Flapping Mechanism Design and Aerodynamic Analysis for the Flapping Wing Micro Air Vehicle

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Abstract. This paper introduces a biological flapping micro air vehicle (FMAV) with four wings, instead of two wings, where wing clap-and-fling of real insects has been mimicked. The total weight is 2.236g. A spatial linkage is implemented in the flapping wing system, which is symmetry. This can prevent the flapping wing MAV from tilting toward the left or the right in the course of flight. By using the computational fluid dynamics (CFD), it has been confirmed that the flapping wing system can utilize the clap-and-fling mechanism, which is essential to enhance the lift and thrust in the insect flight.

Introduction

Micro air vehicle is a new type of aircraft developed in the 1990s, according to the request of Defense Advanced Research Projects Agency and it is characterized: the size is 15cm below, the weight is from 10g to 100g, the stagnant time is 20 to 60min, the cruising speed is 30 to 60km/h, the payload is 1 to 18g, flight distance is 1 to 10km, and it can fly Autonomously [1]. Thanks to the recent advancement in the experimental biology, much of secrets behind the insect flight have been revealed [2, 3]. Basically, the Reynolds number of a MAV is about $10^5$, which will cause laminar separation phenomenon occurred on the surfaces of the body. So the lift generation mechanism in the unsteady air flow with the low Reynolds number is totally different from the mechanism in the high Reynolds number regime. Ellington [2] developed flow visualization indicating that the leading edge vortex plays an important role in the insect flight, and Weis-Fogh [3] found that clap and fling of wings is an important mechanism to reduce Wagner effect in the small chalcid hymenopteran. Especially FMAVs draw human being's strong attention, as insect flight is a fascinating natural mode of transportation. Several successful designs currently exist in the world, including Microbat [4], which is equipped with MEMS wings, and Harvard Robotic Fly [5], which is only 60 mg using the piezoelectric actuator.

In this paper, we present a FMAV with four wings. A mechanical linkage system actuated by a DC motor was developed, which transformed the rotation motion into a wing flapping. Clap-fling mechanism is implemented in the FMAV. Finally, we also used CFD to confirm that the flapping system can take advantages of the clap-fling mechanism.

Biologically Inspired Design

The flapping-wing system aims to mimic the clap-fling mechanism in the flight. Each component of the system was mostly hand-made using lightweight material such as balsa wood and carbon/epoxy composites. Fig.1 shows the final assembly of the system. Table 1 summarizes the dimension of the fully assembled flapping system. In the followings, we will explain the linkage system and how the wing clap was implemented in the flapping system.
Flapping Mechanism Design

The driving mechanism of the FMAV which we designed is a crank-and-rocker mechanism driven by a DC motor. Its structure is symmetrical, and it means that it can avoid the incomplete symmetry of the wings’ movement. This is in that the two wings are adhere to rockers and there are no difference among the two angles between two rockers and horizontal line (flap angle), and so do the angular velocities of the two rockers.

Fig. 1 Fully Assemble Device

Fig. 2 The 3D view of the entire mechanism

Table 1 Dimension and weight of the flapping-wing MAV

| Dimension                  | Wing length [cm] | Wing span [cm] | Wing area (one half wing) [cm²] | Length [cm] | Flapping-wing angle |
|----------------------------|------------------|----------------|---------------------------------|-------------|--------------------|
| Weight (gram)              | DC Motor         | Gears          | Wing                            | Structure   | Total weight       |
|                            | 0.646            | 0.262          | 0.123                           | 1.205       | 2.236              |

**Proposed Mechanism.** The flapping-wing mechanism consists of a spatial linkage, and two wings pivot at the same point A. A 3D view of the entire mechanism is shown in Fig.2. A and E joints are revolute and B and C joints are universal joints which can be achieved by using a telescopic joint. It can be viewed as a 4-bar mechanism A-B-C-E-A that actuated using one crank ED. The link CDE is a single rigid link. CD is perpendicular to CE. Points A and E are fixed in the frame of insect thorax. Let the angle made by AB to the horizontal and ED to the vertical be α and β respectively.

