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Development of Flapping Robots using Piezoelectric Fiber Composites - Performance Enhancement by Unique Structure and Drive Control -

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Abstract **– Recently, flapping robots are noticed by many researchers, and the realization of flight motion like insects, birds and so on has many challenges. 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 as well as energy harvesting and sensing fibers can be embedded into the wing as part of the structure, which makes the robot flap while remaining compact and light. This paper describes the performance enhancement of the flapping robots capable of flapping and feathering motions using piezoelectric fiber composites. A unique mechanism with different stiffness for up-stroke and down-stroke and a new drive control using saturated sine wave are proposed in this paper. By introducing the mechanism and drive control, the performance about lift and thrust force has been improved remarkably.**

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

I. INTRODUCTION

Smart materials and structures are a rapidly growing interdisciplinary technology embracing the fields of materials and structures, sensor and actuator system. Piezoelectric fiber composite is a new kind of smart material obtained combining piezoelectric fiber and high-polymer materials [1]-[3]. It 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 is multi-functions, since it can work as actuator, sensor and power generator, while being 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].

On the other side, 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. Usually, the wings of many flight robots are driven by the actuators mounted at their bodies [9]-[14]. Recently, the concept using active wing has been proposed and some simulation work has shown that better flying capability can be obtained by deforming the wing itself [15]-[17]. Therefore, the development of flight robots using active wings is an attractive and challenging topic now.

Motivated by the feature and multi-functions of piezoelectric fiber composite, the purpose of our work is to develop new flight robots with active wings utilizing piezoelectric fiber composites. By embedding the piezoelectric fiber composites into the wings, the wing can be controlled by part of the fibers as actuator according to the deformation information from part of the fibers as sensors. Besides, the part of fibers as actuator can be used for harvesting the energy from the motion of the wing [18].

In this paper, performance enhancement of the flapping robot by unique structure and drive control is described. Firstly basic characteristic of piezoelectric fiber composite is introduced in section II. In section III, the basic method to improve the performance of the flight robots is given. The structural approach is proposed in section IV and drive control approach is proposed in section V. In section VI, the experimental results by the developed prototype are described. Section VII concludes the results.

II. BASIC CHARACTERISTIC OF PIEZOELECTRIC FIBER COMPOSITE

Here, one kind of piezoelectric fiber composite, MFC shown in Fig. 1, is used. MFC is developed at NASA Langley Research Center and is manufactured 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 between 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.

Usually, the deformation of MFC is small. 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, how to design the structure for pasting MFC because the resonant frequency depends on the size, shape, density and the stiffness of the material, and how to drive the MFC are the problems to be solved to utilize it successfully.

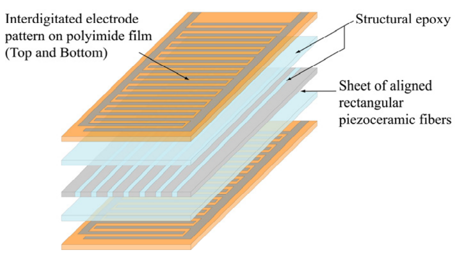


Fig. 1 Structure of MFC

III. BASIC CONSIDERATION

One problem of the previous prototype [19] developed by Authors is that the performance of the flapping robot, specially the generated lift should be enhanced. To solve the problem, structural and control approaches are considered in this paper.

A model of a wing with flapping motion and feathering motion is shown in Fig. 2. F is the resultant vector of the lift and the drag, L_m is vertical force, T_m is the thrust. v is the up-down inflow velocity vector by flapping motion, V is inflow velocity by forward movement, V_m is airflow speed. α is the attack angle, θ is pitch angle, ϕ is inflow angle.

