

Numerical Investigation on the Flow Field Produced by Oscillating Foils

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Abstract. In present manuscript, the flow field produced by oscillating foils in a duct were under investigation numerically. The flow field was considered as an incompressible laminar transient flow. In this paper, the oscillating frequencies were 2, 4 and 6 Hz; the span angles of the foil were 30°, 60°, 90°, 120°, and 150°, respectively. The flow field produced by a particular oscillating pattern (fast forward slow backward, FFSB) has been made in comparison with that by the sinusoidal oscillating pattern. The flow field produced by dual oscillating foils was also analysed. Two foils oscillated in the same direction (in-phase) and in the opposite direction (counter-phase) were studied as well. Commercial software ANSYS-FLUENT was employed for the 2D numerical simulation. A moving grid technique was utilized in the analysis. Results present the flow average velocity increases as the oscillating frequency increases. It is also shown that the flow average velocity with span angle of 120° is the largest among these cases. In addition, the flow average velocity with dual foils is better than that with a single foil.

1 Introduction

The progress of semiconductor industry has reduced the scale of electronic devices and increases the heat flux of heat sources. The heat dissipation rate from electronic devices requires new designs of miniaturized cooling components. Due to limitations of space in electronic devices, forced convective cooling with fans was not available. However, electronic cooling with combined conduction and free convection was hardly sufficient for electronic devices. One of the potential issues is the convective heat transfer with miniature oscillating foils. Therefore, research on the oscillation of small plate become one of the important issues for compact electronic cooling.

In cases where rotary fans are ineffective for dissipating heat, the piezoelectric fan provides a potential and reliable alternative approach to heat transfer. Piezoelectric fans can be fabricated in small sizes to fit applications that require miniature cooling modules. Toda [1, 2] first proposed the concept of piezoelectric fans for a cooling system with small size and low power consumption. He employed piezoelectric material as driven element with driving voltage of 110V and the frequency of 13Hz. As the plate was oscillating in the resonance frequency, its amplitude would increase and the surrounding air was driven greatly. The oscillating plate could be miniaturized and therefore considered as the cooling of small electronic devices with considerable potential.

Yoo et al [3] studied the resonant frequencies for various foil designs. The resonant frequency was found to be inversely proportional to square of foil length. The maximum flow velocity close to the tip of foil can reach 3.0 m/sec at appropriate resonant frequency. Wait et al [4] measured the amplitudes of piezoelectric fan for higher resonance modes. The energy consumption and flow field were assessed for various foil lengths and resonant frequencies. Acikailn et al. [5] observed the flow field around fan tip and investigated the heat transfer coefficient on heat source. Liu et al [6] tested the thermal performance of fans with various fan geometries and horizontal/vertical arrangements. Kimber and Garimella [7] measured various piezoelectric fans mounted perpendicular to a constant heat flux surface and studied the thermal performance across specific range of fan dimensions, vibration frequency, and amplitude. The experimental results show that vibration frequency has more significant effect on the heat transfer rate than vibration amplitude. Li et al [8] studied the effects of configuration, foil location, and heat sink design.

Fan array was a further development on this issue. Multiple fans were utilized in driving air flow and cooling system. Kimber and Garimella [9] built dual fan array to study the cooling performance on vertical surface. Ma et al. [10] designed multiple vibrating-fan cooling system actuated by combining piezoelectric force and magnetic force.

From the literatures cited above, it is found that most of the studies are investigated through experiment. Numerical analysis on the flow field induced by oscillating foil has been rarely studied. The main purpose of this paper is to investigate the air flow induced by single and dual oscillating foils. The effects of oscillating frequency, and oscillating pattern, span angle of oscillation have been studied to estimate the average velocity of the air flow.

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2 Numerical analysis

2.1 Physical Model

The physical model of the present study is shown in Figure. 1. The channel length is 400 mm with width of 90 mm and depth of 5 mm. An oscillating foil is located 80 mm away from the inlet and at the centre of the channel, as shown in Figure. 1(a). The foil is rectangular and 40 mm in length with thickness of 1.5 mm and height of 4.5 mm. The span angle of foil is 2θ with oscillation symmetric to the centreline. The span angles of the foil are 30° , 60° , 90° , 120° , and 150° , respectively. In present study, dual foil oscillation is also under investigation. The second foil is located downstream to the first one. The distance between two foils is varied to study its influence on the flow. The distance between two foils are 44 mm, 50 mm, 60 mm, 70 mm, and 80 mm, respectively. The two foils are in the same dimension.

