Development of Micro Aerial Vehicle using Piezoelectric Fiber Composites

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Abstract – Recently, flapping robots are noticed by many researchers, and many challenges are being made toward the realization of flight motions like insects, birds and so on. The purpose of this work is to develop flapping robots using a new type of piezoelectric material, that is, piezoelectric fiber composites. By using the composites, actuating fibers and sensing fibers can be embedded into a wing as part of the structure and it makes flapping robots with compact and light structure. A prototype of flapping robot capable of flapping and feathering motions has been developed. The design and driving method of the robot as well as experimental results about thrust and lift force are shown in this paper.

Index Terms - Piezoelectric fiber composites, Flying robot, Flapping, Feathering, Resonace

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I. INTRODUCTION

Smart materials and structures are a rapidly growing interdisciplinary technology embracing the fields of materials and structures, sensor and actuator system. Macro fiber composite (MFC) is the smart material made by combining with piezoelectric fiber and high-polymer materials [1]-[3]. MFC retains most advantageous features of the early piezoelectric composite actuators, namely, high strain energy density, directional actuation, conformability and durability, yet incorporates several new features [4][5]. It has multi- functions of actuating, sensing and power generating ability but is softer, thinner, lighter and more shock-resistant [6]. As it can be used as an actuator or a sensor, many researches such as embedding in structural for vibration suppression and power generating have been conducted [6]-[8].

Motivated by the features of MFC, the purpose of our work is to develop new and intelligent robots or mechatronic devices utilizing smart material MFC. When MFC is utilized as a sensor, how to treat the output voltage of MFC sensor is a problem to utilize soft and fiber-form piezoelectric sensor. Also, in the case of actuating, because the output displacement or force of MFC is very limited, how to combine the MFC to other material is also a problem.

In this paper, firstly sensing output of MFC is investigated and the method to convert to displacement is considered. Next, a basic characteristic of static drive and dynamic drive concerning actuation is measured and the effective way to use MFC is discussed. Based on the results, the concept of flight machine and the driving method of a MFC-combined wing structure are proposed. The MFC-combined wing structure and parameters are designed by simulation, and an active wing capable of flapping and feathering motions has been developed. The performance of the wing is investigated by an aerodynamics experiment. Also, a new type of active wing to improve the performance is introduced.

II. BASIC CHARCTERISTIC OF MFC

MFC is developed by NASA Langley Research Center and is supplied commercially by Smart Material Co. MFC is a thin plate-like structure consisting of piezoelectric fiber strengthened by interweaving comb-teeth pairs. The PZT fiber is embedded in epoxy to form a rectangular plate which is sandwiched between two layers of electrodes. The electrodes and the rectangular plate are in turn sandwiched by two layers of polymide. Due to the pattern of the electrodes, this structure is more flexible than existing piezoelectric actuators, deforms more easily and is more shock-resistant.

Distortion occurs when the voltage of +1500V to -500V is applied to a thin film of MFC. The distortion in d33 mode is 1800ppm, 2-3 times bigger than traditional piezoelectric materials. MFC can also be utilized as a sensor due to the unique characteristics of piezoelectric materials, that is, voltage is induced when external force or distortion is applied. MFC can be used as a charger as well since it can convert mechanical energy into electrical energy. Although MFC is very thin and soft, substantial power can be generated when it is attached to hard materials like metal plates.

A. Sensing characteristic

MFC generate electricity, when they become deformed or force is added externally. When MFC is used as sensor, the physical substance of output voltage must be known firstly. When MFC combined with a plate is deformed, the output voltage change by strain and strain rate are measured. Strain rate means the change of strain per unit of time.

By measuring the displacement of the tip, strain in the fiber direction can be calculated. The output voltage of MFC is proportional to the strain rate in the fiber direction. And the proportional constant can be calculated from the experimental result. By integrating the strain rate, strain in the fiber direction can be obtained. According to the strain, the tip displacement can be calculated from the geometric relation in the fiber direction. Consequently, the tip displacement can be estimated by measuring output voltage of MFC sensor.