Lift of appearance and total lift can be calculated by equations (1) and (2), total thrust can be calculated by equation (3), the relation between the inflow angle and the pitch angle is shown by equation (4). ρ_{air} is air density, C_L is lift coefficient, C_D is drag coefficient, and S_W is effective wing area of the wing. From the equations, it is known that the lift and thrust can be adjusted by the effective wing area.

$$L = \int_0^R \int_0^C \frac{\rho_{air}}{2} V_m{}^2 C_L dcdr = \frac{\rho_{air}}{2} V_m{}^2 C_L S_W \qquad (1)$$

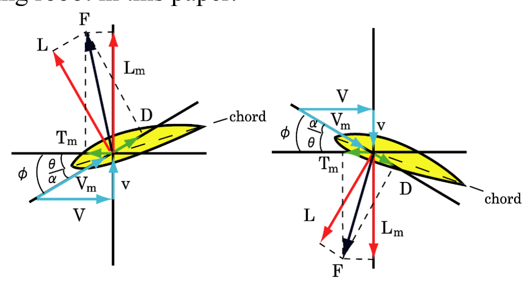
$$L_m = \int_0^R \int_0^C \frac{\rho_{air}}{2} V_m{}^2 (C_L \cos\phi + C_D \sin\phi) dcdr \qquad (2)$$

$$T_m = \int_0^R \int_0^C \frac{\rho_{air}}{2} V_m{}^2 (C_L \sin\phi - C_D \cos\phi) dcdr \qquad (3)$$

$$\phi = \theta + \alpha \qquad (4)$$

Basically, 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 for down-stroke and up-stroke to generate a positive mean thrust is shown in Fig. 2.

To generate a positive mean lift, one method is to reduce negative lift in the up-stroke and to increase the positive lift in the down-stroke. This is the basic idea to be used for the design of mechanism and drive control method for the flapping robot in this paper.



(a) Down-stroke (b) Up-stroke

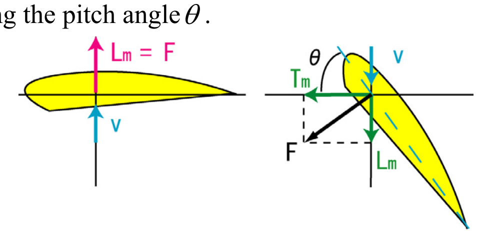
Fig. 2 Wing cross force diagram of down-stroke and up-stroke

IV. STRUCTURAL APPROACH

A. Proposal of new mechanisms

As described above, to enhance the mean lift generated by the flapping robot, it is necessary to reduce negative lift in the up-stroke and to increase the positive lift in the down-stroke.

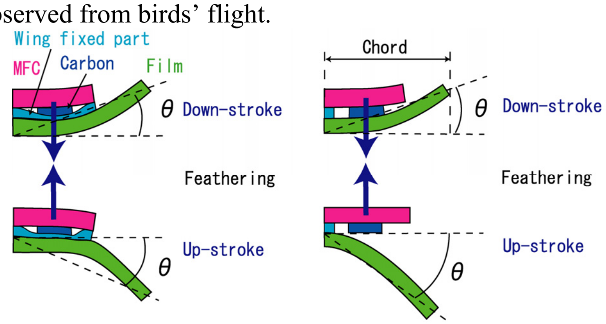
The method to improve the mean lift is to utilize the configuration shown in Fig. 3, in which the effective wing area in down-stroke is larger than that of up-stroke by changing the pitch angle θ.



Small θ to enlarge positive L_m (a) Down-stroke
Large θ to reduce negative L_m (b) Up-stroke

Fig. 3 Feathering method to improve lift (wing cross view)

For comparison, two mechanisms shown in Fig.4 are considered here. One is the edge-and-vein-fixed mechanism which has been used in our previous prototype [19], and another is the edge-fixed mechanism which is newly proposed in this paper. For the edge-and-vein-fixed mechanism, besides the flapping motion, the flexible film moves almost symmetrically in the up-stroke and down-stroke as feathering motion. It is the reason why small mean lift is generated. For the edge-fixed mechanism, because the feathering motion in the up-stroke is easier than that in the down-stroke, the configuration similar to that shown in Fig. 3 can be realized and the improvement on mean lift can be expected. Both mechanisms can be regarded as the mechanism with two joints, one is located at the left side of MFC part driven by the MFC and another is located at the right side of the MFC part driven by the aerodynamic force to the flexible film.The concept shown in Fig. 3 and Fig. 4 can be extended and applied to the mechanism along wing span direction and the similar phenomenon can be observed from birds' flight.



(a) Edge-and-vein-fixed mechanism (b) Edge-fixed mechanism

Fig. 4 Concept of two mechanisms (wing chord wise).

