Experimental PIV investigation of the PZT fans array coupling effect at high Reynolds numbers

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Abstract—Piezoelectric fan arrays are being increasingly emphasized for heat dissipation in small-sized electronic devices. In this study, PIV experiments were conducted to investigate the flow fields induced by piezoelectric fan arrays with different vibration modes and pitches at high Reynolds numbers (324< Re <509) in a stationary air environment. As a result, when the PZT fan array is vibrating in-phase, the saddle points in the time averaged flow field are formed and separated gradually as the pitch increases, the remnant vortex and the induced vortex interact to form a jet with a periodic oscillation in the direction. Jet velocity reaches a maximum at \( P = 3A \). In counter-phase vibration, saddle points are separated from one region under large pitches, the interaction of counter-rotating induced vortices forms a vertical upward jet. The morphology of induced and remnant vortices with different vibration modes and array pitches are responsible for the jet formation and flow field pattern. The interaction of counter-rotating vortices in counter-phase vibration leads the jet intensity higher than in-phase vibration induced jet, the optimal setting of the PZT fan under this study is determined as \( P = 2.5A \) with counter-phase vibration. The experimental results provide validation for the simulation study and give guidance to the application

1. Introduction
Rotary type fans have been widely applied in industrial cooling systems due to high performance and efficiency. However, with the development of electric components which tend to shrink in size, rotary type fans are limited by narrow space because the performance and efficiency of rotary type fans degrade rapidly when fans’ size is too small. The manufacturing dimensions of rotors, bearings and other components also make rotary type fans difficult to popularized used in electronic components cooling. Nowadays, piezoelectric (PZT) fans with the advantages of low power consumption, high reliability, and the small geometric deformation to generate a significate airflow are considered as the better option for tiny electronic components heat dissipating [1, 2].

Toda was the first to investigate the fluid field generated by a single PZT fan in 1978 and made a preliminary study of PZT fan application about cooling [3, 4]. Subsequently, computational simulations and Particle Image Velocimetry (PIV) experimental validation were applied to study the flow field characteristics induced by the PZT fan. Kim et al. used PIV to experimentally investigate the flow field around a vibrating cantilever plate and explained the air flow induced by the cantilever
plate is a pseudo-jet flow dominated by vortical structures. Vortex size, strength and other information is also obtained by wavelet analyze [5]. Ebrahimi et al. conducted the experimental and numerical simulation studied on 3D mean jet downstream and vortex structures produced by the oscillation PZT fan with different oscillating frequency, amplitude and geometric parameter. The results revealed that vibration amplitude and width of PZT fan blade are the main factors that affect the shape of jet [6]. Akshat Agarwal et al. presented a three-dimensional analysis of a single unconfined PZT fan. Phase locked PIV technique is applied to experimental research the formation and shedding of vortices. The structures of vortices appear as a horseshoe shape and then evolve into a hairpin vortex [7]. The aerodynamic performance of PZT fans has also been studied both theoretically and experimentally. Eastman et al. measured the thrust of vibrating oscillating cantilever in the range of Reynolds number from 500 to 5000 and gave out a simple concept sidewall design to maximum the performance based on their experiment data [8]. Stafford and Jeffers studied the aerodynamic performance of a vibrating piezoelectric blade based on experiment under different operating conditions and confinements. The measurement of pressure-flow rate characteristics shows that stall characteristics exists in time-average velocity fields between maximum efficiency and maximum static pressure. Flow reversal dominates at maximum static pressure. A recommended operating range was given between maximum efficiency and maximum flow rate [9].

The flow field induced by a single PZT fan has been well studied. PZT fans array will be more widely used in thermal management than individual fans. However, only a few studies have focused on the flow field details of the PZT fans array. Kimber et al., experimentally investigated the aerodynamic coupling effect of PZT fan arrays. Both in-phase and counter phase vibration mode are explored for both face-to-face and edge-to-edge arrangement. The result showed that for the face-to-face arrangement, the fluid damping is promoted when operates in in-phase mode, and the coupling effect became stronger as the pitch got smaller. The oscillation for the face-to-face configuration behaved in an uncoupled manner when the pitch is above 6 times of the amplitude [10]. Choi et al. simulated the unsteady flow around a vibrating cantilever PZT fan pair operating at different phase angle using a commercial software. They found the interaction between the counter-rotating vortex generated by each cantilever is depended on the phase angle difference. And they also concluded that the cantilever pair performed most effectively in generating airflow when vibrating in counter-phase mode and performed worst when vibrating in in-phase mode [11]. In another research done by Choi et al., by evaluating time-averaged axial velocity and the mass flow rate downstream. They found the best distance between two PZT fans of counter-phase vibrating mode and explained that the performance of in-phase vibrating mode is inferior to the single cantilever regardless of the distance between the beams [12]. Hales and Jiang studies the effect of pitch on the performance of the PZT fan arrays in a confined environment numerically. They also concluded that the performance of the counter-phase oscillation is superior to the in-phase oscillation across the tested pitch range. They highlighted that the formation of vortices is a determining factor for the optimal pitch [13]. In their following publication, the effect of phase variation between the two PZT fan blades in a confined environment is studied numerically. An asymmetrical flow domain is observed when the blade pair is not operating in in-phase or counterphase mode. The skewness of the downstream velocity profile is depended on the interaction of vortex generated between two bladed during an oscillation cycle [14].