B. Actuating characteristic

When a voltage is applied to MFC, it expands and contracts along the fiber direction. MFC combined with a plate can produce the bending displacement.

When the voltage is applied to MFC, The displacement is somewhat different when voltage increases and decreases. It is a hysteresis phenomenon caused by piezoelectric characteristic. Here, an alternating voltage of sine wave is applied to MFC combined with a stainless plate. When the frequency is changed from 10Hz to 30Hz in small increment, the tip displacement of the plate is measured with a laser range sensor. The result is shown in Fig.1. The higher the applied voltage increases, the larger displacement becomes. In addition, the higher the applied voltage increases, the lower the resonance frequency becomes. And the amplitude of the MFC structure at resonant frequency is about nine times of that at static drive. Therefore, it is necessary to drive the MFC structure at resonant frequency in order to make the MFC actuator generate large displacement. For this reason, it is necessary to design the MFC structure carefully because the resonant frequency depends on the size, shape, density and the stiffness of the material.

Motivated by the above points, our proposal is to develop new and intelligent flight machines with active wings by utilizing the features of MFC. By embedding the MFC into the structure of a wing, a light and compact active wing can be realized, because the mechanisms such as links are not necessary. By using some fibers of MFC as sensors, the motion state of the wing can be detected easily. Then, an intelligent flight can be realized by using the feedback control. Besides, by using some or all fibers of MFC for power generating, energy can be stored and longer flight can be realized by the active wing.

A. Basic Principle of flapping wing

Strictly speaking, because flapping wing aerodynamics is vortical and unsteady, a model with considering the vortical effect and unsteady state is necessary [17]. For steady flapping flight except taking off and descending, a simple model ignoring the vertical effect and unsteady state is still useful for explaining the basic principle of flapping flight [18]. The simple model is described as follows for giving hints on designing the motions of the flapping wing.

Basically, lift force L and drag force D for a fixed wing can be calculated by equations (1) and (2).

$$L = \frac{\rho_{air}}{2} V^2 C_L S_W \tag{1}$$

$$D = \frac{\rho_{air}}{2} V^2 C_D S_W \tag{2}$$

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□air is air density, V is flight speed, C_L is lift coefficient, C_D is drag coefficient including inductive drag, and S_W is wing area of the wing. According to the balance of forces, the required thrust for flight can be obtained by equation (3).

$$T_H = \frac{W}{\chi} \qquad (3)$$

□is the lift-to-drag ratio, W is the load of the ornithopter. The lift-to-drag ratio is calculated, including the lift and the drag produced by the wing according to the blade element theory.

From above equations, it can be known that the lift force and drag force can be produced by the flight speed for the case of a fixed wing. The lift and drag force by the fixed wing will be 0 if the flight speed is 0 in case of hovering motion.

For the case of an active wing, a model of a wing with flapping motion and feathering motion is shown in Fig. 2. The motion and the force at a point of r, which is the distance from the root of the wing, is considered. F is the resultant vector of the lift and the drag, T_P is the thrust. v is the wing velocity vector by flapping motion, V_R is the resultant vector of V and v. a is the attack angle, f is the angle between V_R and v.

V_R can be obtained by equations (4) to (6) .

$$V_R = \sqrt{V^2 + v^2} \qquad (4)$$

$$\tan\varphi = \frac{V}{v} \qquad (5)$$

$$v = r\theta_0\omega\cos\omega t \qquad (6)$$

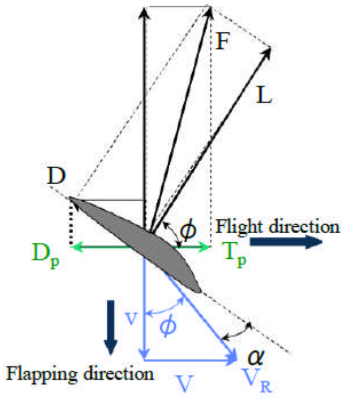


Fig. 2 Force and air flow

on wing cross section..