Many birds utilize the flapping motion by two hinges and a simple model for that is shown in Fig. 5. Birds extend its wing during the down-stroke to achieve large effective wing area and fold its wing during the up-stroke to achieve small effective wing area. The extension and folding actions of the wing are realized by the motion of wrist joint, besides basic flapping motion is realized by the shoulder joint. And the phase shift between the motions of the shoulder joint and the wrist joint is very important to reduce the effective wing area in the up-stroke and to increase the effective wing area in the down-stroke. That is, a synchronization of the motion between the shoulder joint and wrist joint is necessary to improve the mean lift.

Based on the discussion above, a concept for the wing mechanism along the wing span direction is shown in Fig. 6. Basically, the wing is divided into MFC-pasted part and film- only part. The left end of the MFC-pasted part can rotate just like the shoulder joint in Fig. 5. The film-only part bends up and down due to the flexibility of the film and the aerodynamic force on it, and can be regarded that it rotates around the right end of the MFC-pasted part, that is, the wrist joint in Fig. 5.

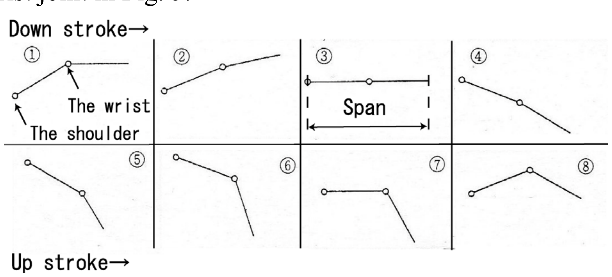


Fig. 5 Method of the bird's flapping by two point hinge

During the down-stroke, the MFC-pasted part goes down by ψ_1 and the film-only part bends up by ψ_2 due to the aerodynamic force. During the upstroke, the MFC-pasted part goes up by ψ_1 and the film-only part bends down by ψ_2 due to the aerodynamic force. If the phase difference between the two parts can be controlled so that $\psi_1 + \psi_2$ during the down-stroke is smaller than that during that during the up-stroke, similar effect with extending the wing during the down-stroke and folding the wing during the up-stroke can be realized by the mechanism. Therefore, it can contribute to the increase of the mean lift.

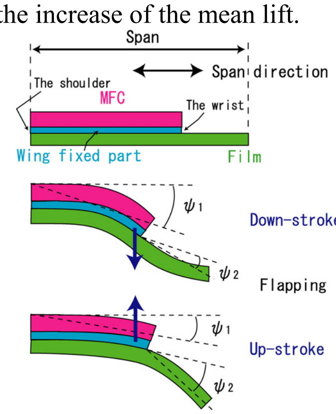


Fig. 6 Concept for wing mechanism along the span direction (wing span wise)

B. *Wing structure*

Another structural approach is to reduce the weight of the wing while keeping the stiffness of it, by referring the structure of wings of insects. As the structure of the wing of insect, 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. A wing 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. Finally, a wing with simplified veins to reduce the weight of the wing shown in Fig. 7 is adopted.

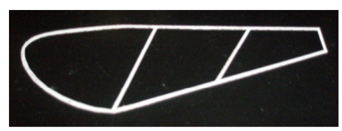


Fig. 7 Wing's veins with reduced middle lines of wing

C. *Prototype*

Two prototypes of wings using the edge-and-vein-fixed mechanism and the edge-fixed mechanism are shown in Fig. 8 and Fig. 9. The specification of the wings is shown in Table 1. For the wing using edge-and-vein-fixed mechanism in Fig. 8, the film is pasted to the MFC in almost of all area of the MFC via veins. For the wing using edge-fixed mechanism in Fig. 9, the film is pasted to MFC only at the front edge part (wing fixed part). Therefore, the feathering motion of the wing in down-stroke is stopped by the MFC to realize a configuration near to that in Fig. 3 (a) and the feathering motion of the wing in up-stroke is very easy to realize a configuration near to that in Fig. 3 (b). And because the film beyond the MFC part along the span direction is just fixed by the veins, a passive bending motion is possible so that the two-joint mechanism shown in Fig. 5 and Fig. 6 can be formed.