Most of the above literature used numerical simulations to investigate the effects of phase and distance on the velocity and flow downstream of the PZT fans array, giving optimal placement distance intervals. There are some simulations to investigate the coupling effect of distance and phase on adjacent fans by measuring PZT fan amplitudes. However, very few experiments have been conducted to verify the coupling effects and performance of PZT fan arrays for validation. In this study, the flow field pattern of the PZT fan array at high Reynolds number was experimentally determined by the PIV technique to investigate the variation of the coupling effect. The Reynolds number range taken in this study is $324 < Re < 509$, and the coupled flow field caused by the larger amplitude shows different characteristics from previous studies. The large amplitude is more consistent with the application of PZT fans to heat dissipation. Meanwhile, the spacing of PZT fans as
a variable was taken more finely. The velocity and vorticity fields induced by two different phase
difference vibrations is measured in an unconfined stationary air environment. The time-averaged
velocity field helps visualize the coupling pattern of the flow field and the air-driven performance of
the PZT fans array. The ensemble-averaged vortex field explains the formation of the velocity field
and shows the instantaneous coupling effects at different pitches.

The structure of the article is as follows. Section 2 introduces the setup of the PIV experiment and
the data processing method. Section 3 shows the flow field characteristics of different degrees of
coupling effect captured by PIV and gives explanations. And section 4 summarizes the conclusions
obtained from the above contents.

2. Experiment Methodology

2.1. PZT fan characteristic parameters and fan array set up
This paragraph gives the settings and specific parameters of the PZT fans array. All PZT fan blades in
the research have the same geometrical parameters length \( l_b = 65\, \text{mm} \), width \( w_b = 15\, \text{mm} \), thickness \( t_b =
0.1\, \text{mm} \) and resonance frequency \( f_r = 58\, \text{Hz} \). The visualization parameters are labelled in Fig. 1. The
PZT Fan array consisted by two PZT fan blades is mounted on two \( x-y \) movable manual adjustment
translation stages at the bottom of a container box in the central position. Distance between two PZT
fan blades can be regulated by the two translation stages. The range of distance between two blades
can be adjusted from 3mm to 28mm. Manual adjustment translation stages reading by
micrometer caliper has accuracy 0.01mm, distance between two blades with a reading error of \( \pm 0.001 \)
mm. The different vibrating amplitudes of single PZT fan reached by a series of voltages in the range
of \( 5.52\, \text{mm} < A < 8.67\, \text{mm} \) with an uncertainty of \( \pm 0.09\, \text{mm} \), corresponding to 1 pixel in the image.
The range of deflection in this study was determined as \( 0.085 < A/l_b < 0.133 \). The characteristic trailing
edge velocity in this study is defined as

\[
U_t = 4fA
\]

which is the average velocity of the trailing edge in a cycle. The PZT fan amplitude varies for different
degrees of coupling. Due to the piezoelectric effect, even if the signal generator sends the same
voltage signal to the PZT fan array, they may consume different amounts of power. In this study, the
power difference due to different coupling levels was measured to be less than 1%. Therefore, PZT
fans arrays driven by the same voltage signal at different pitches are considered to have the same
power dissipation together for comparison. The same Reynolds number is used to represent the single
PZT fan and PZT fans array driven by the same amplitude voltage signal. The Reynolds number is
defined as follows:

\[
Re = \frac{U_t w_b}{v} = \frac{f A w_b}{v}
\]

Fig. 1 Geometric parameters of the PZT fan array and the illuminated plane for the PIV experiment,
with frame (b) PIV experimental view of computing plane (x-y plane)
2.2. Particle Image Velocimetry experiment set up

The experiment system for Particle Image Velocimetry (PIV) is shown in Fig. 2. The size of the transparent acrylic glass container box is 300mm×300mm×300mm, which is large enough to reduce the sidewall effect. Transparent outer walls facilitate observation and laser penetration. The closed container box avoids the interference of the outside flow field. The bottom of the container box is fixed on an X-Y translational platform. The translational platform is driven by a Daheng Optical GCD-202002M stepper motor with a resolution of 0.001mm.

