International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:9, No:7, 2015

Performance of Piezoelectric Cooling Fan with Rectangular Blade

Thomas Jin-Chee Liu, Yu-Shen Chen

***Abstract*—**Using the numerical and experimental methods, this paper discusses some primary studies on the vibration and cooling performances of the piezoelectric cooling fan with the rectangular blade. When the fan works at its natural frequency, the vibrating displacement is largest and the cooling performance is best. Due to the vibration behavior, the cooling performance is affected by the geometry, material property, and working frequency of the piezoelectric cooling fan.

***Keywords*—**Piezoelectric cooling fan, finite element, vibration, natural frequency.

I. Introduction

FOR modern technology, piezoelectric materials and actuators are widely used in various products or equipment. As shown in Fig. 1, the piezoelectric cooling fan is one of the equipment for the electronic cooling. The piezoelectric actuator can drive the blade to flap and produce an air flow.

The cooling design idea such as Fig. 1 was first proposed by Toda and Osaka [1]. With the flapping motion, the blade can produce the air flow to reduce the temperature of hot electronic devices. In the past studies [1]-[5], the experimental, analytical and numerical methods of solid and fluid mechanics are adopted in those researches. Many studies concluded that the piezoelectric cooling fan consumes low power and has good cooling performance for the electronic devices. For smaller electronic products, the space may not allow to set a rotary cooling fan. To solve this problem, the small-sized piezoelectric cooling fan is a good solution.

The purpose of this paper is to discuss the vibration and cooling performances of the piezoelectric cooling fan. The numerical and experimental methods are adopted in this study. The finite element analysis is employed for predicting the natural frequency of the fan. The experimental equipment is used to measure the natural frequency, amplitude and temperature difference. A primary design guide for the piezoelectric cooling fan is proposed in this paper.

Thomas Jin-Chee Liu, Associate Professor, is with the Department of Mechanical Engineering, Ming Chi University of Technology, Taishan, New Taipei City, Taiwan. (corresponding author to provide phone: 886-2-29089899 ext 4569; e-mail: jinchee@mail.mcut.edu.tw)

Yu-Shen Chen was a graduate student in the Graduate Institute of Electro-Mechanical Engineering, Ming Chi University of Technology. Taishan, New Taipei City, Taiwan.

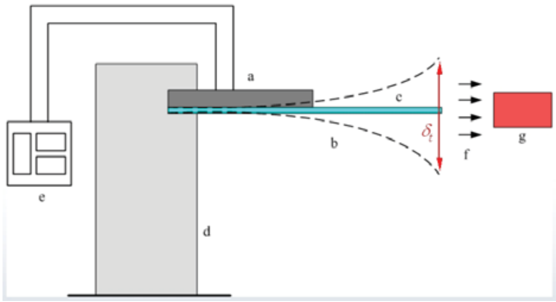


Fig. 1 Piezoelectric cooling fan (a: piezoelectric actuator; b: piezoelectric cooling fan; c: blade; d: fixture; e: electric power; f: air flow; g: hot electronic device; δ_t: total tip displacement)

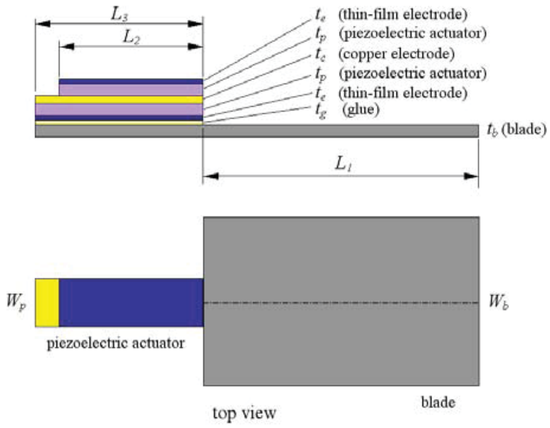


Fig. 2 Geometry property of piezoelectric cooling fan

II. Problem Statements

In Fig. 2, it shows the parameters L_1, L_2, L_3, W_b, and W_p of the piezoelectric cooling fan. The blade shape is a rectangle. The thicknesses t_e, t_p, t_c, t_g, and t_b belong to the thin-film electrode, piezoelectric actuator, copper electrode, glue, and blade, respectively. As shown in Fig. 2, the actuator with two bonded piezoelectric materials is named as the bimorph actuator. The piezoelectric material is actuated by the electric field between two electrodes. When the voltage (electric potential) difference is applied on both electrodes, the piezoelectric actuator deforms or bends due to the electric field.