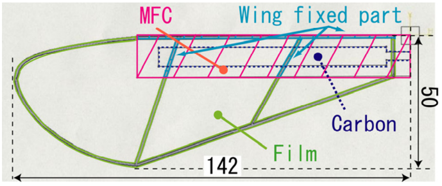


Fig. 8 Detailed structure of the edge-and-vein -fixed wing

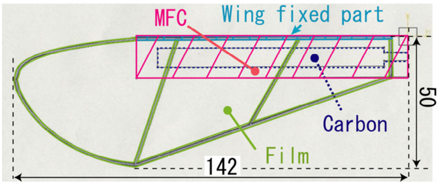


Fig.9 Detailed structure of the edge-fixed wing

Table 1 Wing specification

wing weight	$1.96g$
wing area	$5000mm^2$
wing span	$142mm$
resonance frequency	$12Hz$

V. DRIVE CONTROL APPROACH

As mentioned before, the structure using piezoelectric fiber should be driven at resonant state to realize large motion for flapping and feathering. Basically the flapping robot should be driven at resonant state to achieve maximum performance. Besides, because the mechanisms proposed are the nonlinear mechanisms with more than two degree-of-freedoms, drive control to motivate the resonant vibration of each mode with ideal phase difference is very important. For example, Fig. 5 shows one ideal combination of the motions by two joints.

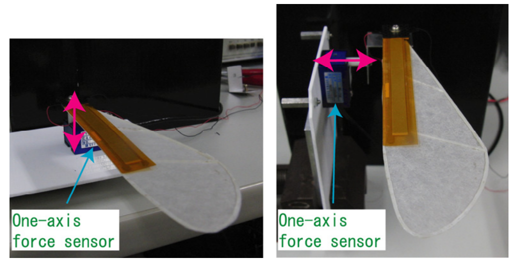
Because the motion analysis of such mechanisms is very difficult, it is hard to find out optimal drive control signal to motivate the multiple modes with ideal phase difference. As an experimental approach, two waves with different frequencies, sine wave and saturated sine (refer to section VI for details) wave, have been used for driving the wing mechanism and the performance have been measured to find out the suitable drive signal.

VI. EXPERIMENTAL RESULTS

To confirm the effectiveness of our proposal, two kinds of wings using the edge-and-vein fixed and the edge-fixed mechanism have been driven by sine wave and saturated sine wave with different frequencies. To estimate the performance of the wings, the generated lift and thrust by the wing are measured by an experiment setup shown in Fig.10.

A. Results driven by sine wave

To investigate the effect of structural approach, drive control using sine wave (+1500V to -500V) is used. The mean lift and mean thrust of each wing are measured. The mean lift and mean thrust for different drive frequencies of the edge-and-vein-fixed and the edge-fixed wings are shown in Fig.11



(a) Measuring lift (b) Measuring thrust

Fig. 10 Experimental setup.

and Fig.12. From the figures, it is known that both mean lift and mean thrust are improved much by using the edge-fixed mechanism. It is due to change of effective wing area, which is realized by the small pitch angle at the down-stroke and large pitch angle at the up-stroke by using the asymmetric structure of edge-fixed wing.

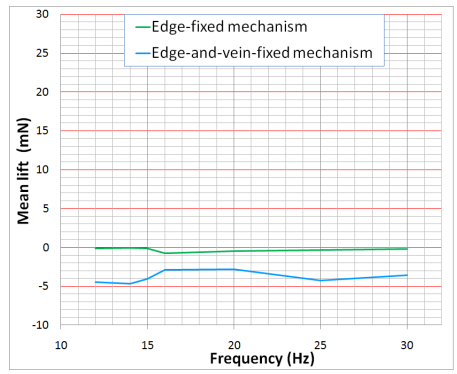


Fig. 11 Mean lift using sine wave

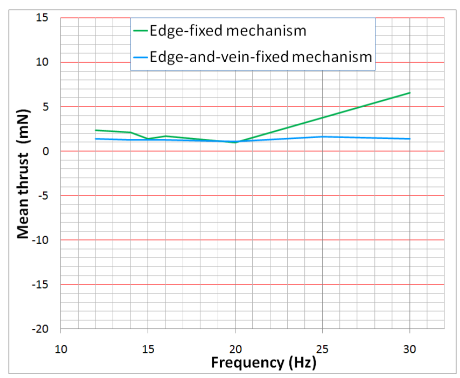


Fig. 12 Mean thrust using sine wave

Table 2 Mean lift and thrust of the edge-fixed wing using sine wave

Frequency (Hz)	Mean lift (mN)	Mean thrust (mN)
12Hz (resonance)	− 0.12	+ 2.33
15Hz	− 0.11	+ 1.40
20Hz	− 0.46	+ 0.98
30Hz	− 0.21	+ 6.58