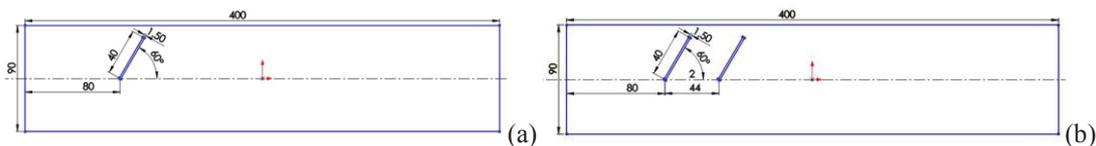


Figure 1. Two-dimensional physical model with (a) single foil; (b) dual foils.

2.2 Analysis

Because of the physical model, the depth of the channel is relatively small compared with its length and width, the air flow is considered as two-dimensional flow. Due to small amount of air drawn into the channel, the induced air flow is assumed to be incompressible laminar flow with constant properties in the present model. Actually, the foil would deform due to eccentric force by oscillation. However, the foil is considered rigid in order to simplify the problem.

The commercial software of ANSYS-Fluent was employed to analyse the physical 2D model. The dynamic mesh scheme was adopted in the area of foil sweeping, the meshes are defined as deformable meshes, such that they can be stretched or compressed while the foil is in motion. Therefore, the elements around oscillating foils would be stretched or compressed as shown in Figure. 2. As for the boundary conditions, oscillating foil and the wall were set as wall condition, the inlet was set as vent inlet, and the outlet was set as vent outlet. A transient flow with oscillating foils in motion for 10 s has been calculated. There are 20 steps for one complete cycle.

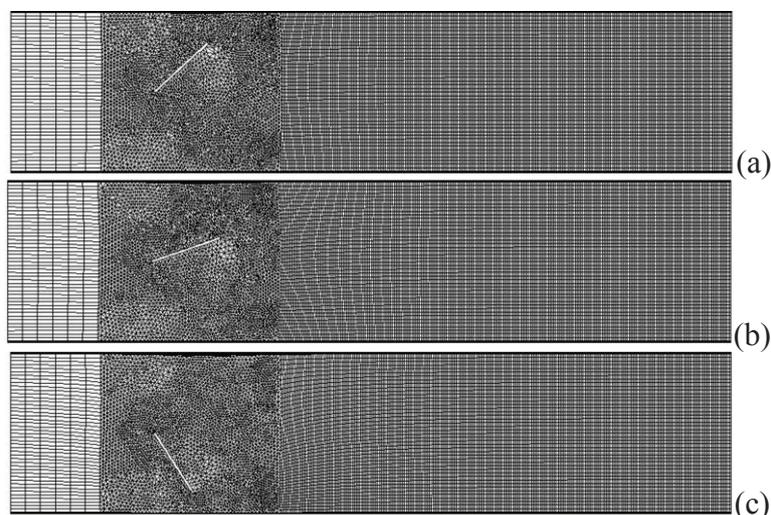


Figure 2. Sketch diagram of the dynamic meshes.

Most of the researches considered oscillating velocity symmetric to the central axis of the oscillation. However, the optimal oscillating velocity profile may not be in the sinusoidal form or a harmonic function. From the aspect of fluid dynamics, the rotating velocity should be higher as the foil is sweeping toward downstream. In other word, the rotation of foil from one end to the central line could be faster than that from the central line to the other end. In this paper, a fast forward slow backward (FFSB) oscillating pattern has been generated to investigate the effect of oscillating pattern on the induced air flow. In the FFSB pattern, as the foil rotates from one end to the central line, the angular velocity is higher; while the foil rotates from the central line to the other end, the angular velocity is lower. The oscillating pattern can be generated in the user defined function in ANSYS-Fluent. The oscillating patterns are presented in Figure. 3.

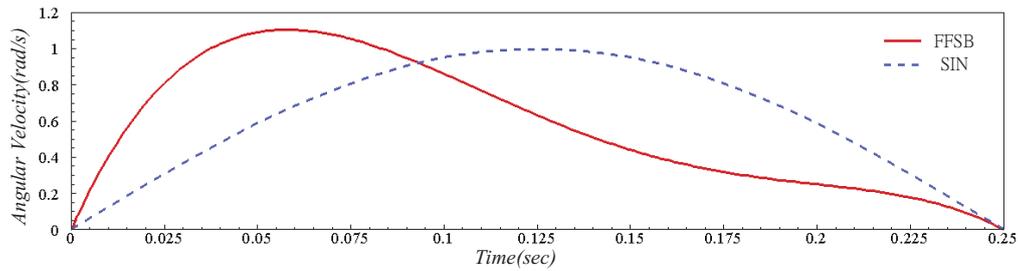


Figure 3. Oscillating pattern as a function of time for oscillating frequency of 2 Hz.

