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Effects of the distance between a vibrating cantilever pair

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ABSTRACT

Two dimensional unsteady numerical simulations were conducted using a commercial code with a user-defined-function to investigate the effect of the distance between two cantilevers vibrating in counter-phase or in phase. The performance of the cantilevers with different distances was mainly evaluated by the time-averaged axial velocity and the mass flow rate. It is evident that there is no interaction between the vortices by two cantilevers if they are too far apart. However, if two cantilevers are too close, they hinder each other in vortex generation. In particular, the interaction between two inner vortices generates a reversed flow which has a negative effect on the performance. Unless the distance is too close, the performance of the cantilever pair vibrating in counter-phase is always superior to the cantilever pair vibrating in phase. The optimal distance between two cantilevers in counter-phase is approximately equal to twice the size of a fully-grown vortex generated by the single cantilever, while there is no distinct optimal distance for a cantilever pair vibrating in phase. In case the distance is larger than three times the vortex size, the flow field generated by each cantilever is similar to the flow field of a single cantilever, which implies that two cantilevers work independently of each other.

1. Introduction

Rotary type fans with high efficiency and performance have been widely used for thermal and flow control in conventional large-sized devices. However, it is difficult to make the components of rotary fans, such as the rotor, bearings, motor and shaft, smaller than a critical size for small electronics. This situation forces designers to develop new types of cooling devices with a small size and a simplified structure. An alternative device of generating air flow is a hand-held fan, whose advantage is its simple structure, specifically, a vibrating flat plate. Any flat plate with a simple harmonic oscillation can induce an airflow, and consequently can be used as a cooling device. To obtain sufficient airflow, a fast vibrating motion is required and it can be generated using a piezoelectric material. When AC power is applied to the piezoelectric fan, the plate moves back and forth, because of the electrical potential difference across a piezoelectric material deposited on the plate, and consequently the device generates an airflow.

In spite of the simple structure of piezoelectric fans, the airflow generated by the fan has not been fully understood. Toda [1,2] was one of the earliest researchers to perform experiments on the cooling effectiveness of a piezoelectric fan and confirmed that the fan can be used as a cooling device for a transistor. To characterize the flow structure around vibrating flat plates, Watanabe et al. [3], Ihara and Watanabe [4], Tsutsui et al. [5] and Takato et al. [6] investigated the airflow using LDV (Laser Doppler Velocimetry) measurements. However, the low spatial resolution of LDV was insufficient to clearly observe the vortex motion generated by the oscillating plates. Thereafter, a few attempts to characterize a small cantilever fan for electric devices were made by Burmann et al. [7], Acikalin et al. [8–10], Wait et al. [11] and Kimber and Garimella [12] using analytical, computational and experimental methods. In particular, Kimber et al. [13,14] investigated the heat transfer enhancement and the aerodynamic damping in a vibrating cantilever pair. Lin [15,16] found that the piezoelectric fan, based on his experimental and numerical results, can enhance the heat transfer coefficient significantly in comparison to natural convection. With the flow measurements around a vibrating cantilever, Kim et al. [17,18] were able to identify the cyclic generation of counter-rotating vortices induced by the cantilever in detail. They analyzed the vortex motion in a quantitative manner with high-resolution PIV (Particle Image Velocimetry) measurements and wavelet analysis. Eastman et al. [19] measured the thrust generated by a single slender cantilever and investigated the 3-D structure of the flow field around it. Recently, Choi et al. [20] have analyzed numerical simulations thoroughly and found that the static pressure difference across the cantilever tip plays an important role in the formation and development of counter-rotating vortices.

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Nomenclature

c	Effective length of cantilever
CCW	Counter-clockwise
CW	Clockwise
d	Distance between two cantilevers
f_0	Vibrating frequency
h_0	Maximum tip deflection amplitude
l	Actual length of cantilever
m_d	Mass flow rate generated by a pair of cantilevers
m_s	Mass flow rate generated by a single cantilever
p	Static pressure
V_T	Maximum tip speed
V_{xd}	Maximum axial velocity induced by a pair of cantilevers
V_{xs}	Maximum axial velocity induced by a single cantilever
φ	Phase angle
ω	Vorticity

