DEVELOPMENT OF AN MAV MANEUVERED BY SHIFTING THE LOCATION OF CENTER OF GRAVITY

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Abstract

The development and evaluation of an original maneuvering method of micro air vehicles are described. The idea is to produce the desired maneuvering pitching moment by shifting the center of gravity forward or backward, hence change the relative position between the center of gravity and the aerodynamic center. Moment balancing model was built and a set of equations was established to analyze the pitching moment trimming and the longitudinal stability. Wind tunnel tests and theoretical analyses were performed to achieve a feasible configuration. Flight prototype was also built. The flight tests showed that such configuration attained expected performance and achieved satisfactory stabilities.

1 Introduction

Over the last decade the field of Micro Air Vehicles (MAVs) becomes more and more attractive. Many researches were performed and a lot of prototypes were built.

Because the dimension limitation of MAVs, most of these MAVs have very low aspect ratio, plate-like wings, like the Black Widow [1], the Micro Star[2] and theUF MAV[3], etc. In such case, due to the short moment arm of elevator and the low Reynold number, the traditional-type-elevator will be very low efficient. Furthermore, the generation of pitching moment simultaneity produces considerable reverse force, namely, to provide nose-up moment for more lift, the elevator must primarily produce downward force. A study of the University of Florida[3] shows that a 10 degree deflection of the elevator may cause 32%~35% variation of total lift (positive and negative).

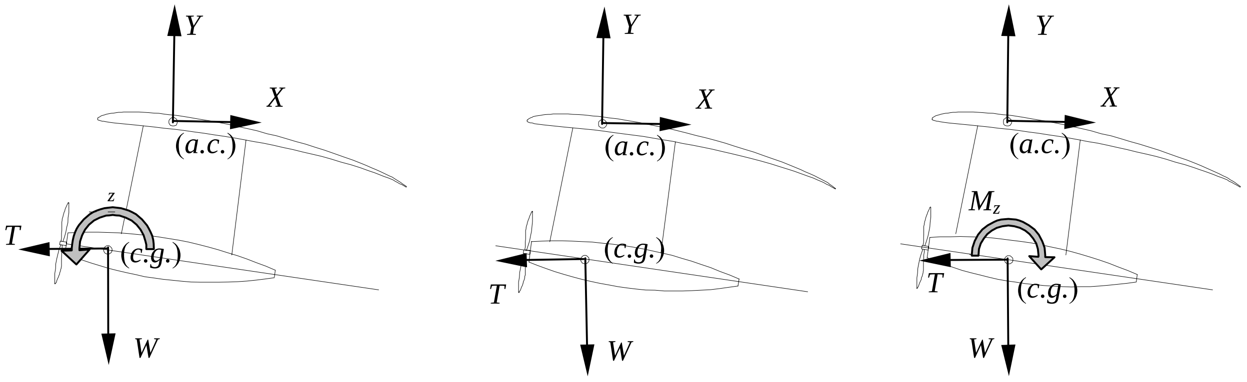
To avoid the disadvantages of such traditional-type-elevator, a new method of shifting the fore-and-aft location of the center of gravity (c.g.) to produce pitching moment was studied. The essential of such method is to change the longitudinal distance between c.g. and the aerodynamic center (a.c.), i.e. by moving the c.g. forward will produce additional nose-down moment, and vice versa, as shown in Figure1.

Actually it is not a whole new maneuvering method, because in the very early flight attempts people tried to control their vehicles by twisting and moving their bodies. It may be the origin of this method. As the airplane become more and more large, heavy and rapid, such kind of maneuvering quitted the stage. But for MAVs, it is still feasible. Because the mini dimension and the light weight of MAVs, such method will have little weight and complexity penalty. And since it is more important for MAVs to keep stable, the problem of sluggish response caused by moving c.g. will be less extrusive.

2 Overview of the prototype

2.1 Layout

Figure 2 shows the prototype developed at the Northwestern Polytechnical University. It consisted of an individual wing that mounted on the fuselage by a parallelogram mechanism, a vertical tail with rudder, an electric-motor driven propeller, Lithium batteries, and remote



(a) c.g. forward, nose down (b) Balanced position (c) c.g. backward, nose up

Fig.1. Sketch of the pitching moment generation

control system. No horizontal tail or elevator was needed in this design.

