructed trailing edge vigorously flapping and obtaining a negative camber at a positive angle of attack which is when large vibra-
tion of a membrane is stuck within a hysteresis loop and this condition is termed as luffing[4].

3 Methodology and numerical approach

3.1 Numerical approach and tools

The simulations and results presented in this study were carried out using open source software. The OpenFOAM distribution was used since it offers a wide range of solvers. OpenFOAM was also chosen due to its ability to support parallel computing which significantly reduces computational time. Lian et al.[4] highlights the need to use a transient solver to capture the behaviour of the flow over membrane wings. They also indicate that the PISO method is generally more efficient. For these reasons, the icoFoam included within this distribution was chosen as the main solver. This solver is capable of simulating low Reynolds number flows. Additionally, the simpleFoam solver was employed in order to initialise the simulations. This helped reduce the risk of numerical instability and it also helped reaching the transient solution sooner. The simpleFoam solver is solves the RANS equations using the standard $\kappa-\epsilon$ model. The solver was used to calculate 500 iterations since it was found to provide an acceptable level of accuracy. Figure 1 shows the solution convergence for the pressure residual. Also, the mesh for all the difference simulations presented was prepared using SALOME-Meca. The mesh was made up mostly of hexahedral elements, however, some prism cells were also present. Figure 2 provides an example of a typical mesh.

Two different computational domains were utilised. For the cases without cross-winds, the domain was set up to take advantage of the symmetry of the geometry. Therefore, only half of the number of cells is needed for such simulations, significantly reducing the computational cost. On the other hand, the cross-wind simulations required the full definition of the geometry since the flow field is no longer symmetrical. The dimensions of the bounding box used are 1x1x1.3 metres. Details of the number of cells are shown in table 1. Finally, all the pressure boundaries were given a zero gradient condition and a reference pressure was set at 0 Pa. This implies that the pressure values calculated are relative. The MAV boundary was given a no-slip velocity condition and the bounding box boundaries were set up as slip boundaries with a velocity magnitude appropriate to the case in hand (see table 3 on page 6). This was implemented using the InletOutlet boundary available in OpenFOAM.

3.2 MAV model overview

The MAV model used in this study is inspired on the work of Lian [4]. However, the final geometry used differs. The main difference is the presence of a larger portion of the airframe comprised of straight lines which are also not rounded (at the wing tips).
This change was introduced for two reasons, firstly, in order to increase the overall surface area with the hope to increase lift generation, and secondly, in order to assess the effect that such sharp wing tips have on the flow field when subjected to cross-winds. The thickness of the MAV is 0.002 m, both the maximum span and length are 0.1 m, giving the MAV an aspect ratio approximately equal to 1. In addition, two different configurations were considered. The first configuration with 3% upstream camber and 3% inverse camber was chosen as the datum flight configuration. The high-lift configuration to be used in synchrony with the pulsed engine has an upstream camber of 5%.

4 Results and discussion

4.1 Introduction

The effect of both cross-winds and upstream camber will be presented herein. Two airframe configurations were considered with different percentage camber, 3% camber as the initial estimate for a glide configuration and 5% camber as the high-lift or pulse on configuration. Also, the effect of cross-winds is investigated, both 25% and 50% cross-winds are investigated (percentage based on the freestream velocity magnitude).

4.2 Camber effects without cross-wind

The effect that the upstream camber has on the flow field around the MAVs airframe will be examined in this section. Two camber configurations are considered, 3% and 5% upstream camber. The inverse camber is kept constant an equal to 3%. The first evidence of the significant effect that camber has on the flow field is shown in figure 4. This figure shows that for 3% camber, the airframe exhibits both a velocity and pressure distribution as expected from a lift generating surface. However, as the percentage camber is increased to 5%, the velocity field points to the presence of a region of significant low velocity at the bottom surface at approximately 25% chord. At this same location, the corresponding pressure field at t = 0.0275s shows both a region of low pressure, followed by a region of high pressure located further downstream downstream. These regions develop as a result of a separation bubble that is generated due to the increase in camber to 5%, indicating that the laminar boundary layer was subjected to an unfavourable pressure gradient leading to a local flow reversal and eventual separation. The pressure distribution on the lower surface of the MAVs airframe is shown in figure 6. This figure shows the negative effect that the formation of a separation bubble has on the ability of the airframe to generate lift. Figure 6 (top left) corresponds to t = 0.0025s, at this moment the airframe exhibits a significant region of high pressure up to approximately 40% chord. However, at t = 0.0275, the adverse effects that the separation bubble has on the performance of the airframe become more evident mostly due the subsequent decrease in pressure up to 20% chord. Furthermore, as the flow continues to develop and the separation bubble continues to travel downstream, there is a further reduction on the pressure distribution highlighting a further deterioration of the performance of this airframe configuration. This indicates that there is a need to continue to investigate and test different configurations to enhance the performance of the high-lift configuration in order for the airframe to operate more efficiently. However, despite the need for further consideration and study, the 5% camber airframe still generates significantly more lift than the 3% camber configuration as it will be discussed later.

4.3 Cross-wind effects

It has already been established that the choice of camber will affect the flow field around the MAVs airframe significantly. Also, the cross-wind is expected to have a substantial effect on the flow field. For instance, figure 7 shows the same airframe configuration as figure 5, in this case however, a 50% cross-wind has been applied. First of all, the velocity field indicates a larger magnitude of the free-stream velocity. This is due to the addition of a cross-wind velocity component (the direction of the cross-wind component is towards the page). The velocity field shows a distribution of the velocity magnitude similar
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</table>

Figure 3: Simulation summary

Figure 6: Lower surface pressure distribution (flow from right)
to that when there was no cross-wind applied. That is, a separation bubble is also present, as evidenced by the low velocity region coupled with a low-high pressure distribution. However, in the presence of 50% cross-winds, the separation bubble appears reduced and the low-high pressure regions are lower and higher respectively.