Considering a unit bounded by r and r+dr, we assume that all of the unit move at same speed. The lift force and the drag force of the whole wing can be derived by equations (7) and (8). b_W is the wing cord length. The lift coefficient and drag coefficient depends on attack angle and can be referred to experimental data [19]. And the mean lift and mean drag can be calculated by equations (9) and (10). t_T is the time duration of one cycle for flapping motion. Then, the thrust component and the drag component of the whole wing can be derived by equations (11) and (12). And the mean thrust and mean drag can be calculated by equations (13) and (14). For the case of flapping wings with feathering motion, the lift-to- drag ratio□in equation (3) can be calculated by the vertical component of the mean lift in equation (9) and the drag in equation (14).

$$L = \int_0^R \frac{1}{2} b_w \rho_{air} V_R^2 C_L dr \qquad (7)$$

$$D = \int_0^R \frac{1}{2} b_w \rho_{air} V_R^2 C_D dr \qquad (8)$$

$$\overline{L} = \int_0^{t_T} \int_0^R \frac{1}{2} b_w \rho_{air} V_R^2 C_L drdt \qquad (9)$$

$$\overline{D} = \int_0^{t_T} \int_0^R \frac{1}{2} b_w \rho_{air} V_R^2 C_D drdt \qquad (10)$$

$$T_p = \int_0^R \frac{1}{2} b_w \rho_{air} V_R^2 C_L \cos\varphi dr \qquad (11)$$

$$D_p = \int_0^R \frac{1}{2} b_w \rho_{air} V_R^2 C_D \sin\varphi dr \qquad (12)$$

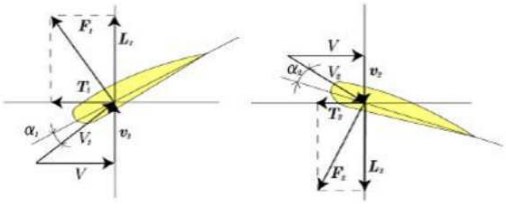
$$\overline{T_p} = \int_0^{t_T} \int_0^R \frac{1}{2} b_w \rho_{air} V_R^2 C_L \cos\varphi drdt \qquad (13)$$

$$\overline{D_p} = \int_0^{t_T} \int_0^R \frac{1}{2} b_w \rho_{air} V_R^2 C_D \sin\varphi drdt \qquad (14)$$

Notice that because the flapping motion is a symmetric up-down motion, the mean lift in one cycle of the flapping motion is 0, if all parameters in equation (9) are constant, that is, if a flapping motion with no feathering motion is considered. From equation (13), the mean thrust in one cycle of the flapping motion is 0, if a flapping motion with no feathering motion is considered.

From above discussions, to realize the flights including hovering, a feathering motion coupled with the flapping motion adequately is necessary to generate a positive mean thrust and a positive mean lift. One ideal configuration of the relation between the flapping motion and feathering motion to generate a positive mean lift is shown in Fig.

3. By the configuration, a positive mean lift can be generated by an adequate attack angle. This is basic principle to be used for the design of motions for flapping wings in this paper.



(a) Down-stroke (b) Up-stroke
Fig.3 Wing cross force diagram of down-stroke and up-stroke

B. Development of Flapping Wing

A prototype of the flight robot with structural active wings has been made based on the consideration. The configuration of the flight robot is shown in Fig. 4.

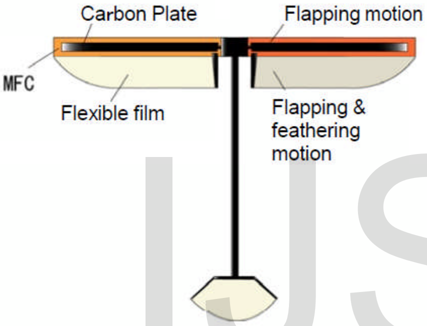


Fig. 4 Configuration of flight robot with structural active wings.

The structure between the wing and the body is shown in Fig. 5.

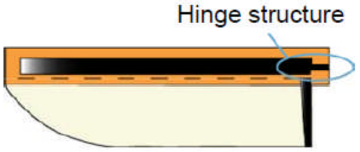


Fig. 5 Hinge structure..