Table 3 Mean lift and thrust of the edge-and-vein-fixed wing using sine wave

Frequency (Hz)	Mean lift (mN)	Mean thrust (mN)
12Hz (resonance)	− 4.48	+ 1.41
15Hz	− 4.07	+ 1.25
20Hz	− 2.81	+ 1.08
30Hz	− 3.55	+ 1.39

By increasing the drive frequency of sine wave from 12 to 20Hz, the mean thrust doesn't varies almost, because the feathering angle is too small for the frequency period. By increasing the drive frequency of sine wave from 20 to 30Hz, the mean thrust increase gradually because the feathering angle is large. Typical results are included in Table 2 for the edge- and-vein-fixed mechanism and in Table 3 for the edge-fixed mechanism. From the results, the effect to improve both mean lift and mean thrust by using the edge-fixed mechanism is confirmed.

B. Result driven by saturated sine wave

From Fig. 11, it is known that mean lift has not been improved much by drive control using sin wave even for the edge-fixed mechanism. As mentioned in Section V, drive control to motivate the resonant vibration of each mode with ideal phase difference is necessary.

Preliminary experiments using various driving waves have been tried. It is known that although rectangular wave can pump most electric power to MFC. It motivated higher frequency vibrations which reduced the mean lift. As the final result, a saturated sine wave shown in Fig. 13 is effective for the purpose, because the saturated sine wave can both pump more electric energy to MFC than sine wave and contains one, three, five … times of basic frequency of sine wave, which may motivate specified multiple resonant modes of the wing mechanism.

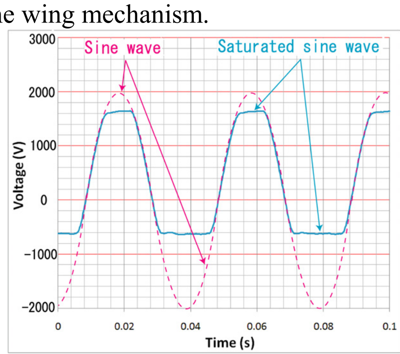


Fig. 13 An example of saturated sine wave.

By drive control using saturated sine wave, mean lift and mean thrust for the edge-fixed mechanism are shown in Fig. 14 and Fig. 15, and the values are concluded in Table 4. From the figures and table, it is known that mean lift is improved much at some frequencies and the mean lift has been improved remarkably while the mean thrust becomes lower than that of sine wave at the frequency of 30 Hz. It is a relation of the lift and thrust trade-off. Fig. 16 shows the high speed movies of the wing for the condition. From the high speed movies of the wing for the condition. From the figure, it can be known that an ideal feathering motion described in Fig. 4 and an ideal flapping motion described in Fig. 5 are motivated by the saturated sine wave of 30 Hz. On the other side, there exist some minimum points in Fig. 14. It is also known that those minimum points are due to that the phase difference between the two joints is opposite to the ideal phase difference from the analysis of the movie of the wing. For the frequencies more than 30Hz, the mean lift will decrease.