Figure 8 shows the pressure distribution on the lower surface of the airframe with 25% crosswind. First of all, as expected, an inspection of this figure demonstrates that the pressure distribution is not symmetrical as it was the case when there were no cross-winds applied. This figure also shows the changes of the pressure distribution over time. It can be observed that at $t = 0.0025s$ the distribution is almost symmetrical. This result is the consequence of the initialisation of the results to be used with the transient solver. However, as time increases, $t = 0.0275s$, a region of relatively higher pressure develops on the right side of airframe. For $t = 0.04s$, this region occupies a larger portion of the lower surface, as the lower region on the left becomes even smaller. However for $t = 0.05s$, the low pressure region recovers pressure an increases in magnitude. This behaviour highlights the unsteady nature of the flow that develops as a result of cross-wind. Consequently, it can also be deduced that under the influence of cross-winds the stability of the MAV would be strongly affect. For example, figure 8 indicates that initially the MAV is in steady conditions (figure 6) followed by a tendency to roll, however, due to the unsteady nature of the flow and the relatively sudden increase in pressure on the opposite side the MAV would oscillate in roll at a relatively high fundamental frequency. This highlights the potential challenges encountered in MAV flight control, therefore,
a fundamental understanding of this behaviour is of paramount importance if MAV applications are to proliferate.

When the cross-wind component is increased to 50% keeping the same airframe configuration the corresponding pressure distribution at the lower surface is shown in figure 9. This figure is of particular interest, not only because it confirms that under the influence of cross-winds the flow is asymmetrical, but also it emphasises the unsteady nature of the flow that develops. In this particular case a rather interesting feature develops. Figure 9 (2nd from top), for $t = 0.0275s$, shows near the top right corner the development of a surface normal vortex. Figure 9 (3rd) shows that the vortex travelled to the left, until eventually, figure 9 (bottom), it dissipates. Interestingly, there is evidence in the literature suggesting that the development of a wall normal vortex could be prevented by the use of membrane materials.
4.4 Effects on aerodynamic coefficients

Partly due to the low Reynolds nature of the flow, it has been observed that the flow field around the MAVs airframe is significantly affected by geometry changes, as well as by the presence of cross-winds. Consequently, the performance of the MAV will also be influenced by the choice of airframe configuration. Firstly, the combined effects of the geometry and the cross-wind on the lift coefficient are shown in figure 10. This figure shows some interesting trends. For instance, it confirms that increasing the upstream camber leads to a significant increase of the lift coefficient.
This increase appears to be present regardless of the magnitude of the cross-wind. This indicates that employing camber as a means to increase lift during the active cycle of the MAVs engine could potentially be implemented. Figure 10 also shows that when the cross-wind magnitude is 25% of the free-stream velocity, there is an increase in the lift coefficient regardless of the camber percentage. However, the increase in the lift coefficient is more pronounced when the camber is 5%. This increase in lift coefficient can be attributed to a larger velocity magnitude which includes the free-stream and the cross-wind components. Nonetheless, as the cross-wind increases to 50% of the free-stream velocity, the increase in lift coefficient is rather modest, particularly for the 5% camber case.

Figure 11 shows the effects that camber variations and cross-winds have on the drag coefficient. This figure follows a very similar trend to that observed in figure 10. As expected, the drag coefficient increased in the presence of cross-winds. However, for the 5% camber case the increase in drag coefficient is more marked compared to the 3% camber case. This observation hints to the possibility that the effects of cross-winds on the performance of MAVs may not be a straight forward. For instance, figure 12 shows the lift-to-drag ratio for the different cases considered in this study. As expected, this figure shows that for the 5% camber case the effect of cross-winds is to deteriorate the performance of the MAV by reducing the lift-to-drag ratio. Interestingly, for the 3% camber case, and despite an initial decrease of the lift-to-drag ratio for cw = 25%, when the cross-wind is further increased to 50%, there is in fact an increase in the lift-to-drag ratio. This increase is linked to the increase in the lift coefficient shown in figure 10. However, further research is needed to fully understand this behaviour.

5 Conclusion

The low Reynolds numbers at which MAVs operate, in addition to the low aspect ratios of common MAV designs, lead to complex flow physics in numerous occasions. In this study two airframe configurations with different upstream camber values (3% and 5%) were considered. In addition, they were examined under the influence of cross-winds. It was found that simply increasing the airframe camber led to significant changes in the flow physics observed. For instance, increasing the camber from 3% to 5% led to the generation of a separation bubble which adversely affects the aerodynamic performance of the airframe configuration. However, as a proof of concept, it was also found that it is possible to use in-flight morphing to develop a high-lift airframe configuration which could be employed with a pulsed cycle powerplant. It was also found that cross-winds have a dramatic impact on MAV aerodynamics. For instance, the adverse effects of increasing camber were accentuated in the presence of cross-winds. Under normal conditions separations bubble can emerge. However, when operating with cross-winds such a separation bubble gave way to entirely different flow physics, in other words, the flow became unsteady. Although, generally speaking cross-winds had an adverse effect, the opposite effect was also observed. For instance, for 3% camber when the cross-wind components was increased to 50% it led to an increase of the lift-to-drag ratio, needless to say, a very desirable effect, particularly in relation to MAVs flight. This study also highlights some areas of interest which deserve further consideration. For instance, the effect cross-winds have on the vorticity field and subsequent stability.
characteristics of MAVs is yet not fully understood.

References