To increase the cooled area or the performance of the system, it is beneficial to use multiple piezoelectric fans. Although many researchers have experimented on designing a piezoelectric fan, testing its performance and investigating the flow field around it, only a few papers have been published regarding the flow around two oscillating plates. Ihara and Watanabe [4] have performed numerical simulations using the discrete vortex method and applied smoke visualization to investigate the flow field around two plates oscillating in-phase and in counter-phase. However, the data from their simulation and experiment were insufficient to resolve the flow field in detail. Kimber and Garimella [13] tested the cooling effectiveness of a vibrating cantilever pair in phase on the heated surface and found it can increase the heat transfer coefficient in comparison to the single cantilever. Kimber et al. [14] found that the air damping decreases significantly with in-phase vibration while it increases with counter-phase vibration. Recently, Choi et al. [21] have simulated a 2D flow field generated by oscillating cantilever pair with different phase angles and reported that the interaction of two vibrating cantilevers changes the flow field significantly depending on the phase angles. In this study, the researchers found that the performance of the cantilever pair reaches its maximum when two plates are vibrating 180° out of phase. In addition, Ihara and Watanabe [4] observed that the distance between two vibrating plates in counter-phase has a significant effect on the induced flow field but could not explain this phenomenon in detail due to insufficient data. Therefore, the present study investigates the effect of the distance between two vibrating cantilevers on the performance and focuses on finding the underlying mechanisms of the performance variation.

2. Validation for a single cantilever

Prior to the validation of the numerical results, it is necessary to define the phase angle. Fig. 1 shows the relationship of the phase angles to the deflections of the cantilever. In the previous paper of Choi et al. [20], the numerical results for a single cantilever were compared with the experimental velocity data measured by Kim et al. [17]. A brief comparison, therefore, between the computational results and the experimental data is shown in Fig. 2. In the experiment, the unsteady flow around a vibrating cantilever was visualized by smoke particles and the captured particle images showed the process of the vortex formation, as presented in the left of Fig. 2. The PIV technique has then been applied to obtain the quantitative flow field from the particle images and the results are shown in the middle of Fig. 2. Finally, the computed flow field in the right of Fig. 2 was compared with the measured flow field. The process of the vortex formation matches well between experimental and computational data. In addition to the flow field, in the previous paper of Choi et al. [20], the deflection shape of the modeled cantilever was matched accurately to the experimentally measured vibration shape at each phase angle. In order to check the accuracy of the computed flow fields, the size of vortices and their trajectories were compared with the experimental data quantitatively. These comparisons confirmed that the computation can capture the overall features of the vortices observed in the experiment during a period and is thus well suited to perform a parameter test.

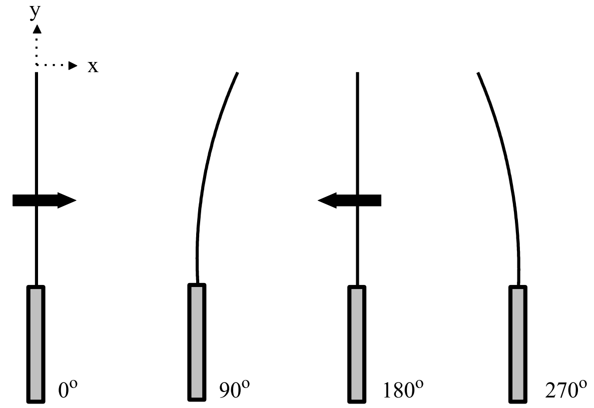

Fig. 1. Definition of the phase angle.

3. Computational method

3.1. Geometry of a vibrating cantilever pair

This part begins with a brief description of the shape of the cantilever, which is the same as that in the experiment of Kim et al. [17]. The piezoelectric fan is a thin metal plate fixed to the apparatus in a cantilevered manner with its bottom end and its top end is free as shown in Fig. 3, the bottom part of which is coated with a piezoelectric material. The actual length (l) of the cantilever is 31 mm but its moving part, referred to as the effective length (c), is 25.4 mm. The plate with the thickness of 0.13 mm vibrates at its fundamental natural frequency (f_0) of 180 Hz. The tip deflection is fixed at $h_0/c = 0.054$, where h_0 is the maximum tip deflection amplitude, and the corresponding maximum tip speed (V_T) is 1.54 m/s. More details on the experimental setup and the measurement can be found in Kim et al. [17].

Choi et al. [21] simulated the flow around two vibrating cantilevers with eight different phase angles and a fixed distance between both cantilevers. They found that the cantilever pair vibrating in counter-phase is more effective in generating the airflow than the cantilever pair vibrating in phase. The distance between two cantilevers (d) was fixed at $8h_0$ and this value was chosen based on the size of the counter-rotating vortices generated by a single vibrating cantilever. As shown in Fig. 2, two vortices are generated alternately by the cantilever and they move downstream within $-3h_0$ and $3h_0$ on the x-axis.

Two cantilevers could work as obstacles in the vortex generation process if they are too close, while there would be no interaction between them if they are too far from each other. In the present study, two vibrating cantilevers with different distances between them were tested in phase or in counter-phase in order to find an optimal distance for the highest performance. The distance between the cantilevers was changed from $4h_0$ to $20h_0$.