A 527 nm double-pulse Nd:YLF laser (VLite-Hi-527-40, BeamTech) is used to illuminate the experimental measurement area. The time interval $\Delta t$ between the two image frames used for the PIV computing is set as 60 $\mu$s. A high-speed camera (FASTCAM Nova S12 type 200KS-M-32G, Photron) is used to record the images with a capture rate of 5800Hz, which is 100 times of the frequency $f$ of the oscillating PZT fans array, so that 100 pairs of PIV images can be obtained in one oscillation period, equivalent to 5800 pairs of PIV images per second. The image resolution is set to 1024×1024 pixels, 12 bits per pixel. The pulsed laser and high-speed camera are controlled by a laser pulse synchronizer (TSI model 6130036 LaserPulse). Before the PIV experiment, the air-olive oil droplets mixture is deposited for 5 minutes and then ejected from a Laskin nozzle to form stationary aerosols.

The transient example images obtained from the shooting are processed by the commercial software TSI Insight 4G. The entire image processing is divided into three parts. In pre-process, all pixels are subtracted to the average brightness of the corresponding pixels of all images to reduce the effect of the background color on the image processing results. Then multiplication operation is used for the pixel points to increase the brightness.

In the second step, the pre-processed images are further processed. The particle velocity was computing using a recursive Nyquist grid with an overlapping grid spacing of 50%. The size of the interrogation window was set to 32 × 32 pixels, ensuring that at least 15 particles exist in the interrogation area. An FFT correlator is chosen as the correlation engine, and a Gaussian Peak with the signal to noise ratio of 1.5 is used for the peak engine. Finally, the computed images are post-processed, and the data are validated globally by a standard deviation speed range filter with a standard deviation factor of 7, followed by local validation using a median test method with a $5 \times 5$ pixels neighborhood size. Empty spaces in the data are filled recursively with a $5 \times 5$ pixels neighborhood size local averaging method. Finally, all data were smoothed with a filter size of $5 \times 5$ pixels and a $\sigma$ value of 0.8

3. Results and discussion

In this study, the amplitudes of the PZT fans array at different pitches at multiple Reynolds numbers are determined. Fig. 3(a) and Fig. 3(b) define the in-phase (IP) vibration and counter-phase (CP) vibration, which correspond to PZT fans pair phase differences of 0° and 180°, respectively. Due to the coupling effect, the amplitude of single PZT fan when vibrating in-phase and counter-phase will change as the coupling effect increases. Fig. 3(c) shows the blade vibration amplitude varies with blade pitch at five different Reynolds numbers. The vibration amplitude of PZT fans array is divided by the single blade amplitude of its corresponding Reynolds numbers. Under in-phase vibration mode,
the amplitude is larger than single blade vibration amplitude. The coupling effects at different Reynolds numbers follow a similar trend. Starting from $P = 1A$, the amplitude gradually decays from 1.2A to near 1A. When the blade pitch is greater than 3.5A, the coupling effect is weak. The coupling under counter-phase vibration weakens the vibration amplitude of the blades, the coupling effect decays as the blade pitch increases and the coupling strength of the two vibration modes is similar at different blade pitches. The same Reynolds number and pitch intervals that are of interest for the following study, coupling effects persist under these conditions.

3.1. Time-averaged flow field

In the current study, the time-averaged flow field of a single PZT fan is obtained from the PIV measurements as a contrast to study the effect of PZT fans array coupling effect. 2000 pairs PIV images are captured at 100x the PZT fan intrinsic frequency, which equals to 5800hz, then time averaging computing is applied to the 20 periods images to obtain the flow field. Fig. 4 shows the contour of time-averaged velocity magnitude ($U_{mag}$) in x-z planes in the case of $Re = 417$. The point $x = 0$mm, $y = 0$mm corresponds to the position of the tip of the leaf of PZT fan at rest. The previous study indicated that the flow patterns are similar with different Reynolds numbers. In general, the flow pattern in the x-y plane shows a highly symmetrical “Y” shape. [5]

Fig. 3 Amplitude variation due to coupling effect of PZT fans array: (a) schematic of in-phase vibration; (b) schematic of in-phase vibration. (c) Amplitude ratio profile under different Reynolds numbers and pitches