The program consisted of experimental, computational elements and flight-tests that examined the validity of the above-mentioned approach. The design relied heavily on analysis include analytical and physical models. Both CFD and wind tunnel test are employed to obtain the aerodynamic characteristics. Then a set of equations was established to study the pitching moment balancing, trimming, and the longitudinal stability.

Fig.2. Layout of the MAV (with an underside bracket)

2.2 Wing design

It is suggested that at low Reynold number as the MAVs will encounter(e.g. at 10^4 to 10^5), the inversed-Zimmerman wing planform has the best performance[4]. But it's bended outlines make it too difficult to fabricate. And as our wind tunnel tests showed, slight inaccuracy of wing shape will produce great difference of aerodynamic characteristics. To decrease the inevitable manufacture imprecision, a simple but easy to fabricate rectangular wing planform was chose, instead of the optimum curved shapes.

To attain slower flight speed, relative larger wing geometry was decided: span 30cm and chord 25cm.

The chosen airfoil is S5020. It was designed by Michael Selig for low Reynold number. The S5020 is 8.4% thick, and has a nearly neutral moment coefficient. The latter character makes it easy to trim.

2.3 Construction

The wing was constructed of balsa wood and thin polymer film. After the wing geometry was decided, the appropriate shape of rib was cut out using a computer controlled laser cutter. The laser cutter could machine complex shape with precision of 0.2mm. Cut ribs and frames were fitted together and glued, then coated with the thin film.

All other equipments such as the motor, the receiver, the speed adjuster, servos and batteries are mounted on the body. The body was also cut out of balsa wood. Some cavities are cut to hold the equipments.

The wing and the body were connected by two links, with two pair of hinges. The hinges were constructed with vulnerable-connection-design. When in harsh landing or in violent colliding, the hinge will break first to absorb the impact energy and protect the wing, body and the fragile equipments from further damages.

2.4 Weight breakdown

The final fabric weighed 82g. The motor and batteries dominate the mass breakdown with 33g. Since all of the electronic components are off-the-shelf products, there was a considerable space remained for weight reduction.

Tab.1 Weight breakdown

Wing	9 g
Fuselage and links	12 g
Receiver	8 g
Servos	12 g
Speed adjuster	5 g
Motor	17 g
Battery	16 g
Others	3 g

3 Longitudinal trim & stability

3.1 Lower the center of gravity

The longitudinal stability can be effectively augmented by lowering the center of gravity. Previous researches[5] revealed that, for a MAV without tail and elevator, longitudinal static stability can be achieved and the static margin can be disposed by adjusting the vertical distance between the a.c. and the c.g..

In this sample, we choose the distance as 90 mm, about 45% of the wing root chord. This result in a static margin of 10% at the loitering state.

3.2 Pitching-moment and trim

The coordinates and forces relationship are shown in figure 3, where the x_t, y_t are body-axis, x_q, y_q are wind-axis, α is the angle of attack (AoA), Y is lift and X is drag. The coordinates origins are fixed at the center of gravity.

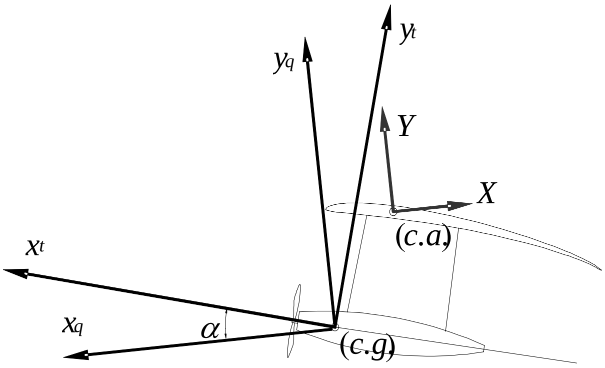


Fig.3 coordinates system

The pitching-moments caused by fuselage and propulsion system are relative small and often remain constant. So the total pitching-moment is mainly affected by the aerodynamic forces, namely, the lift and drag of the wing.