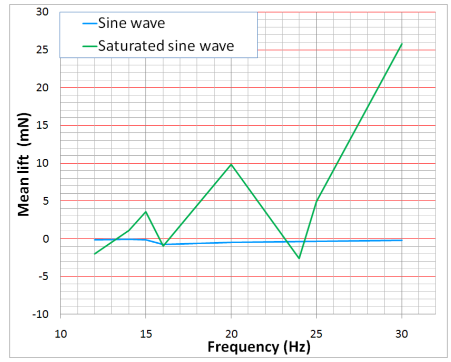


Fig. 14 Mean lift using edge-fixed mechanism

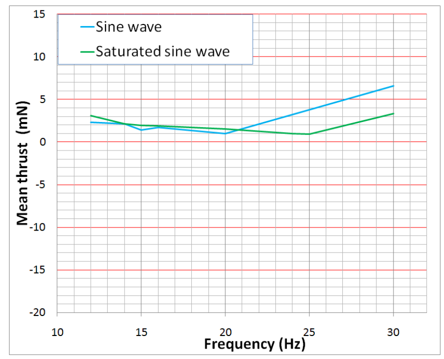


Fig. 15 Mean thrust using edge-fixed mechanism

Table 4 Mean lift and thrust of the edge-fixed wing using saturated sine wave

Frequency (Hz)	Mean lift (mN)	Mean thrust (mN)
12Hz (resonance)	− 1.96	+ 3.08
15Hz	+ 3.56	+ 1.94
20Hz	+ 9.81	+ 1.51
30Hz	+ 25.78	+ 3.32

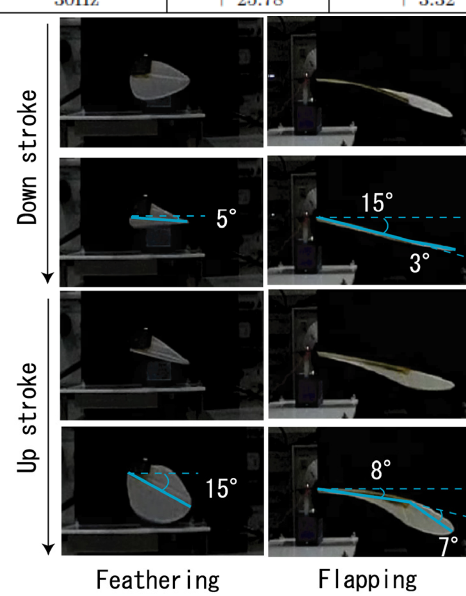


Fig. 16 Flapping and feathering at a frequency of 30Hz

Moreover, mean lift and mean thrust for the edge-and-vein-fixed mechanism wing are shown in Fig. 17 and Fig. 18, and the values are concluded in Table 5. From the results, it can be known that saturated sine wave drive is very effective for the edge-and-vein-fixed mechanism to achieve large mean lift and large mean thrust. There exist maximum and minimum points in both figures. Those points are also due to that the ideal phase difference or opposite to the ideal phase difference between the motions of two joints is realized.

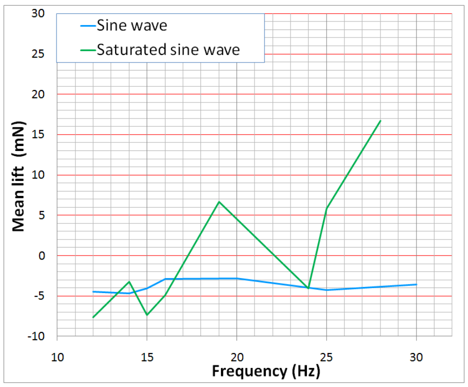


Fig. 17 Mean lift using edge-and-vein-fixed mechanism

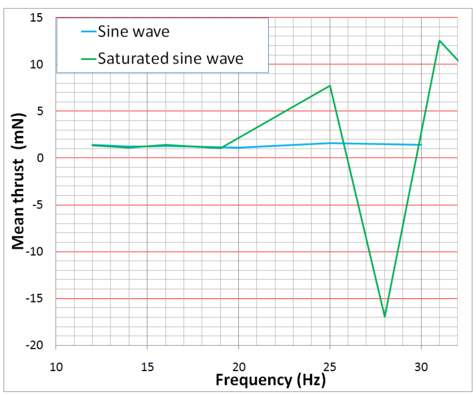


Fig. 18 Mean thrust using edge-and-vein-fixed mechanism

Table 5 Mean lift and thrust of the edge-and-vein-fixed wing using saturated sine wave

Frequency (Hz)	Mean lift (mN)	Mean thrust (mN)
12Hz (resonance)	− 7.65	+ 1.34
14Hz	− 3.22	+ 1.13
19Hz	+ 6.68	+ 1.02
28Hz	+ 16.74	− 16.96

VII. CONCLUSION

This paper describes the performance enhancement of the flapping robots capable of flapping and feathering motions using piezoelectric fiber composites. A unique mechanism with different stiffness for up and down stroke and a new drive control using saturated sine wave are proposed. By using the mechanism and drive control, the performance about lift and thrust force has been improved remarkably.