To perform the vibrating motion and air flow, the piezoelectric cooling fan must be fixed and subjected to the electric power with the alternative current (AC). Fig. 3 shows the boundary conditions of the piezoelectric cooling fan. The copper electrode is grounded (V_2 = 0 V), and two thin-film electrodes are subjected to the AC voltage $V_1 = V_{amp}\sin(2\pi ft)$ V. In above equation, the parameters f and t are the AC frequency and time, respectively.

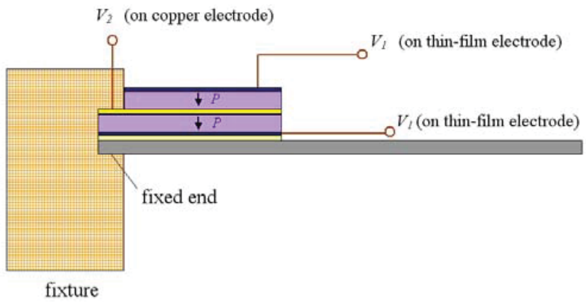


Fig. 3 Boundary conditions of piezoelectric cooling fan

The electro-mechanical coupling behavior of the transversely isotropic piezoelectric material is ruled by the constitutive equation under the Cartesian coordinate x_1-x_2-x_3 [6]:

$$\begin{Bmatrix} T_{11} \\ T_{22} \\ T_{33} \\ T_{23} \\ T_{13} \\ T_{12} \\ D_1 \\ D_2 \\ D_3 \end{Bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 & 0 & 0 & e_{31} \\ & c_{11} & c_{13} & 0 & 0 & 0 & 0 & 0 & e_{31} \\ & & c_{33} & 0 & 0 & 0 & 0 & 0 & e_{33} \\ & & & c_{44} & 0 & 0 & 0 & e_{15} & 0 \\ & & & & c_{44} & 0 & e_{15} & 0 & 0 \\ & & & & & c_{66} & 0 & 0 & 0 \\ & & sym. & & & & -\varepsilon_{11} & 0 & 0 \\ & & & & & & & -\varepsilon_{11} & 0 \\ & & & & & & & & -\varepsilon_{33} \end{bmatrix} \begin{Bmatrix} S_{11} \\ S_{22} \\ S_{33} \\ 2S_{23} \\ 2S_{13} \\ 2S_{12} \\ -E_1 \\ -E_2 \\ -E_3 \end{Bmatrix} \quad (1a)$$

$$c_{66} = \frac{1}{2}(c_{11} - c_{12}) \quad (1b)$$

where T, S, D, E, c, e and ε are the stress, strain, electric displacement, electric field, elastic constant, piezoelectric constant, and permittivity, respectively. In (1), the poling direction of the piezoelectric material is along the x_3-axis. In this study, the bimorph actuator is made of the piezoelectric ceramic PZT-5H. Fig. 3 shows the poling directions (P vectors) of both piezoelectric materials of the bimorph. Due to the relatively thin thickness, the thin-film electrode and glue can be ignored in the numerical analysis.

The piezoelectric cooling fan as shown in Fig 4 is used in this study. The constant dimensions are L_2=32 mm, L_3=36 mm, W_p=10 mm, t_c=0.1 mm, and t_p=0.3 mm. Two thicknesses t_e and t_g can be ignored in the analysis. The blade dimensions L_1, W_b and t_b are variable parameters for the cooling design. Two materials, PET and PC plastics, are used to make the blade.

III. Numerical Method for Prediction of Natural Frequency

Using the finite element software ANSYS, the natural frequency of the piezoelectric cooling fan can be predicted. Fig. 5 shows the finite element model composed of SOLID226 and SOLID95 elements. The SOLID226 elements are used to simulate the piezoelectric effect. In Tables I and II, the material constants for the finite element analysis are listed. In ANSYS, the modal analysis is used to calculate the natural frequencies and mode shapes of the structure.