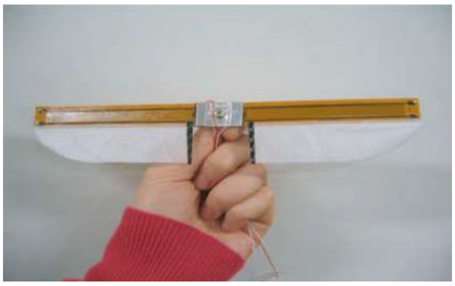


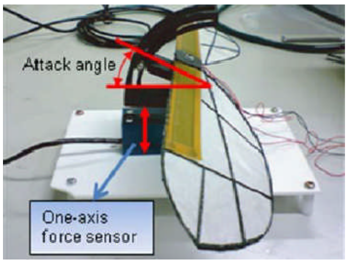
Fig. 6 The prototype.

Table 1 Specification of structural wing (one side)

Weight	1.4 g
Width	21.6cm
Resonant frequency	17.75Hz
Flapping amplitude	34.8°
Area	35.92cm^2

To estimate the performance of the wing, the generated lift and thrust by the wing are measured by an experiment setup shown in Fig. 7. The attack angle of the wing is adjusted by a fixture. As the force sensor, a precise load cell WBJ-05N with a rated load of 500mN made by Showa Measuring Instruments Inc. is used. Because the flapping wing is driven at resonant frequency, the inertia force is almost balanced with the elastic force. So the force measured by the force sensor can be regarded as the aerodynamic force by the motions of wing. The measured lift and thrust for different attack angles are shown in Fig. 8 and Fig.9, and the calculated mean lift and thrusts from the two figures are shown in Table 2. From the figures ant the table, we can know that the mean lift reaches 4.32mN at the attack angle of 60 degree, which is still small to support the weight of the wing. But, it can be said that the adequate attack angle for hovering is around 60 degree. And thrust reaches 7.35mN at the attach angle of 10 degree.

From the movies taken by high speed camera, it is found that the deformation of the part of the flexible film is too large due to its low stiffness.



(a) Measuring lift

(b) Measuring thrust

Fig. 7 Experimental setup

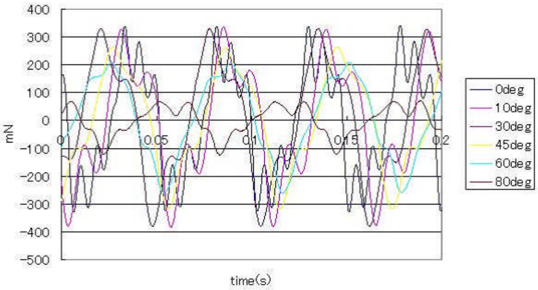


Fig. 8 Measured lift.

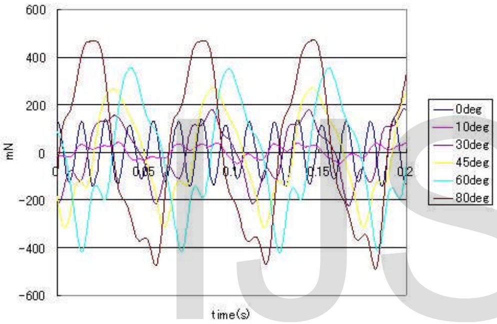


Fig. 9 Measured thrust.

Table 2 Mean lift and mean thrust

Angle	Mean lift(mN)	Mean thrust(mN)
$\theta = 0°$	-0.35	1.58
$\theta = 10°$	0.27	3.17
$\theta = 30°$	0.39	1.95
$\theta = 45°$	2.15	3.70
$\theta = 60°$	4.32	0.09
$\theta = 80°$	-2.87	-1.09

C. Improvement of the Flapping Wing

To improve the performance of the flapping wing, enhancement of the stiffness of the part of the flexible film without large increment of the total weight is considered.

First, we invetigated the structure of wings of insects. Fig. 10 shows the structure of the wing of Nervule. Two points are noticed here. One is the veins, which plays an important role to keep the high stifness of the wing with a comapct and light structure. Another is the shape of the wing, which becomes wider and wider from the root to the end of the wing. Such a shape may contribute to the increase of lift and thrust of a wing.

