# DEVELOPMENT OF FLAPPING WING MICRO AIR VEHICLE

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## Abstract

*This paper presents the successful development of flapping wing Micro Air Vehicles "Npu-sentinel". A light-weight, low-friction transmission mechanism was fabricated to drive flapping wing. Dynamic characteristic of the flapping wing was investigated in the Low Turbulent Flow Wind Tunnel at Northwestern Polytechnical University (NWPU). The "Npu-sentinel" prototype has undergone successfully flight tests many times. It weighs approximately 40 grams, with a 40cm span and 21cm fuselage length. The onboard electronic subsystems are smallest and lightest among the commercial products.It is radio-controlled and is capable of turning left or right, pitching up or down. So far, the best flight duration achieved is 10 minutes on two KoKam 360-mAhr Ni-Cad cells. The success of "Npu-sentinel" prototype proves preliminarily that 40-centimeter span micro air vehicle is feasible and usable.*

## 1 Introduction

"Micro Air Vehicles" (MAV) are small flying objects used for operations ranging from traditional military mission to normal commercial applications[1]. It is designated by the Defense Advanced Research Projects Agency(DARPA)of the United States(US)as a class of aircraft with a largest linear distance between any two points located on the vehicle no greater than 6 inches and are capable of operating at speeds of 40miles per hour or less[2].Recently years, many countries have been carried on tremendous observation in micro air vehicles and obtain abundant production [3-5]. MAV includes fixed wing and rotorcraft and flapping wing, but flapping wing is well suited to MAV missions because it could enable short takeoff and landing and agile maneuverability. By flapping of wings, the birds and insects effectively increase the Reynolds number without increasing their forward flight speed [6]. On the other hand, the flapping wing generates lift and thrust without excessive size or weight. Hence the flapping wing is an efficient/useful option in designing Micro Air Vehicles.

It has taken almost several hundred years of development in flapping-wing flight. The development of flapping-wing can be dated back to the early days when Leonardo da Vinci designed his flapping-wing around 1500 A.D.The first flapping-wing that had flown successfully was in 1870 when Gustave Trouve's ornithopter, powered by an internal combustion engine using gun powder, flew 70 meters in a demonstration to the French Academy of Sciences[7].At Present, there have a lot of investigation on the development of flapping wing.For example,the famous flapping-wing MAVs "microbat " and "Mentor" are developed by California Institution of Technology and Toronto University.

However the ever-decreasing size and ever-increasing functional complexity of flapping wing has presented us many challenging problems including wing design and fabrication, development of flapping mechanism, wind tunnel test and flight test and so on. Based on the practicability and the current miniaturization level of China,we decided to development a flapping-wing,which has 40-centimeter span and is larger than the MAV defined by DARPA. In this paper, the development of first successful flapping wing called "Npu-sentinel" is discussed, ranging from design of wing and mechanism to wind tunnel test and flight tests of prototype.

## 2 Wing Design and Fabrication

It is all known, flapping wing generates lift and thrust by flapping of wing. It is apparent that wing is very important of the overall system. To flight, the wing should have high efficiency of aerodynamic and should not easily stall during flight. So designed wing must have very appropriately stiffness compliant to achieve the excellent performance of aerodynamic. On the other hand, to be practical, the wing should also be inexpensive and easy to manufacture. Base on these factors, designed wing is rectangle(Fig.1).The wing has 40cm span and 8cm chord, aspect ration is 5. The framework of wing is composed by carbon rods which diameter is difference. A thin polystyrene sheet is attached to carbon rods as wing membrane as seen in Figure 1.Flight test indicates that the wing has good performance for the present application. It is not only very light and easy to fabricate but also has sufficient stiffness.

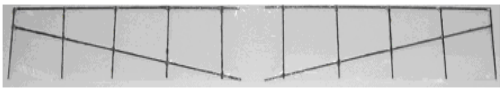

Figure 1: Configuration of wing

## 3 Mechanism Description

### 3.1 The crank link mechanism

The mechanism is the quite importance factor for the flapping wing MAV. It affects flapping rule of wing. A light-weight, low-friction transmission mechanism was built to convert the rotary motion of the driving motor into the flapping motion of the wing. This mechanism is named as crank link mechanism. It comprises three components, which are actuator, linkage system and retardment system. For the entire design, the center of crank disk is considered as the origin. The distance between the right and left wing link joints is called as link distance(w). It is fixed in the whole mechanism. One end of the connecting rod is attached to the crank disk. The other edge of the connecting rod is connected with the wing.Crank disk is attached to a gear shaft, which transfers the running of crank into the flapping action on the other end where the wing is to be attached. When the crank completes one rotation, one flapping cycle would be completed.The flapping mechanism is shown in Fig.2. All the connecting rods are made of aluminium-alloy, which have high specific strength and stiffness.The gears are made of plastic, which have not only high stiffness but also very light. The overall mass of the flapping mechanism is 15g. The maximum amplitude of flap is 77.21 degree. A small DC motor used to drive the mechanism. The power of 6 watts can be used to drive this motor. At this power, with no wing attached, the transmission can flap up to 15 Hz continuously for a few minutes without overheating the motor. When wings were mounted to the mechanism, flapping frequency can flap up to 10 Hz.