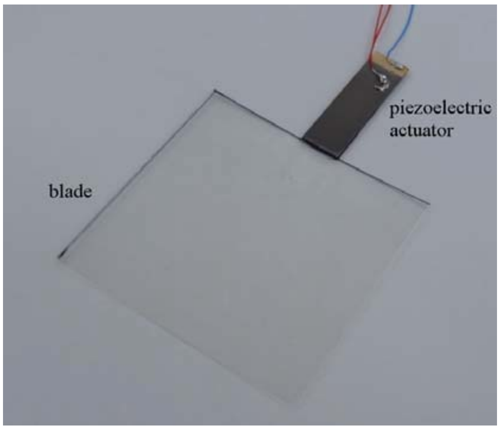


Fig. 4 Piezoelectric cooling fan with rectangular blade

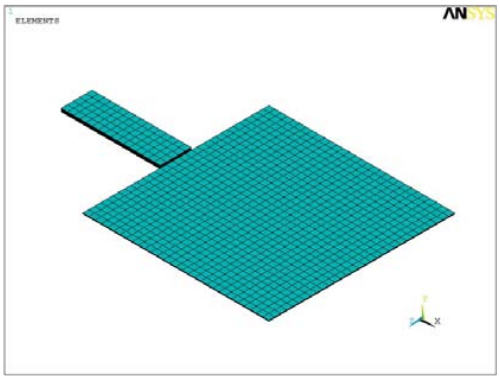


Fig. 5 Finite element model

TABLE I
MATERIAL PROPERTIES OF PZT-5H [6]

Material: PZT-5H		
Stiffness constants ($\times 10^{10}$ N/m^2)	c_{11}	12.6
	c_{12}	7.91
	c_{13}	8.39
	c_{33}	11.7
	c_{44}	2.3
	c_{66}	2.35
Piezoelectric constants (C/m^2)	e_{31}	-6.5
	e_{33}	23.3
	e_{15}	17
Permittivity ($\times 10^{-8}$ C/ Vm)	ε_{11}	1.505
	ε_{33}	1.302
Density (kg/m^3)	ρ	7500

TABLE II
MATERIAL PROPERTIES OF ISOTROPIC MATERIALS

Material	Young's modulus E (GPa)	Poisson's ratio ν	Density ρ (kg/m^3)
Copper	110	0.33	8800
PC plastics	2.803	0.32	1205
PET plastics	5.384	0.242	1420

IV. Experimental Method for Vibration and Cooling Performance

Fig. 6 shows the experimental equipment for measuring the cooling performance. The piezoelectric cooling fan is actuated by the AC voltage (i.e., $V_1=V_{amp}\sin(2\pi ft)$) made from the electric signal source and amplifier. The input of the voltage V_1 is applied on the piezoelectric actuator. The heater and heatsink are cooled by the piezoelectric fan. The temperature at the measuring point is measured by the thermo-couple and thermo-meter.