3 Results and Discussions

In present study, numerical simulation on the induced air flow by oscillating foils has been conducted. Effects of oscillating frequencies, span angles, oscillating patterns, and dual foils are considered. The oscillating frequencies are 2, 4, and 6 Hz; the span angles of the foil were 30°, 60°, 90°, 120°, and 150°, respectively. The flow field produced by dual oscillating foils was also analysed. Two foils oscillated in the same direction (in-phase) and in the opposite direction (counter-phase) were studied. The distance between two foils is varied to study its influence on the flow. The distance between two foils are 44 mm, 50 mm, 60 mm, 70 mm, and 80 mm, respectively.

3.1 streamline, velocity, and pressure distributions of flow field

Figure 4 shows the streamline diagram of the air flow with single oscillating foil at the frequency of 4 Hz and span angle of 120°. Figure 4(a) is the flow streamline as the foil is at the bottom; while Figure 4(c) is the flow streamline as the foil is at the centre. It is found that the air is drawn into the channel uniformly. In addition, vortices continuously occur towards channel outlet after the air flow passing through the oscillating foil. The corresponding velocity and pressure contours are presented in Figure. 5 and 6, respectively. It is seen that the high velocity occurs where stream lines are dense; while the pressure is low. It is also notice that vortices move downward regularly. However, some vortices are affected between the foil and the channel walls.

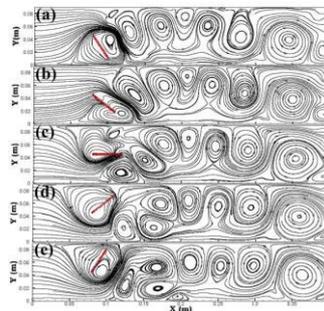


Figure4. Streamline diagram with single oscillating foil.

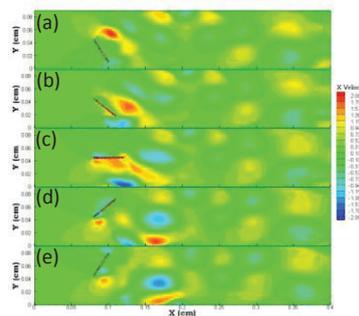


Figure 5. Velocity contour with single oscillating foil with oscillating frequency of 4Hz.

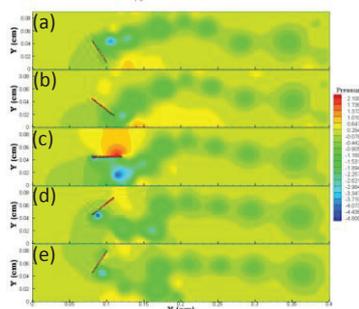


Figure 6. Pressure contour with single oscillating foil with oscillating frequency of 4Hz.

3.2 Effect of span angle

The air flow induced by the oscillating foil is affected by the span angle of the foil. In this study, the effect of span angle on the averaged velocity in the channel has been investigated. The span angles are 30°, 60°, 90°, 120°, and 150°, respectively. Figure 7 presents the effect of oscillating span angle on the average velocity in the channel for three oscillating frequencies. It is found that the flow average velocity increases as oscillating frequency increases at each span angle. It is also discovered that the optimum flow average velocity occurs at the span angle of 120°. It is observed from the numerical flow animation that the flow velocity is hindered by the channel wall, resulted in a lower flow average velocity in the channel.

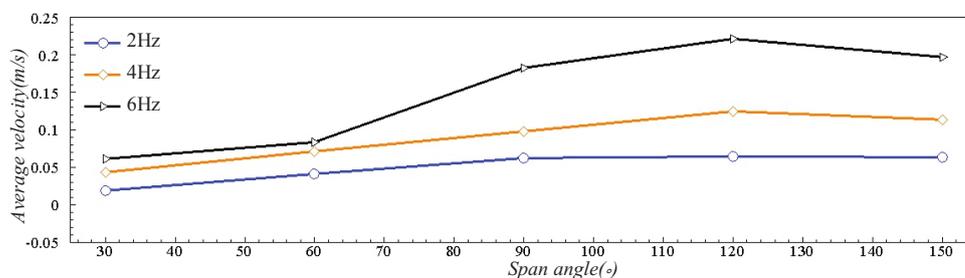


Figure 7. Effect of span angle on the flow average velocity in the channel for three oscillating frequencies.