Fig. 4 Time-averaged velocity magnitude ($U_{mag}$) field of single PZT fan at $Re = 417$. 
The high-speed area at the tip of the blade gradually evolves into two oblique upwards jets. The velocity magnitude between two jets is relatively low. The two saddle points are on both sides of the leaf tip, below the jet. The formation of two saddle points is related to the fan-induced formation of two vortices. The vortex generated at phase $\tau = 0.25$ by a single PZT fan is shown in the Fig. 5. The definition of $\tau$ and the phase-locked PIV measurement for generating images will be mentioned in the next section. The leftward motion of the leaf tip induces a CW vortex. Above the CW vortex is the remnant vortex generated by the last vibration cycle. In addition, due to the motion of the blade body, the pressure difference causes the air near the blade body to move in the direction of its motion and upwards. A blade body-induced vortex in the opposite direction of the blade tip-induced vortex is generated. Due to the high strength of the Tip-induced vortex and the continuous presence for a while during the entire periodic vibration of the PZT fan to keep the position nearly fixed. Therefore, two saddle points appear in the time-averaged flow field at the locations of the CW and CCW tip induced vortex cores, respectively.

Fig. 5 Vortex induced by the periodic motion of the PZT fan.

Fig. 6 shows the time-averaged flow field pattern of PZT fans array with different pitches $P$ between two blades. Symmetrical “Y” shape flow field similar to the single blade is presented when $P = 1.5A$. With the increase of the interval, the flow field exhibits different characteristics. When $P = 2.5A$, a new high-speed region appears between the two jets, and a low-speed region appears in the region encircled by the two blades. At $P = 2.5A$, the area of the low velocity region continues to expand, and the saddle points are starting to show at the top of the region. As the pitch continues to increase, the intermediate high velocity region evolves into a new jet. When $P = 3.5A$, in the middle low speed region with the same height with blade tips, three saddle points appears. The two saddle points below are in the position of the CW and CCW vortices cores. The interaction of the vortices forms a new saddle point and leads to the creation of the jet. The inverse flow observed by Choi et al. [11] can be found in the Fig. 6. The periodic motion of the blades creates two vortices between the blades. Although these two counter-rotating vortices are generated at different phases, the time averaging within the cycle causes the horizontal component of the velocity to be eliminated and the two counter-rotating vortices act to generate the reversed flow. The formation of vortices will be discussed in detail in the next section. The velocity field induced by the low-deflection PZT fans array is presented as two jets starting from the blade tip vertically upward and gradually combining to form a low velocity region with one saddle point [11]. The high Reynolds number flow field at the corresponding pitch retains two pseudo-jets to the side and has two additional saddle points at the position of vortex core in the low velocity region.
Fig. 6 Time-averaged velocity magnitude ($U_{mag}$) field of IP PZT fans array with different pitches at $Re = 417$.

Fig. 7 (b) shows the time-averaged velocity profile of PZT fans array alone the line $y = 0$mm and $0mm < x < 40mm$. In the case $P = 1A$ and $P = 1.5A$, velocity magnitude increases monotonically along the x-axis, with a high velocity magnitude near the tip of the blade and decreasing to zero at 40mm. The velocity magnitude peak appears when the blade spacing is greater than $P = 2A$, and the horizontal coordinate of the velocity magnitude peak becomes larger with increasing blade spacing. The case $P = 2.5A$ has the highest velocity magnitude peak along the x-axis. Because of the vortices interaction in blade spacing, the velocity magnitude near the midspan line is small when $P > 2A$. Due to the blade displacement, the dropping tendency mitigates and causes the velocity magnitude residual when approaching the image edge. The velocity profile along the midspan line is also investigated as shown in Fig. 7 (c). Along the line $x = 0$mm and $0mm < y < 40mm$, contrary to the monotonic decreasing of $P = 1A$ and $P = 1.5A$, when $P > 2A$, there is an upward trend in velocity for a period near the tip of the blade, a turning point appears at $y = 10mm$. Before $y = 10mm$, the velocity magnitude of the case $P > 2A$ is much smaller than the case $P = 1A$ and $P = 1.5A$, but relatively far away the final velocity is almost the same at different pitches. The change in velocity magnitude profile monotonicity is related to the generation of saddle points.