REFERENCES

[1] R. Brett Williams and Daniel J. Inman, "An overview of composite actuators with piezoceramic fibers," Proc. of the 20th International Modal Analysis Conference, Los Angels, CA, February 2002

[2] H.A., Park, G., Inman, D. J. "An investigation into the performance of macro-fiber composites for sensing and structural vibration applications Sodano," Mechanical Systems and Signal Processing 18, pp. 683-697, 2004

[3] SMART MATERIAL Web page: http://www.smart-material.com/

[4] Wilkie, W., et al, "Piezoelectric Macro-Fiber Composite Actuator and Method for Making Same," U.S. Patent No.6,629,341, October 7, 2003

[5] High, J., Wilkie, W., "Method of Fabicating NASA-Standard Macro-Fiber Composite Actuators," NASA/TM-2003-212427, ARL TR 2833, June 2003

[6] Henry A.Sodano, Daniel J.Iman and Gyuhae Park "A review of power harvesting from vibration using piezoelectric materials", The Shock and Vibration Digest, Vol. 36, No. 3, pp. 197-205, 2004

[7] Eric Ruggiero, Gyuhae Park, Daniel J. Inman, John A. Main "Smart materials in inflatable structure applications," 43rd AIAA/ASME/ ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Denver, Colorado, April 2002

[8] Henry A.Sodano, Gyuhae Park , Donald J. Leo, Daniel J. Inman "Use of piezoelectric energy harvesting devices for charging batteries" Smart Structures and Materials 2003: Smart Sensor Technology and Measurement Systems, Daniele Inaudi, Eric Udd, Editors, pp.101-108, July 2003

[9] J. D. DeLAURIER, "An Ornithopter Wing Design," Canadian Aeronautics and Space Journal, pp.10-18, March 1994.

[10] T. Nick Pornsin-Sirirak, Yu-Chong Tai, Chih-Ming Ho, Matt Keennon, "Microbat: A Palm-Sized Electrically Powered Ornithopter," Proceedings of ISM2000 International Symposium on Smart Structures and Microsystems, Hong Kong, China, October, 2000.

[11] Cox A., Monopoli D., Cveticanin D., Goldfarb M.,Garcia E., "The Development of Elastodynamic Components for Piezoelectrically Actuated Flapping Micro-air Vehicles," Journal of Intelligent Material Systems and Structures, Vol. 13, pp. 611-615. , September, 2002

[12] Erik Steltz, Srinath Avadhanula, Ronald S. Fearing "High lift force with 275 Hz wing beat in MFI" Proceedings of 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2007), pp. 3987-3992

[13] R.J. Wood, "The first takeoff of a biologically-inspired at-scale robotic insect" IEEE Transactions on Robotics, Vol. 24, No. 2, pp. 341-347, April, 2008.

[14] Hiroto Tanaka, Kiyoshi Matsumoto and Isao Shimoyama, "Design and performance of micromolded plastic butterfly wings on butterfly ornithopter," Proceedings of 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS2008), pp. 3095-3100, September 22-26, 2008.

[15] J. Yan, R. J. Wood, S. Avadhanula, M. Sitti, R. S. Fearing, "Towards flapping wing control for a micromechanical flying insect," Proceedings of IEEE International Conference on Robotics and Automation (ICRA2001), Vol.4, pp. 3901-3908, 2004.

[16] Anthony Colozza, Curtis Smith, Dr. Mohsen Shahinpoor, Dr. Kakkattukuzhy Isaac, Phillip Jenkins, Teryn DalBello, "Solid state aircraft concept overview," Proceedings of NASA/DoD Conference, pp. 318 – 324, July 2004.

[17] Ansari et al, "Aerodynamic modelling of insect-like flapping flight formicro air vehicles", PROGRESS IN AEROSPACE SCIENCES, 42(2) 129-172, 2006

[18] Aiguo Ming, Yawen Huang, Yuichi Fukushima and Makoto Shimojo: Development of an Active Flapping Wing using Piezoelectric Fiber Composites, Proceedings of the 2008 IEEE International Conference on Robotics and Biomimetics, Bangkok, Thailand, pp.2144-2149 (2009.2)