Vibration and cooling performances of piezoelectric cooling fan: numerical and experimental investigations

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Abstract. In this paper, the vibration and cooling performances of the piezoelectric cooling fan are studied. The finite element and experimental methods are adopted for the analyses. The natural frequency, mode shape, flapping amplitude, and cooling performance are discussed for the primary design. The numerical results have good agreement with the experimental measurements. For the cooling purpose, the piezoelectric cooling fan has to work under the natural frequency. The aspect ratio 2:3 is the optimal geometry of the fan blade.

1 Introduction

As shown in Fig. 1, the piezoelectric cooling fan uses the flapping blade to make the air flow for the electronic cooling. It is quite different from the traditional rotating cooling fan. Using the piezoelectric actuator, the piezoelectric effect makes the cyclic deformation so that the blade can vibrate and flap. Under the natural frequency, the piezoelectric cooling fan can perform the maximum flapping displacement and air flow.

In the past references [1-6], it is concluded that the piezoelectric cooling fan consumes lower electric power. Also, it has good cooling performance for the small-size electronic devices. Undoubtedly, the piezoelectric cooling fan is a good cooling solution for many electronic products.

Fig. 1. Working condition of piezoelectric cooling fan.

Recently, detail researches have been finished by using the fluid mechanics and flow analysis [7-9]. In Ref. [7], at peak skewness, the vortex behind the phase leading blade is 101% larger than its counterpart. Evenly matched vortices between the two blades are optimal for generating peak mass transfer [7]. In Ref. [9], it was found that the propagation of the side vortex is a key factor in determination of the flow pattern. Based on the numerical results, it was found that whether the side vortex propagates or not is an important factor in

determining three-dimensional flow pattern around the piezoelectric fan [9].

In this paper, the vibration and cooling performances of the piezoelectric cooling fan will be studied. The numerical and experimental methods are adopted for the analyses. The natural frequency, mode shape, flapping amplitude, and cooling performance will be discussed for the primary design. Based on the vibration mechanics and temperature reduction, the present study will find the optimal geometry of the fan blade and associated conditions.

Fig. 2. Geometry of piezoelectric cooling fan.

Fig. 3. Photo of piezoelectric cooling fans.

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2 Definition of research

The geometry and photo of the piezoelectric cooling fan are shown in Fig. 2 and 3. It contains two main parts: the blade and piezoelectric actuator. The dimensions of the rectangular blade (W_b , L_b , t_b) are variables and will be studied for the vibration and cooling performances.

In Fig. 4, the detail geometry of the bimorph piezoelectric actuator is illustrated. All dimensions are constant values. The piezoelectric material type is PZT-5H, i.e. a kind of the piezoelectric ceramic. The P -arrows define the poling directions. Three electrodes are attached to the piezoelectric material. Due to relatively thin value, the thickness of the thin-film electrode is ignored in the numerical analysis.

Fig. 4. Geometry of piezoelectric actuator.

As shown in Fig. 4, the piezoelectric material is actuated by the electric field between two electrodes. When the voltage difference ($V_2 - V_1$) is applied on both electrodes, the piezoelectric actuator deforms and bends due to the electric field and poling direction. For making the cyclic deformation, the alternative current (AC) is applied on two thin-film electrodes as $V_1 = V_{amp} \sin(2\pi ft)$ V. In addition, the copper electrode is grounded ($V_2 = 0$ V). In above equation, the parameters f and t are the AC frequency and time, respectively. The AC amplitude is $V_{amp} = 100$ V.

The electro-mechanical piezoelectric behavior is ruled by the constitutive equation under the Cartesian coordinate x_1 - x_2 - x_3 as follows [10]:

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

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

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 Eq. (1), the poling direction of the piezoelectric material is along the x_3 -axis.

The piezoelectric material is PZT-5H. Two materials, PET and PC plastics, are used to make the blade. Table 1 and 2 list all material data for the numerical simulations.

Table 1. Material data of PZT-5H [10].

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 2. Material data 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

Fig. 5. Finite element model of piezoelectric cooling fan.

3 Methods of analyses

3.1 Numerical method

In this study, the numerical method is the finite element method. Also, the software ANSYS is employed. In Fig. 5, it shows a typical finite element model of the piezoelectric cooling fan. The model composes of SOLID226 and SOLID95 elements. The SOLID226 elements have the coupled-field analysis so that the

piezoelectric effect can be simulated. In ANSYS, the modal analysis is used to calculate the natural frequencies and mode shapes of the vibration behaviors.

3.2 Experimental method

In Figs. 6-8, the experimental equipments for the flapping amplitude and cooling performance of the piezoelectric cooling fan are shown. The AC power drives the piezoelectric cooling fan so that the air flow can be produced for the cooling process. The laser displacement sensor and thermo-meter are used to obtain the data of the flapping amplitude (δ_f) and cooling performance (temperature reduction of the heatsink). The distance between the blade and heatsink is 10 mm.

Fig. 6. Experimental equipments for flapping amplitude.

Fig. 7. Experimental equipments for cooling performance.