Acccoding to the considerations above, a model of the wing for new prototye of flapping robot has been designed as shown in Fig. 11. By cosidering the complex of manufacturing, the veins are simplified and are made by resin. Fig. 12 shows the prototype of new wing and Table 3 shows the specification of it. Comparing with the old type in Section B, the new prototpe is a little heavier with smaller resonant frequency. The lift and thrust are measured using same experimental setup shown in Fig. 7. The measured results for different attack angles are shown in Fig.13 and Fig.14. And the mean lift and thrust for different attack angles are shown in Table 4. As the result, the maximum lift reaches 28.5 mN at the attack angle of 60 degree, which is 6.6 times of that by old prototype. Although the lift itself is still smaller than the weight of the wing, it can be said that it is possible to t approach or exceed the weight, which is the condition for hovering, by further improvement. Also, the maximum thrust reaches 7.35 mN at the attack angle of 10 degree, which is 2 times of that by the old prototype.

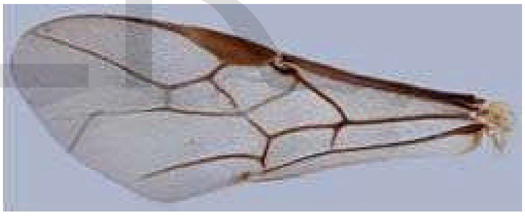


Fig.10 Nervule(Ichneumonidae)

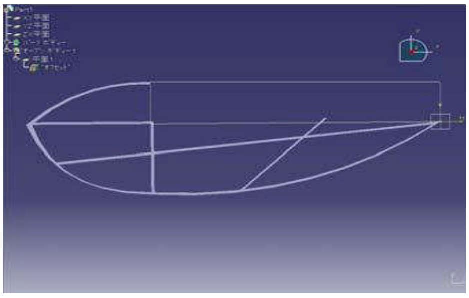


Fig. 11 Model of the new wing

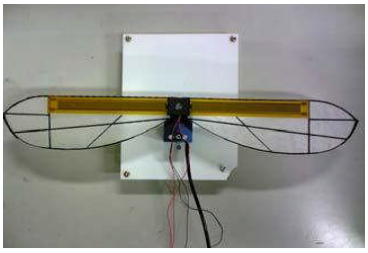


Fig. 12 New prototype of flapping robot.

Table 3 Specification of new prototype of wing (One side)

wing weight(single wing)	2.25g
wing area(single wing)	4200mm^2
wing span	297mm
resonance frequency	16Hz

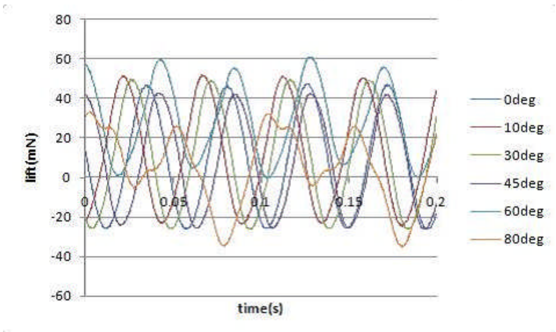


Fig. 13 Measured lift (New prototype).

Table 4 Mean lift and mean thrust (New prototype)

Angle	Mean lift(mN)	Mean thrust(mN)
$\theta = 0°$	9.93	6.45
$\theta = 10°$	12.4	7.35
$\theta = 30°$	10.5	6.11
$\theta = 45°$	8.14	4.20
$\theta = 60°$	28.5	2.85
$\theta = 80°$	4.54	-1.78

CONCLUSION

In this paper, the development of flapping robots using piezoelectric fiber composites is described. Following results are obtained.

1) Basic characteristics of piezoelectric fiber composites for sensing and actuating are investigated and the method for mechanism design and driving to use piezoelectric fiber composites for flapping robots are given;

2) Active wings using piezoelectric fiber composites for flapping robots have been developed, and experimental results have shown the potential feasibility of hovering by active wings using piezoelectric fiber composites.

Further work to improve the performance by designing more complicated wing including body will be done.

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