Time-averaged flow field of PZT fans array with counter-phase vibration is also obtained from 2000 images over 20 cycles, which is shown below in Fig. 8. The flow field is highly symmetrical. The flow field pattern does not change significantly as the blade pitch increases, a vertical upward jet and two lateral jets are captured at different blade pitches. The reversed flow is also present in the flow field pattern. The intensity of the lateral jet is weaker compared to the in-phase vibration-induced jet. The strength of the lateral jet increases as the blade pitch increases. The coupling effect of the PZT fans array weakens the strength of the lateral jet by reducing the maximum tip velocity in a vibration period. When $P > 3A$, three saddle points in the center of the blade spacing appear. Unlike the in-phase vibration-induced flow field, the low velocity region that becomes saddle points exists at low pitches. This is due to the fact that counter-phase vibrations can induce vortices in the spacing of the array at
low pitches. Reverse rotation of the vortex core is too close to make saddle points difficult to distinguish and connect into a low velocity region. The causes of jet and reversed flow formation are different from those of in-phase vibration-induced flow, it will be claimed more clearly in the next section. Two counter-rotating vortices in the same phase are beneficially coupled, the symmetry of the vibration allows the flow velocity on the midspan line to have no component in the $x$-axis. The high Reynolds number flow field maintains the similar characteristics as we mentioned before, with two lateral jets and two saddle points located below that can be identified in the velocity magnitude flow field.

The velocity magnitude of counter-phase vibration in the axial direction was also sampled and velocity profiles were plotted for different blade pitches. Fig. 9 (b) and Fig. 9 (c) is the axial velocity magnitude extracted from the horizontal line and the midspan line as analyzed before. Along the $+x$ direction, the velocity magnitude shows a similar changing mode of variation at different blade pitches. Velocity magnitude appeared the maximum peak from $x = 7$mm to $x = 17$mm, and with the increase of blade pitch, the curve with peak velocity point gradually moved forward. The change in spacing also allows the high-speed area to be expanded. In the line alone $x = 0$mm, the velocity of the counter-phase induced flow field is smaller and the reduction of blade amplitude due to vibration is the cause of this phenomenon. Along the midspan line, the velocities at different blade pitches all reach a maximum at $y = 10$ mm, followed by a slow decrease. In addition, at high pitch, the velocity shows a period of decreasing trend in the first few millimeters in the direction of $+y$-axis at the tip of the leaf due to the gradual formation of three stagnation points. Compared to the velocity characteristics of the flow induced by in-phase vibration mode along the midspan line, the velocity under counter-phase has a higher closing velocity at the end due to a slower decrease and has higher peak.

Fig. 9 Velocity magnitude at streamwise and spanwise lines of CP PZT fans array with different pitches: (a) schematic of the lines for data extraction. (b) Velocity magnitude ($U_{mag}$) profile of the flow
field along the line $y = 0$, $0 < x < 40$, (c) velocity magnitude ($U_{mag}$) profile of the flow field along the line $x = 0$, $0 < y < 40$.

3.2. Vortex evolution

In this paper, the vibration period of a PZT fan was divided into different phases. The formation process of velocity field and vortex is obtained by the ensemble-averaged method under different phases. The phase $\tau$ is defined as $\tau = t/T$, where $t$ represents the time and $T$ represents the period of vibration of a single PZT fan. The evolution of the vortex is obtained from the ensemble-averaged images of 8 different phases. The time when the PZT fan blade swings to the far right is defined as 0. For an array of two PZT fans, the reference blade is set to the right blade and the time corresponding to the phase is 0 when the right PZT fan swings to the far right. The definition of the specific position at phase $\tau$ is shown in Fig. 10.