Figure 2: flapping mechanism

### 3.2 Mechanism Design Parameters

1. The maximum angle of flap

The maximum angle of flap is given by,

$$\phi = \arccos\frac{l_4^2 + l_6^2 - (l_1 + l_2)^2}{2l_4 l_6} - \arccos\frac{l_4^2 + l_6^2 - (l_2 - l_1)^2}{2l_4 l_6} \quad (1)$$

Where $l_1$ is the radius of crank and $l_2$ is the length of connecting rod and $l_4$ is the length of the other connecting rod and $l_6$ is the distance between wing joint and the center of crank running. The theory figure of flapping mechanism was shown in Fig. 3.

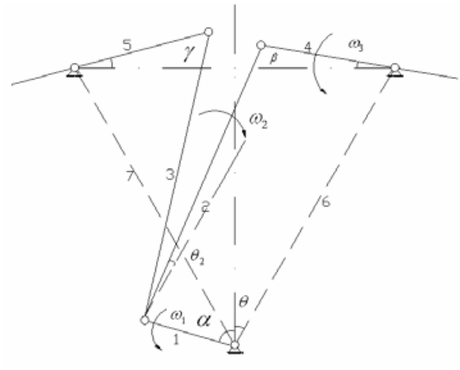

Figure 3: theory figure of flapping mechanism

2. Transmisson angle

Transmisson angle is an important criterion which was used judge for the transmit force performance of mechsnism. Transmisson angle is variational with mechanism flapping.The transmisson angle shouldn't less than 40° if the transmit force performance of mechsnism is excellent.The transmisson angle is given by:

$$\rho_1 = \arccos\frac{l_2^{\,2} + l_4^{\,2} - (l_6 - l_1)^2}{2l_2 l_4}$$

$$\text{or } \rho_2 = \pi - \arccos\frac{l_2^{\,2} + l_4^{\,2} - (l_6 - l_1)^2}{2l_2 l_4}$$

The transmisson angle of mechanism is about 48 degree.

## 3.3 Wing Lag

The motion of flapping mechanism is unsymmetrical.This introduces a lag between the right and the left wings(Fig.4). When the crank circumvolve 90$^\circ$(the most left position of crank) the lag is as high as 5.61$^\circ$ .As the revolving angle of the crank approaches $n\pi$( n = 0,1,2…), the lag reduces to 0$^\circ$. This clearly indicates that the flapping of wing is symmetrical only at the rotation angles $n\pi$ (n = 0,1,2…). The disadvantage is the unequal lift produced by the wings at any instant. This causes flapping motion in the lateral direction. We optimized the mechanism parpmeteres by genetic algorithm[8]. The right-and-left asymmetry of wing motion of flapping-wing was greatly improved. It was proved at later flight tests of prototype.

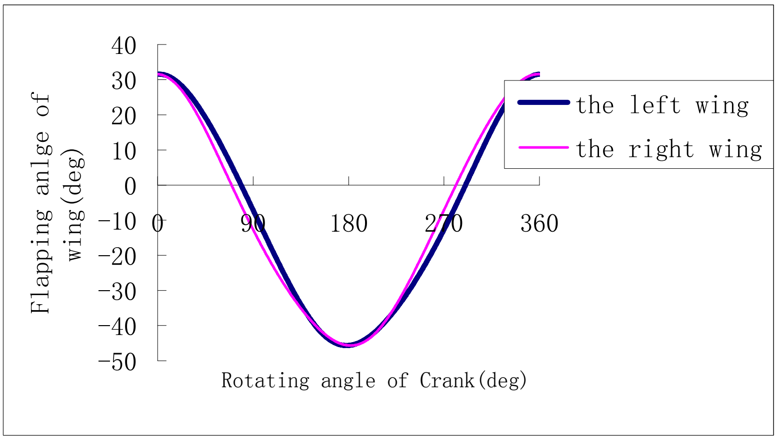


Figure 4: Wing Lag graph

## 4 Wind Tunnel Test

A high quality low-speed wind tunnel with velocity uniformity of 0.22% and speeds from 0m/s to 20.3m/s was constructed in NPU(Northwestern Polytechnical University). The wind tunnel has a 50 cm x50 cm x80cm test section. The precision of experiment is 0.47%. This test setup is shown in Fig.5. Wind tunnel tests were conducted to measure lift and Drag produced by the flapping wing. The flapping frequency from 4Hz to10Hz with 1Hz increment was chosen to investigate the change of lift and drag around the flapping frequency. The controlling parameters of experiments are the free stream velocity (U) and the flapping frequency (f), the free stream velocity in the test section had been controlled by adjusting the speed of the blower fan. The flapping frequency was controlled by adjusting the input voltage of D.C motor. The aerodynamic force measurements were taken using low capacity 2-D force loadcell.