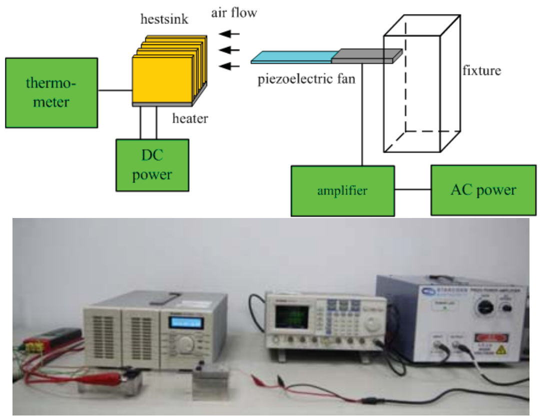


Fig. 6 Experimental equipment for cooling performance

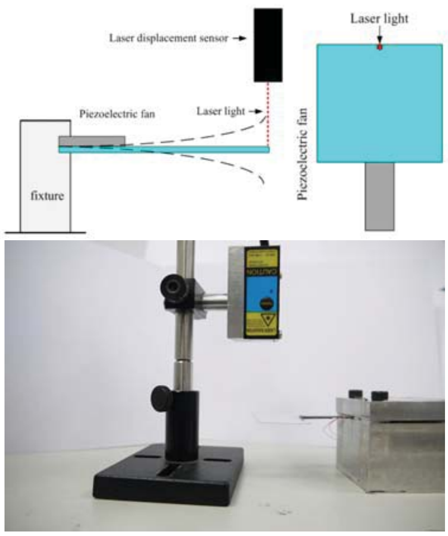
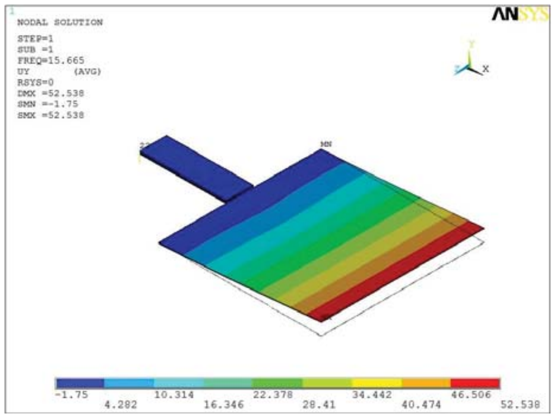
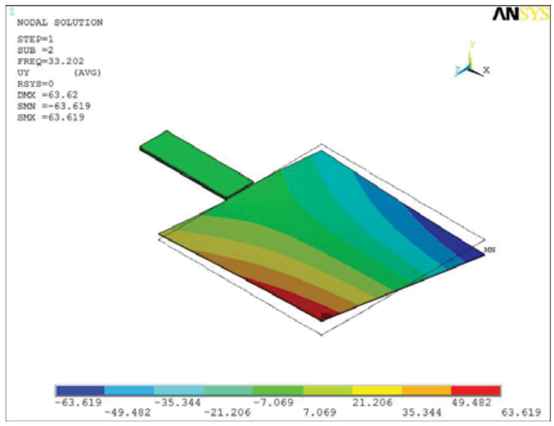


Fig. 7 Experimental equipment for vibration



(a)



(b)

Fig. 8 Mode shapes of piezoelectric fan obtained from numerical analysis. (a) First mode, (b) Second mode. (L_1=60 mm, W_b=60 mm, t_b=0.25 mm; PET)

The total tip displacement δ_t of the vibrating blade is measured by the laser displacement sensor as shown in Fig. 7. According to the magnitude of δ_t with different exciting frequency, the natural frequency can be determined. Also, the vibrating mode shape can be confirmed.

V. Results of Vibration Performance

From the numerical analysis, Fig. 8 shows the first and second mode shapes of the piezoelectric cooling fan. The first mode shape is used for the electronic cooling due to its better performance. In Fig. 9, the experimental result shows the flapping behavior of the blade under the first-mode vibration.

In Fig. 10, the blade's total tip displacements (δ_t) with various exciting frequencies are obtained from the experiment under the first-mode vibration. The input voltage is V_{amp}=100 V. The frequency associated with the peak displacement value is defined as the natural frequency. When the fan works at its natural frequency, the air flow is the maximum and the cooling performance is best.