As the blade pitch increases, the intermediate jet induced by PZT fans array with in-phase vibration gradually strengthens, and stagnation points are formed. In this section, the case of $P = 1A$, $P = 2A$ and $P = 3.5A$ is analyzed separately. At $P = 1A$, the velocity field is shown as a Y-shaped jet. $P = 2A$, the intermediate jet is generated, and stagnation points appear. $P = 3.5A$, three stagnation points are clearly visible. The images in Fig. 11 were subjected to the ensemble-averaging method. 200 pairs of images were used to generate location-specific ensemble-averaged images, and the results of the ensemble-averaged processing at 8 different locations were presented. Fig. 11(a) shows the vorticity image of one cycle of vibration from the rightmost position under in-phase vibration when $P = 1A$ at $Re = 417$. When $P = 1A$, a CW vortex and a CCW vortex are generated in one vibration cycle. For the phase $\tau = 0$ and $\tau = 0.5$, the PZT fans blade is at right and left ends, the blade tip speed is zero and the vortex generated is the weakest. Take $\tau = 0$ as an example, with the blade to swing, a CW vortex is generated, when $\tau = 0.25$, the blade moves to the midspan line, the strongest vortex is generated by the blade tip. When $P = 1A$, due to the small spacing, in-phase vibration of the two blades produced only one vortex, the overall characteristics are similar to the single blade vibration. When $P = 2A$, as shown in Fig. 11(b), the maximum vorticity is minimum at $\tau = 0$. As the blade moves to the left, two CW vortices are generated from the tips of the two blades, and the two vortices can be clearly distinguished because the blade spacing is large enough to vortex generation and existence. The vortex intensity reaches its maximum at $\tau = 0.25$, and as the blade oscillates in reverse after $\tau = 0.5$, two new CCW vortices are generated, the remnant CW vortices gradually merge at the periphery. In addition, a vortex core with relatively large vortex intensity between the two blades can be clearly observed at $\tau = 0.25$ and $\tau = 0.75$. Since the blade positions are still relatively close, the vortex core induced by the leading blade cannot be effectively distinguished, which leads to the low velocity region in the velocity magnitude field between the two blades in the flow field pattern. When the blade pitch $P$ reaches 3.5A,
which has shown in Fig. 11(c). The evolution of the vortex is close to the flow field evolution process induced by the vibration of two independent PZT fans. During the vibration of the PZT fans to the left, two CW vortices are generated from the lobe tips, respectively, while the remnant CCW vortices generated in the previous oscillation cycle continue to propagate upward in evolution. Unlike the case when the $P = 2A$, the remnant vortex generated by the two blades do not merge, they propagate separately because a part of the newly generated vortices occupies the areas between two PZT fan blades. The newly generated vortex interacts with the remnant vortex produced in the previous cycle of the other blade to produce an upward jet. At $\tau = 0.25$ and $\tau = 0.75$, the two blades produce two vortices of higher intensity each because the blade tip velocity reaches its maximum. However, the vortex generated by the leading blade is obviously compressed, the compressed vortices in $\tau = 0.25$ and $\tau = 0.75$ resulting in two compressed vortices on both sides of the midspan line, which are corresponding to the velocity field calculated by the time-averaged method as two saddle points below. And above these two points, as the velocities in different directions are cancelled out, a new saddle point is created above these two points because the velocities in different directions are cancelled by the algorithm. Unlike the case where the vortices generated by the two blade tips are not separated, in the case of separation, the vortex core strength generated by the leading blade in vibration is stronger than that generated by the following blade when it is compressed. In the whole vibration cycle, due to the asymmetry of the blade motion, although the jets in the time-averaged flow field are symmetric, the ensemble-averaged flow field corresponding to each phase is highly asymmetric, and the upward jets are periodically biased to the left and right sides with the movement of the blade.
Fig 11. Evolution of vorticity ($\omega_z$) in one cycle of IP PZT fans array at Reynolds number $Re = 417$, with pitches (a) $P = 1A$, (b) $P = 2.5A$ and (c) $P = 3.5A$

To better reveal the details of the flow field at different pitches, the ensemble-averaged images with $\tau = 0.25$ for different blade spacing at Reynolds number $Re = 417$ are shown in Fig. 12. At $\tau = 0.25$, the tip-induced vortex has the maximum intensity, because the blade has the maximum tip velocity. At $P = 1A$, the vortices generated by the vibration of the two PZT fans merge due to the lack of space, as the remnant vortex of the previous cycle is located above the newly generated vortex. At $P = 1.5A$, the tip-induced vortex tends to separate, and when the blade pitch is expanded to $2A$, the tip-induced vortex is almost separated, and it can be observed that the vortex generated by the leading blade already has a more obvious vortex core. When $P = 2.5A$, the tip-induced vortex is completely separated, and the vortex generated by the leading blade is severely compressed, which becomes stronger than the vortex induced by the backing blade. The remnant vortex generated during the last cycle of vibration is separated. A part of the CW vortex appears between the two remnant vortices and interacts with them to produce an upward jet. As the blade pitch continues to increase, the compression of the vortex induced by the leading blade is relieved.

Fig. 12 Phase-locked vorticity field induced by IP PZT fans array with different pitches at Reynolds number $Re = 417$ and $\tau = 0.25$.