Fig. 8. Photo of experimental equipments.

4 Results and discussions

4.1 Vibration behaviours

In this section, the dimensions of the PET blade are $W_b=10$ mm, $L_b=60$ mm, and $t_b=0.25$ mm. The natural

frequency is determined according to numerical modal analysis and experimental maximum flapping amplitude. In Fig. 9 and 10, the finite element and experimental results show the mode shapes and natural frequencies of the piezoelectric cooling fan. Both numerical and experimental values are almost the same. It confirms the good accuracy of the research methods. Also, the finite element method can predict the vibration behaviour of the piezoelectric cooling fan before the real cooling system is established.

The maximum flapping amplitude occurs under the natural frequency, i.e. the resonance condition. The larger flapping amplitude makes larger air flow and better cooling performance.

Fig.9. Numerical mode shapes. (a) first-mode natural frequency = 21.853 Hz, (b) second-mode natural frequency= 135.094 Hz.

Fig. 10. Experimental mode shapes. (a) first-mode natural frequency= 21.9 Hz (b) second-mode natural frequency= 134.8 Hz. ($V_{amp}=100$ V)

Fig. 11. Variation of δ_f with different geometric properties.

4.2 Flapping amplitude

According to Fig. 10, the flapping amplitude of the first-mode vibration is larger than that of the second-mode. In this study, the first-mode flapping amplitude δ_i (as shown in Fig. 6 and 10a) is adopted for the electronic cooling. Also, the amplitude δ_i is obtained under the first-mode natural frequency and $V_{amp}=100$ V.

The variations of δ_i with different geometric properties are shown in Fig. 11 and 12. The wider, shorter and thicker blades have smaller δ_i . The larger flapping amplitude makes larger air flow and better cooling performance. The amplitude δ_i is an important value for the piezoelectric cooling fan design.

Fig. 12. Variation of δ_i with different geometric properties.

Fig. 13. Typical temperature history.

4.3 Cooling performance

In Fig. 7 and 8, it shows the experimental configuration for the cooling performance. To prevent from environmental disturbance, the transparent structure covers the heat source and piezoelectric cooling fan. The temperature at the heatsink bottom is measured by the thermo-meter. Figure 13 shows the typical temperature history. During $t=0\sim600$ s, the DC power and heater

provide the thermal energy and temperature rise from T_i to T_{max} . At $t=600$ s, the piezoelectric cooling fan begins to work under the first-mode natural frequency. The steady-state temperature T_{ss} is obtained at $t=2000$ s. The temperature reduction ΔT of the heatsink is defined as $T_{max}-T_{ss}$. The larger value of ΔT expresses the better cooling performance.

In Table 3~6, the ΔT values of different blades are listed. Four cases: 46.8×70 mm, 40×60 mm, 33.4×50 mm, and 27×40 mm have largest ΔT values, i.e. best cooling performance. These optimal cases have the same geometric property: $L_b/W_b \approx 2/3$.

Table 3. Cooling performances.

PET, $t_b = 0.25$ mm							
$L_b \times W_b$ (mm)	ΔT (°C)	$L_b \times W_b$ (mm)	ΔT (°C)	$L_b \times W_b$ (mm)	ΔT (°C)	$L_b \times W_b$ (mm)	ΔT (°C)
70 × 70	14.1	60 × 60	16.3	50 × 50	17.4	40 × 40	19.4
70 × 58	13.6	60 × 50	15.2	50 × 42	15.8	40 × 34	18.4
70 × 46	12.8	60 × 40	14.4	50 × 34	14.6	40 × 28	17.8
70 × 34	12.4	60 × 30	12.6	50 × 26	13.4	40 × 22	16.7
70 × 22	9.7	60 × 20	11.3	50 × 18	12.9	40 × 16	15.9
70 × 10	6.8	60 × 10	9.1	50 × 10	10.1	40 × 10	14.8
70 × 70	14.1	60 × 60	16.3	50 × 50	17.4	40 × 40	19.4
58.4 × 70	15.5	50 × 60	18.2	41.7 × 50	18.3	33.5 × 40	20.2
52.5 × 70	16.6	45 × 60	18.5	37.5 × 50	20.2	30 × 40	22.3
46.8 × 70	18.4	40 × 60	20.1	33.4 × 50	21.6	27 × 40	23.6
40.8 × 70	17.5	35 × 60	19.7	29.2 × 50	20.3	23.3 × 40	21.1
35 × 70	16.1	30 × 60	18	25 × 50	18.7	20 × 40	19.2

Table 4. Cooling performances.