**Forward Kinematics.** The motion of driving mechanism is defined in Fig.2. The parameters of the systems are connecting rod length $L_{ab}$, crank length $L_{ed}$, and the distance between two points B and C be $L_{bc}$. The distance between points B and C is given by:

$$L_{bc} = \sqrt{(X_b - X_c)^2 + (Y_b - Y_c)^2 + (Z_b - Z_c)^2}.$$  \hspace{1cm} (1)

The angular displacement of the crank α, the angular displacement of the connecting rod β can be obtained:

$$L_{bc}^2 = (L_{ab} \cos \beta - L_{cd})^2 + (L_{ab} + L_{ab} \sin \beta - L_{de} \cos \alpha)^2 + (L_{de} \sin \alpha)^2.$$  \hspace{1cm} (2)

Let $L_{ab} = 13$mm, $L_{bc} = 21.4$mm, $L_{cd} = 10$mm, $L_{de} = 5$mm, $L_{ae} = 19.6$mm. Then, we can plot the variation of flap angle over a cycle, as shown in Fig.3. To get different largest flap angles, we can change the parameters. On the other hand, the wing flapping frequency is defined by the voltage on DC motor and the gear reduction ratio.
Clap-fling Mechanism

Since a detailed description of the aerodynamic mechanisms is outside the scope of the present paper, we only focus on the occurrence of the clap-fling mechanism, which some insects utilize, within the flapping motion to produce larger aerodynamic force [6]. In the clap phase, the air between the wings is expelled down in the form of a momentum jet which means an increase in lift, in Fig.4 A-C. In the fling phase, when the leading edges move away from each other, air is sucked into the gap enhancing lift, in Fig.4 D-E [7].

Numerical Stimulation Method

In this paper, we also use CFD to verify that this flapping wing MAV can utilize the clap-and-fling mechanism. A simplified model is implemented in a commercial flow solver which solves the governing incompressible Navier–Stokes equations on a two-dimensional computational mesh. To simulate the flow around moving wings with predefined motions, the commercial CFD solver Fluent v 6.1.22 is used. Let the angle of attack (AOA) is 0° and four wings are rigid. Wing1 and Wing3 have the same angular velocity, so do Wing 2 and Wing4.

It is no doubt that the clap-fling mechanism makes contribution to the lift production. However, few FMAVs with two wings utilize this aerodynamic mechanism. This FMAV does not use the mechanisms in the same manner as most MAVs do, which have four wings instead of two. The essential difference between the two wings configuration and that of the four wings is that this FMAV uses an X-wing configuration with the wings on top of each other, which can enhance aerodynamic force.

Fig. 5 shows the air vector generated by the flapping wing system during a flapping cycle. At the end of Wing2 and Wing3’s upstroke, wings are clapped together and push the air out (Fig.5, A). At the fling movement, the leading edges are opened (B), at the same time the trailing edges staying together, so that the air around the leading edges is rushed to fill the space between Wing2 and Wing3. As Wing2 and Wing3 continue to normal downstroke, they are clapped with Wing1 and Wing4 respectively (C, D). We can confirm that this kind wings configuration utilize the clap-fling mechanism.

Conclusion

In this paper, a FMAV with four wings has been introduced. A crank-and-rocker mechanism driven by a DC motor is implemented in the FMAV. Instead of only two wings, four wings configuration can create wing clap-and-fling as well as flapping motion mimicking the flapping motion of insects. With results of the CFD stimulation, we can confirm that the occurrence of the clap-and-fling mechanism. Further efforts should be devoted to the wing manufacture, energy and others of FMAV before taking off.
Fig. 5 The velocity vector diagram of a flapping cycle (AOA = 0°)

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