3.3 Effect of oscillating pattern

Figure 8 depicts the effect of oscillating pattern on the flow average velocity in the channel for three oscillating frequencies. It is discovered that the flow average velocity with FFSB pattern is larger than that with sinusoidal pattern for three oscillating frequencies. This indicates that sinusoidal oscillating pattern is not an optimal oscillating pattern in producing air flow. This confirms the concept that a FFSB is a better oscillating pattern for producing air flow with oscillating foil.

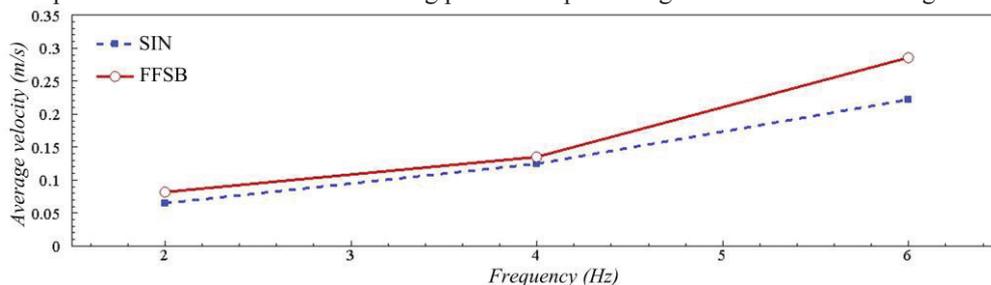


Figure 8. Effect of oscillating pattern on the flow average velocity in the channel for three oscillating frequencies.

3.4 Dual oscillating foils

In the present study, the air flow induced by dual foil oscillation was studied as well. In addition, two foils oscillated in the same direction (in-phase) and in the opposite direction (counter-phase) were studied. Figure 9 presents the effect of distance between two foils on the flow average velocity in the channel with three oscillating frequencies for both in-phase and counter-phase pattern. It is found that dual oscillating foils generate higher air flow than a single foil. In addition, it is obviously observed that the flow average velocity for counter-phase pattern is always larger than that for in-phase pattern. As for the effect of distance between two foils, it shows an optimum in the counter-phase pattern. However, the optimum condition does not appear in the in-phase pattern.

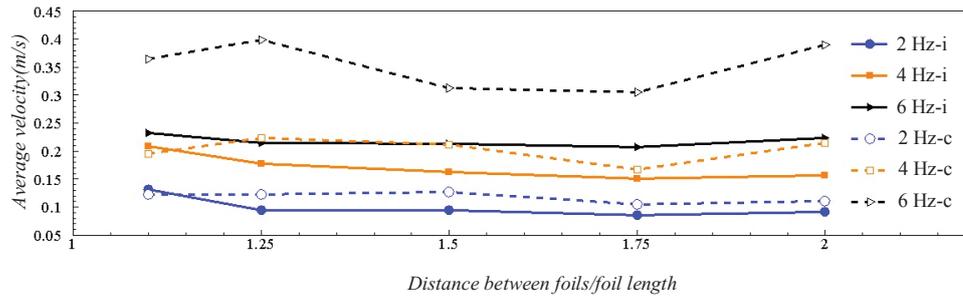


Figure 9. Effect of distance between two foils on the averaged velocity in the channel with three oscillating frequencies for both in-phase and counter-phase pattern.

4 Conclusions

In this paper, the air flow driven by oscillating foils in a channel has been numerically studied in detailed. Brief summaries are listed below:

1. Oscillating foils with higher frequencies generate higher flow average velocity than those with lower frequencies.
2. The effect of span angle on the flow average velocity in the channel has been investigated. It is discovered that the optimum flow average velocity occurs at the span angle of 120° .
3. It is discovered that the flow average velocity in the channel is larger than that FFSB pattern with FFSB pattern is larger than that with sinusoidal pattern for three oscillating frequencies.
4. In the oscillating range, it is observed that dual oscillating foils generate higher air flow than single foil. In addition, dual foil with counter-phase oscillating mode produces higher velocity air flow than that with in-phase oscillating mode. Besides, it shows an optimum in the counter-phase oscillating mode. However, the optimum condition does not appear in the in-phase oscillating mode.

Acknowledgement

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