Resultant aerodynamic force in x_t axis:

$$\sum F_{x,a} = Y\sin\alpha - X\cos\alpha \tag{1}$$

Resultant aerodynamic force in y_t axis:

$$\sum F_{y,a} = Y\cos\alpha + X\sin\alpha \tag{2}$$

Pitching-moment caused by aerodynamic forces:

$$\begin{aligned}\sum M_{z,a} &= \sum F_{y,a}\cdot x_a - \sum F_{x,a}\cdot y_a + M_{z0}\\ &= (Y\cos\alpha + X\sin\alpha)x_a\\ &\quad - (Y\sin\alpha - X\cos\alpha)y_a + M_{z0}\end{aligned} \tag{3}$$

Where x_a, y_a are the distance between a.c. and c.g. in body axis x_t, y_t. Positive moment is nose up.

The former equation can be changed into non-dimensional coefficient form:

$$\begin{aligned} m_z &= \frac{M_z}{qSb}\\ &= \frac{(Y\cos\alpha + X\sin\alpha)x_a - (Y\sin\alpha - X\cos\alpha)y_a + M_{z0}}{qSb}\\ &= (C_y\cos\alpha + C_x\sin\alpha)\bar{x}_a\\ &\quad - (C_y\sin\alpha - C_x\cos\alpha)\bar{y}_a + m_{z0}\end{aligned} \tag{4}$$

Where q is the dynamic pressure, S is the planform area of the wing, b is the mean aerodynamic chord, and $\bar{x}_a$, $\bar{y}_a$ represent x_a/b, y_a/b .

It can be seen that the pitching-moment balance is concerned with two aspects: aerodynamic characteristics *Cx, Cy* and the relative position between a.c. and c.g. .

At a balanced state, the total pitching moment will be zero. The relative coordinate $\bar{x}_a , \bar{y}_a$ can be determined consequently:

$$\frac{\bar{x}_a}{\bar{y}_a} = \frac{C_y \sin\alpha - C_x \cos\alpha + m_{z0} / \bar{y}_a}{C_y \cos\alpha + C_x \sin\alpha} \qquad (5)$$

3.3 Aerodynamic characteristics of the wing

Wind tunnel setup

This work was conducted in a small wind tunnel facility at the Northwestern Polytechnical Uni. The wind tunnel is composed of driving section, transition section, stabilizing section, shrinking section, testing section and diffusing section. The tunnel section measured 50×50×70 cm. The speed range in the tunnel is 3~21 m/s. Range of angle of attack is –4°~22°.

Fig.4 Wind tunnel

Wind tunnel test result

Figure 4 show the wind tunnel test result of the equipped wing. It demonstrates that for such low aspect ratio wing in low Reynold number, the slope of lift coefficient with respect to angle of attack is rather flat. And the pitching moment coefficient is near zero at low angle of attack.

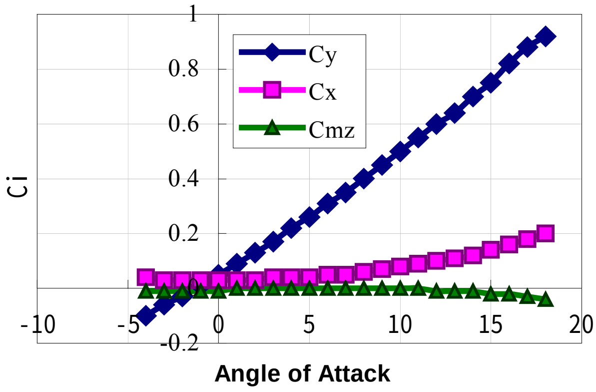


Fig.5 Lift, drag and moment coefficients

3.4 Moment trim

The expected loiter speed is 6m/s, the required lift coefficient can be educed by

$$C_y = W / (1/2 \rho V^2 S) \qquad (6)$$

Take the weight(W=82*g*) and the wing planform area(S=750cm^2) into Equ.6, the required lift coefficient can be decided as 0.49, and the corresponding AoA is 9.8 degree.

It can be derived from the wind tunnel test results that in this case the drag coefficient of the wing is 0.06.