The coupled flow fields of the PZT fans array at different Reynolds numbers were also investigated, and the results are shown following. Fig. 13 shows the coupled flow field for different Reynolds numbers at $P = 2A$. From the above conclusion, $P = 2A$ is a critical distance for the coupled flow field, and at this distance, the coupled flow field for all three different Reynolds numbers maintains the similar characteristics, the tip-induced vortex is not completely separated, and the remnant vortex surrounds the whole tip-induced vortex at the periphery. However, with the increment of the Reynolds numbers, the induced vortex also produces a slight separation, the center strength of the remnant vortex becomes weaker.
vortex becomes weaker, the evidence supports the idea that larger PZT fans amplitude leads to the weakening of the coupling effect of PZT fans. So, the conclusions drawn in the previous section should only apply to the vibrating PZT fans with a specific range of Reynolds numbers between 378 and 457. More studies are needed on the change in the degree of coupling due to Reynolds number variation.

![Phase-locked vorticity field induced by IP PZT fans array](image)

Fig. 13 Phase-locked vorticity field induced by IP PZT fans array with pitch $P = 2A$ at different Reynolds numbers in the range of $324 < Re < 509$.

The vortex evolution under counter-phase vibration shows different characteristics with in-phase vibration. The counter-phase vibrational ensemble-averaged images at two different pitches were investigated as shown in Fig. 14. Fig. 14. (a) display the case of $P = 2A$, this is the shortest distance to ensure that fan blades do not touch each other. The PZT fan blade vibrating in the opposite direction produces a vortex also in the opposite direction. At the time of $\tau = 0$, the tips of the double blades of counter-phase vibration are biased to the sides and are in the open state. With the inward contraction of both sides of the blade, the left and right blades produced CCW vortex and CW vortex respectively, and the size and intensity of the vortex reached the maximum at $\tau = 0.25$. After that, the two induced generated vortices converge toward the midspan line and propagate upward. The remnant vortex structure exists throughout the vibration cycle and does not dissipate, and this pair of interacting vortices works together to produce an upward jet. Therefore, unlike the unstable jet under in-phase vibration of the PZT fans, the upward jet in counter-phase vibration mode is continuous and stable in the direction. After $\tau = 0.5$, the two PZT fans blades start to move to both sides, two CW vortex and CCW vortex are generated from the left and right blades respectively, the intensity of the vortex reaches the maximum at $\tau = 0.75$ but due to the lack of space between the two blades, the vortex is compressed. After that, the intensity of both vortices decreases, and each propagates to both sides and dissipates. The details of the vortex’s evolution in the case of $P = 3.5A$ is shown in Fig. 14 (b). There is no significant difference between the different pitches. Compared to $P = 2A$, the degree of compression of the vortices is reduced at $\tau = 0.75$, and the cores of both vortices are more pronounced and farther apart. Therefore, two lower saddle points, corresponding to the two vortex cores, and one higher saddle point, corresponding to the zero-velocity point generated by the two vortices coupling, can be observed in the time-averaged image with a large pitch.
Fig 14. Evolution of vorticity ($\omega_z$) in one cycle of CP PZT fans array at Reynolds number $Re = 417$, with pitches (a) $P = 2.5\,A$ and (b) $P = 3.5\,A$

At $\tau = 0.75$, the blades of PZT fans are in vertical position. The two blades are moving to the two sides, and two vortices in opposite directions are generated in the space between the PZT fans array, and the compression of the vortices varies at different distances. Fig. 15 investigates the coupling of the flow field by comparing the compression of the vortices at different Reynolds numbers. At $P = 2\,A$, the intensity of the induced vortex is low, but the intensity of the remnant vortex is relatively high. As the pitch increases, the degree of vortex extrusion decreases, and the intensity of the induced vortex increases while the intensity of the remnant vortex decreases. The core of the induced vortex has started to become clear at $P = 2.5\,A$, and the time averaged velocity flow field image also indicates that the stationing point is formed near $P = 2.5\,A$. As pitch continues to increase after reaching $3\,A$, the coupling of the flow field weakens significantly and the remnant vortex changes from a compressed circle to a bar shape. Half side of the image is similar to the flow field image induced by a single PZT fan.
Fig. 15 Phase-locked vorticity field induced by IP PZT fans array with different pitches at Reynolds number $Re = 417$ and $r = 0.25$.

The increase of Reynolds number makes the intensity of the vortex increase, but the change of Reynolds number also changes the flow field pattern. Like the in-phase vibration, Increasing the Reynolds number brings a change in the flow field pattern similar to increasing the pitch. Fig. 16 shows the flow pattern changes various Reynolds numbers. At low Reynolds numbers, the cores of the two reversed vortices are not obvious and the whole vortex is squeezed in the horizontal direction and the vortex is in an elliptical shape. And at $Re = 509$, it can be observed that the vortex becomes a more uncompressed circle. The core of the vortex becomes apparent at $Re = 417$, and at $Re = 457$ or greater, focusing on the left part of the pattern, the remnant vortex begins to combine with the CW vortex produced by the blade body to wrap the CCW vortex produced by the blade tip.