PET, $t_b = 0.188$ mm							
$L_b \times W_b$ (mm)	ΔT (°C)	$L_b \times W_b$ (mm)	ΔT (°C)	$L_b \times W_b$ (mm)	ΔT (°C)	$L_b \times W_b$ (mm)	ΔT (°C)
70 × 70	9.6	60 × 60	12.1	50 × 50	14.7	40 × 40	17.1
70 × 58	8.8	60 × 50	11.6	50 × 42	13.2	40 × 34	16.6
70 × 46	8.2	60 × 40	11.1	50 × 34	12.8	40 × 28	15.7
70 × 34	7.3	60 × 30	10.5	50 × 26	12.2	40 × 22	13.6
70 × 22	6.6	60 × 20	9.3	50 × 18	11.4	40 × 16	12.3
70 × 10	5.3	60 × 10	8.8	50 × 10	9.8	40 × 10	11.8
70 × 70	9.6	60 × 60	12.1	50 × 50	14.7	40 × 40	17.1
58.4 × 70	12	50 × 60	13.9	41.7 × 50	16.2	33.5 × 40	18
52.5 × 70	13.9	45 × 60	15.8	37.5 × 50	17.9	30 × 40	19.2
46.8 × 70	16.4	40 × 60	17.8	33.4 × 50	18.8	27 × 40	21.4
40.8 × 70	15.5	35 × 60	16.6	29.2 × 50	18.1	23.3 × 40	20.2
35 × 70	14.7	30 × 60	16.1	25 × 50	17.4	20 × 40	18.3

Table 5. Cooling performances.

PC, $t_b = 0.25$ mm							
$L_b \times W_b$ (mm)	ΔT (°C)	$L_b \times W_b$ (mm)	ΔT (°C)	$L_b \times W_b$ (mm)	ΔT (°C)	$L_b \times W_b$ (mm)	ΔT (°C)
70 × 70	10.8	60 × 60	11.9	50 × 50	14.7	40 × 40	18.1
70 × 58	10.1	60 × 50	11.1	50 × 42	12.8	40 × 34	16.8
70 × 46	9.6	60 × 40	10.7	50 × 34	11.9	40 × 28	16.1
70 × 34	8.8	60 × 30	9.8	50 × 26	11.1	40 × 22	15.3
70 × 22	7.3	60 × 20	8.3	50 × 18	10.2	40 × 16	13.1
70 × 10	5.6	60 × 10	6.2	50 × 10	8.6	40 × 10	11.9
70 × 70	10.8	60 × 60	11.9	50 × 50	14.7	40 × 40	18.1
58.4 × 70	11.9	50 × 60	14.6	41.7 × 50	18	33.5 × 40	18.9
52.5 × 70	14.8	45 × 60	17.9	37.5 × 50	18.7	30 × 40	20.5
46.8 × 70	18.4	40 × 60	19.4	33.4 × 50	19.9	27 × 40	22
40.8 × 70	16	35 × 60	18.1	29.2 × 50	19.2	23.3 × 40	20.1
35 × 70	15.4	30 × 60	17.3	25 × 50	16.4	20 × 40	17.9

Table 6. Cooling performances.

PC, $t_b = 0.38$ mm							
$L_b \times W_b$ (mm)	ΔT (°C)	$L_b \times W_b$ (mm)	ΔT (°C)	$L_b \times W_b$ (mm)	ΔT (°C)	$L_b \times W_b$ (mm)	ΔT (°C)

70 × 70	14.9	60 × 60	17	50 × 50	18.1	40 × 40	19.6
70 × 58	13.8	60 × 50	16.4	50 × 42	16.8	40 × 34	18.6
70 × 46	13.2	60 × 40	15.5	50 × 34	15.6	40 × 28	17.9
70 × 34	12.4	60 × 30	14.3	50 × 26	14.7	40 × 22	16.9
70 × 22	10.9	60 × 20	13.1	50 × 18	13.3	40 × 16	16.1
70 × 10	9.2	60 × 10	11	50 × 10	11.9	40 × 10	15.3
70 × 70	14.9	60 × 60	17	50 × 50	18.1	40 × 40	19.6
58.4 × 70	17	50 × 60	18.6	41.7 × 50	21.6	33.5 × 40	20.8
52.5 × 70	19.3	45 × 60	19.7	37.5 × 50	22.9	30 × 40	23.2
46.8 × 70	20.4	40 × 60	20.9	33.4 × 50	24.8	27 × 40	25.6
40.8 × 70	19.4	35 × 60	20.1	29.2 × 50	22.6	23.3 × 40	23.5
35 × 70	16.7	30 × 60	18.9	25 × 50	21.2	20 × 40	20.1

Fig. 14. Variation of ΔT with different geometric properties.

In Fig. 14, four curves of ΔT variations are plotted according to the data in Table 4. When $L_b/W_b \approx 2/3$, it shows the largest ΔT value in each curve. The wider blade makes larger air flow. Shorter, thicker and stiffer blades have higher natural frequency. The above reasons dominate the cooling performance.

5 Conclusions

The vibration and cooling performances of the piezoelectric cooling fan have been studied in this paper. The natural frequency, mode shape, flapping amplitude,

and temperature reduction have been obtained. The numerical results have good agreement with the experimental measurements. As a result, the piezoelectric cooling fan has to work under the natural frequency. The aspect ratio $2:3$ ($L_b/W_b \approx 2/3$) is the optimal geometry of the fan blade for the cooling purpose.

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.

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