From Equ.5 we know that to keep the pitching moment balance the relative position between a.c. and c.g. should follow the relationship:

$$\bar{x}_a / \bar{y}_a = -0.132$$

3.5 Longitudinal stability

The longitudinal stability can be denoted as:

$$m_z^\alpha = \frac{\partial m_z}{\partial \alpha} \qquad (7)$$

As the expression of m_z include both *Cx* and *Cy*, the derivative of *Cx* with respect to α will be:

$$C_x = C_{x0} + C_{xi} = C_{x0} + A C_y{}^2 \qquad (8)$$

$$\frac{\partial C_x}{\partial \alpha} = 2 A C_y C_y^\alpha \qquad (9)$$

That leads to the final expression:

$$\begin{aligned} m_z^\alpha = &[(C_y^\alpha \cos\alpha - C_y \sin\alpha) \\ &+ (2AC_y C_y^\alpha \sin\alpha + C_x \cos\alpha)]\bar{x}_a \\ &- [(C_y^\alpha \sin\alpha + C_y \cos\alpha) \\ &- (2AC_y C_y^\alpha \cos\alpha - C_x \sin\alpha)]\bar{y}_a \end{aligned} \qquad (10)$$

The static margin is defined as:

$$-m_z^{Cy} = -m_z^\alpha / C_y^\alpha \qquad (11)$$

The final expression is far more complicated than the traditional definition of static margin, as shown in Equ.12. The reason is, in this case the pitching moment produced by the drag plays an important role and cannot be neglected.

$$m_z^{Cy} = \overline{X}_{cg} - \overline{X}_{ac} \qquad (12)$$

In our sample, the longitudinal stability will be:

$$m_z^{Cy} = -0.2276\bar{y}_a$$

If we set the static margin as 10%, the relative distance should be:

$$\bar{y}_a = 0.44$$

and

$$y_a = 88$$

That means the c.g. will be 88mm lower than the a.c..

4 Maneuvering mechanism

The wing was connected to the fuselage by a parallelogram linkage, constructed from two parallel rods, joints on the wing and joints on the fuselage. The parallelogram linkage was driven by a model servo. Driven by the servo, the parallelogram mechanism will lean forward or backward, moves the wing for-and-aftward, hence change the relative position between the c.g. and the a.c..

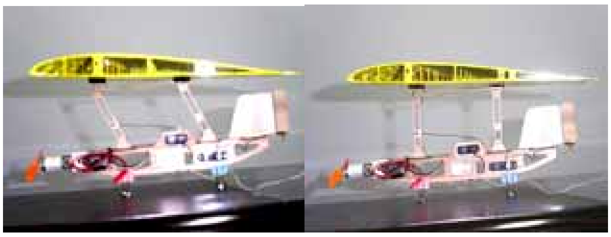


Fig.6 Movement of the mechanism

With the flight speed range of 5m/s ~10m/s, the lean angle of the links will be 5°~15° to maintain pitching moment trimmed. The wing has a travel of 3*mm* to -11*mm* from the balanced position.

5 Flight test and performance

Flight tests are a very important step in the design process. For it can check the accuracy of previous calculation and can also reveal unanticipated problem. The main purpose of our flight test was to validate the stability and maneuverability of such a configuration.

The early prototype had smaller wing area, and flew at higher cruise speed as c.a. 12m/s. It arose considerable difficulties for manipulating and evaluating. It was decided later that a larger wing area should be adopted to slow down the cruise speed.

With a larger wing area, the plane flew at a loiter velocity of 6m/s, endured 20 minutes till the batteries exhausted. It can be maneuvered smoothly with satisfied stability. By pulled or pushed the wing, the plane climbed or descended as expected. Compared to a traditional configured MAV, it was easier to control and flew more stable.

Another design aspect that was expected from the flight test was to check the lateral stability characteristics. The flight showed lateral stability was obviously augmented. This brought tendencies of Dutch roll instability. To remedy this instability, in the later prototype the area of vertical fin was enlarged.

It was also revealed in flight-test that such configuration had less agility. But it is not so severe a problem for the MAVs whose typical missions focuses on slow flight such as surveillance or reconnaissance.

6 Conclusion

The MAV research program in NWPU has been quite successful in proving that, by shifting the relative position between c.g. and a.c. can produce desired pitching moment to maneuver MAVs.

Lowering the c.g. can obviously augment the longitudinal stability, but may over-augment the lateral stability.

Such configuration has less agility hence fit only for missions which base on slow flight.

At last, a skilled R/C pilot is also very useful in identifying stability and maneuverability issues during flight tests.

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