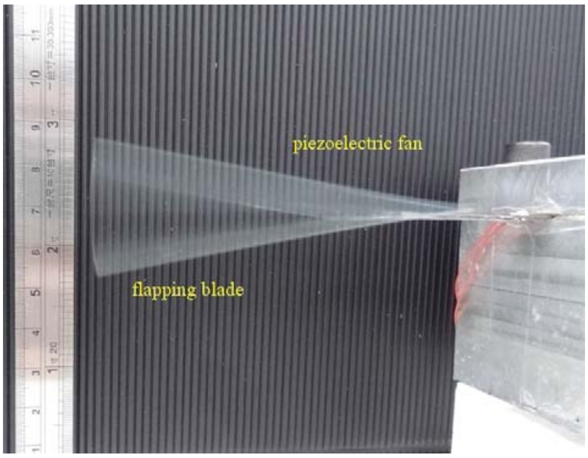


Fig. 9 Flapping behavior of blade

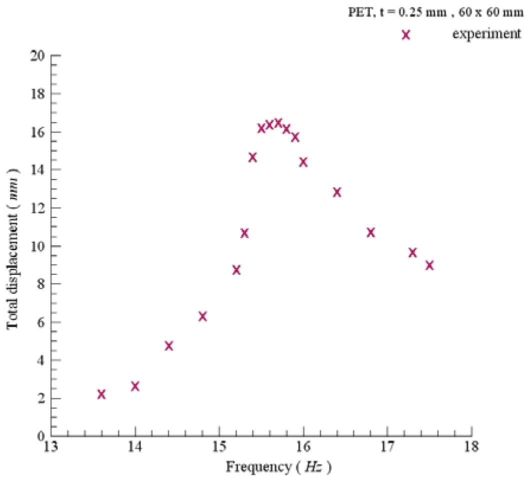


Fig. 10 Total displacement δ_t obtained from experiments (first mode; L_1=60 mm, W_b=60 mm, t_b=0.25 mm; PET; V_{amp}=100 V)

TABLE III
NATURAL FREQUENCIES OF PIEZOELECTRIC FAN WITH PET BLADE (T_B = 0.25 MM)

Blade dimension $L_1 \times W_b$ (mm)	Natural frequency		Error (%)
	ANSYS value (Hz)	Experimental value (Hz)	
60 × 60	15.665	15.7	0.22
60 × 50	16.839	16.7	0.83
60 × 40	18.167	18.1	0.37
60 × 30	19.659	19.6	0.30
60 × 20	21.092	21.1	0.04
60 × 10	21.841	22.0	0.72
50 × 60	21.538	21.5	0.18
40 × 60	31.486	27.5	14.49

In Tables III and IV, the numerical and experimental results are compared. It shows good agreements between both results. Also, it can be seen that the natural frequency is affected by the geometry and material type.

The finite element model can be used to predict the natural frequency of the piezoelectric cooling fan. It can help people to choose the geometry and material type.

TABLE IV
NATURAL FREQUENCIES OF PIEZOELECTRIC FAN WITH PC BLADE (T_B = 0.25 MM)

Blade dimension $L_1 \times W_b$ (mm)	Natural frequency		Error (%)
	ANSYS value (Hz)	Experimental value (Hz)	
60 × 60	11.572	11.2	3.32
60 × 50	12.425	12.2	1.84
60 × 40	13.385	13.1	2.18
60 × 30	14.454	14.3	1.08
60 × 20	15.453	15.4	0.34
60 × 10	15.905	15.9	0.03
50 × 60	15.982	14.9	7.26
40 × 60	23.528	21.5	9.43

VI. RESULTS OF COOLING PERFORMANCE

In this section, all results are obtained from the experiment as shown in Fig. 6. The cooling performance is discussed when the blade geometry is changed.

First, the specified dimensions are used as an example: L_1=60 mm, W_b=60 mm and t_b=0.25 mm. The material used for of the blade is the PET plastics. Fig. 11 shows the temperature history data at the measuring point. At 600 s, the piezoelectric fan is turned on and the air flow is produced. At 2000 s, the temperature drop ΔT of the heater is about 16°C. The piezoelectric fan proves its cooling capability for the hot device.

Using the same experimental procedure, the values of ΔT of other piezoelectric fans are obtained. Figs. 12 and 13 show the effects of W_b, L_1, t_b and material type on the temperature drop. The wider, shorter and thicker blades have larger ΔT and better cooling performance. According to Table II, the Young's modulus of PET is larger than that of PC. Comparing ΔT of PET and PC with the same geometry, larger Young's modulus makes better cooling performance.

The wider blade makes larger air flow. Shorter, thicker and stiffer blades have higher natural frequency. The above reasons dominate the cooling performance.