Figure 5: The MAV Wind Tunnel of NPU

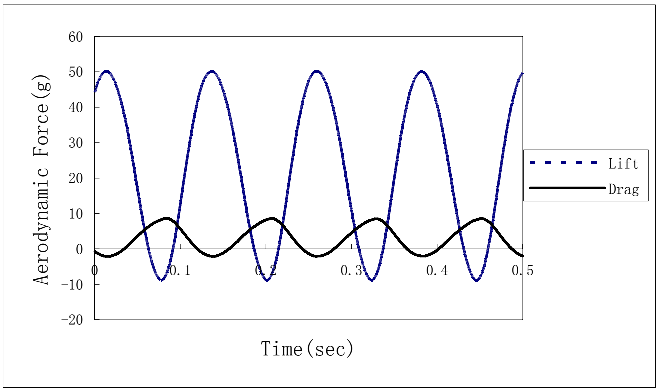


Figure 6: Lift and Drag Force versus Time

Wind tunnel tests were performed to provide data with which to asses whether the lift force generated from the wing is capable of supporting the flapping-wing flight or not and to investigate the unsteady-state aerodynamic performance of flapping wing(Fig.6).

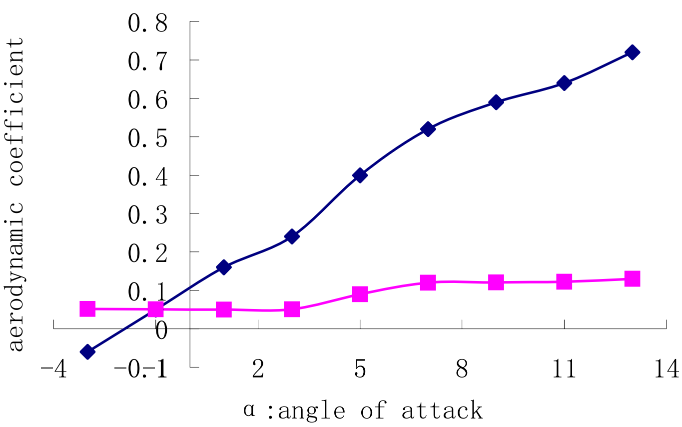


Figure 7: Lift and Drag Force versus Attack of angle

The attack of angle is about 7° and velocity is about 7m/s when the flapping wing flights.The lift coefficient is0.46 when the attack of angle is 7° according to wind tunnel test(Fig.7).The flight velocity V=7m/s and wing area S=0.032m$^2$,the lift is calculated:

$$F = 0.5 C_L \rho V^2 S$$

Where the density of air $\rho$ is taken as 1.225kg.m$^{-3}$.The total lift force of wing is calculated and the result is 45g.Hence,the lift force in a complete flapping cycle is satisfied with the requirement to surpport the weight of flapping-wing.

## 5 Prototype Vehicle and Its Flight Performance

The Npu-sentinel prototype, was shown in Fig.8, has the wingspan of 40 centimeters. The aircraft weighs approximately 40 grams. The structure is made up of carbon rods and basla wood. The body is burrowed with very smaller holes to reduce weight. A simple remote control system was implemented to allow a pilot to control the elevator and rudder on the Npu-sentinel prototype.

To validate the feasibility of the developed Npu-sentinel prototype, many flight tests have been done. On August 5th, 2005, we successfully performed flight test of Npu-sentinel without carrying payload to test the basic flight and control performances. The aircraft flew under radio control, where the pilot could left and right turns, pitching angle, and motor on/off. The maximum flight endurance has reached 10 minutes with two KoKam 360-mAhr Ni-Cad cells. Fig. 9 shows the flight tests of the Npu-sentinel. The flight duration was mainly limited by the power system and vehicle's weight.

We find that there are several challenges in order to achieve a successful sustained flight. First, the wind condition must be perfect. Often during flight test, the wind speed and direction shifted constantly. Second, the position of center of gravity is crucial. It directly affects the flight performance of flapping wing. Finally, each launch motion must be the same. We also believe that our current flapping wing is not the most optimized, thus we hope future flight duration can be improved.

Figure 8: Npu-sentinel Flapping Wing MAV

Figure 9: Npu-sentinel Flying

## 6 Conclusion

In the present paper, we have presented an overall development of Npu-sentinel including wing design and fabrication, mechanism design and fabrication, wind tunnel test and flight test. The success of the Npu-sentinel prototype proves that the 40 centimeters span micro air vehicle is feasible.With radio control system, the flight duration was significantly longer at 10 minutes. Additionally, the MAV concept has opened the doors to many new avenues of research in the fields of aerodynamics, propulsion,control, multidisciplinary design optimization, microelectronics, and artificial intelligence.

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