Fig. 16 Phase-locked vorticity field induced by IP PZT fans array with pitch $P = 2A$ at different Reynolds numbers in the range of $324 < Re < 509$.

The downstream flow velocity of the PZT fan determines the effectiveness of the heat dissipation. In a coupled array of PZT fans, the jet along the midspan line will provide the main air flow to the target components. In the in-phase and counter-phase vibration modes, in the range of Reynolds numbers of interest in this study, the jet appears when $P > 2A$. Fig. 17 (a) illustrates the maximum velocity magnitude of the jet at $y = 20$ mm when $Re = 417$. The counter-phase vibration has a greater downstream velocity than the in-phase because the two vortices generated are beneficially coupled. As the distance increases, the beneficial coupling effect decreases, resulting in a decrease in jet strength, especially at pitch between 2.5A and 3A. The jet generated by the in-phase vibration reaches its maximum at $P = 3A$. The lack of space for vortex formation in the PZT fan array when the distance is too close, and the vortex generated in the space is the condition for jet generation. When the distance is too far, the coupling effect also weaken. The facts lead to the optimal pitch for jet generation in in-phase vibration, which was determined as $P = 3A$ for the conditions of $Re = 417$ in this study.
Fig. 17 maximum jet velocity \((U_{\text{mag. max}})\) and width \((w_{\text{jet}})\) of IP and CP vibrating PZT fans array.

The area affected by the jet is also a parameter that affects the cooling effect. The width of the jet at \(y = 20\) mm was determined and shown in Fig. 17 (b). The jet width of counter-phase vibration remains stable and distinct smaller than the in-phase vibration. The in-phase jet width increases significantly with increasing pitch. This difference in performance stems from the different reasons for jet generation. At high Reynolds number, the large amplitude causes the two vortices generated by a single PZT fan to propagate to both sides. As the blade gap widens, the propagation restriction of the vortex on one side of the PZT fan array to the other side is diminished, allowing the deflection of airflow more severe. This also allows PZT fans with large pitches of in-phase vibration to have a larger area for high speed. While the direction of the jet generated by the counter-phase vibration of the symmetrical flow field remains stable, the intensity of the jet varies with distance but remains constant in the high-speed area. Due to the difference in stability and speed of the jets, counter-phase vibration is the more beneficial vibration method for heat dissipation. The optimal Pitch was determined to be around \(P = 2.5A\). More experiments on the flow rate need to be done in the follow-up studies.

4. Conclusion

In this study, the time-averaged and assembled-averaged flow patterns of PZT fans array with different spacing at high Reynolds number are investigated to research the coupling of PZT fans array at different spacing and Reynolds number. The performance of a piezoelectric fan is measured by the maximum speed and width of the jet. The following are the conclusions drawn from this study.

1. As the space in the middle of the PZT fans array increases, the in-phase vibration generates jets and three saddle points appear and separate in time-averaged flow field. The jet originates from the averaging of the deflected flow which generated by the periodic interaction of an induced vortex and a counter-rotating remnant vortex. The velocity of jet reaches the highest at \(P = 3A\), and the jet width increases with the increase of pitch.

2. In counter-phase vibration, the spacing allow the persistence of induced vortex, causes the jet to persist and produce three saddle points. The maximum velocity of the jet is greater than the in-phase induced jet velocity due to the beneficial coupling of counter-rotating induced vortices. The jet intensity decreases significantly after \(P = 2.5A\), considering the energy consumption per unit length, the optimal location is determined at \(P = 2.5A\).

3. The presence of the vortex core leads to the formation of the saddle points which start generated at \(P = 2A\), and the induced vortex and the remnant vortex begin to separate when PZT fans vibrate in-phase with \(P > 2.5A\). Saddle points separated at under the same pitch. The induced vortex of the PZT fan coupled with the remnant vortex from the last cycle of the adjacent fan generates the jet. While the flow field pattern of the counter-phase vibrating PZT fan is similar at different pitches, saddle points and the position of induced vortices core begin to separate with the increase pitches.

4. The time-averaged PZT fans array flow fields at high Reynolds numbers have two lateral jets and a more pronounced upper lateral saddle point. This is not consistent with the previous simulation results using low deflected PZT fan blades. The flow field with the same pitch at different Reynolds numbers shows a weaker coupling effect with increasing Reynolds numbers. Therefore, the effective
range of Reynolds numbers in this experimental study was determined to be 324< $Re <$509.

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