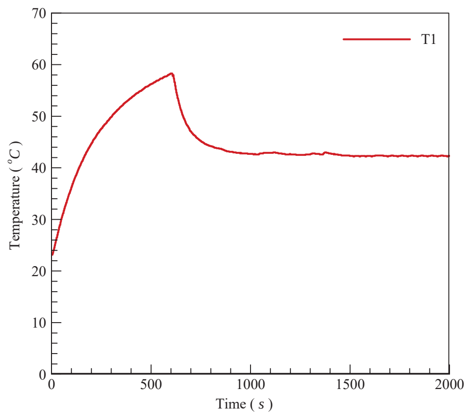


Fig. 11 Temperature versus time

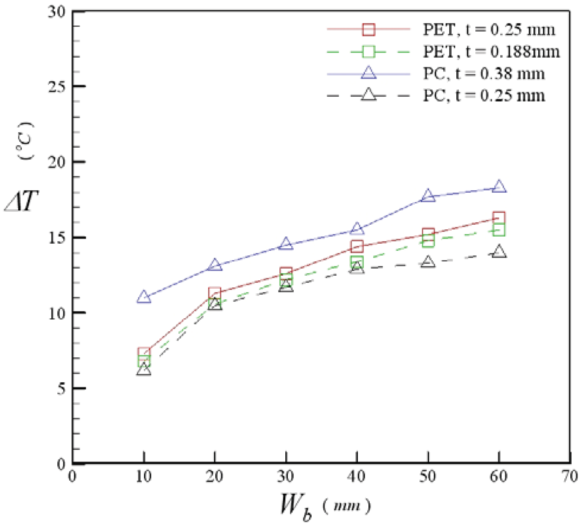


Fig. 12 ΔT versus W_b. ($L_1 = 60$ mm)

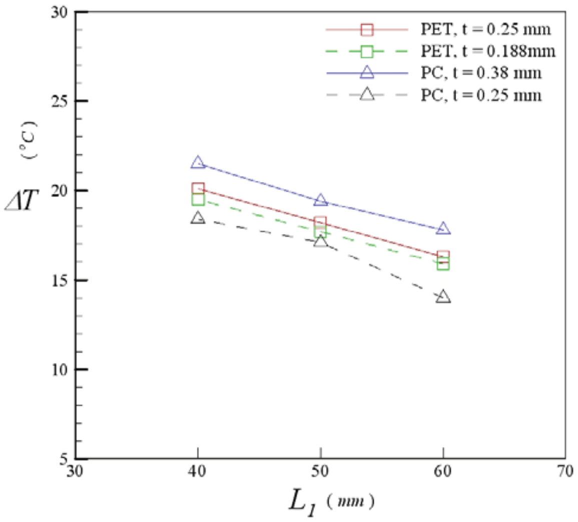


Fig. 13 ΔT versus L_1. ($W_b = 60$ mm)

VII. Conclusions

When the piezoelectric cooling fan works at its natural frequency, the vibrating displacement is largest and the cooling performance is best. Due to the vibration behavior, the cooling performance is affected by the geometry, material property, and working frequency of the piezoelectric cooling fan.

Acknowledgments

The authors are grateful to the Ming Chi University of Technology for the financial support under contract number “100-Start-Academic-Research-E-01”. The authors are also grateful to the Ministry of Economic Affairs of R.O.C. Government in Taiwan for the financial support under contract number 103-EC-17-A-31-S1-207.

References

[1] M. Toda and S. Osaka, “Vibrational fan using the piezoelectric polymer PVF2,” *Proceedings of the IEEE*, vol. 67, pp. 1171–1173, 1979.

[2] J.H. Yoo, J.I. Hong and W. Cao, “Piezoelectric ceramic bimorph coupled to thin metal plate as cooling fan for electronic devices,” *Sensors and Actuators*, vol. 79, pp. 8–12, 2000.

[3] T. Acikalin, S.V. Garimella, A. Raman and J. Petroski, “Characterization and optimization of the thermal performance of miniature piezoelectric fans,” *International Journal of Heat and Fluid Flow*, vol. 28, pp. 806–820, 2007.

[4] M. Kimber and S.V. Garimella, “Measurement and prediction of the cooling characteristics of a generalized vibrating piezoelectric fan,” *International Journal of Heat and Mass Transfer*, vol. 52, pp. 4470–4478, 2009.

[5] W.J. Sheu, R.T. Huang and C.C. Wang, “Influence of bonding glues on the vibration of piezoelectric fans,” *Sensors and Actuators A: Physical*, vol. 148, pp. 115–121, 2008.

[6] J. Yang, *The Mechanics of Piezoelectric Structures.* New Jersey: World Scientific Publishing, 2006.