High fidelity phase locked PIV measurements analysing the flow fields surrounding an oscillating piezoelectric fan

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Abstract. Piezoelectric fans have been studied extensively and are seen as a promising technology for thermal management due to their ability to provide quiet, reliable cooling with low power consumption. The fluid mechanics of an unconfined piezoelectric fan are complex which is why the majority of the literature to date confines the fan in an attempt to simplify the flow field. This paper investigates the fluid mechanics of an unconfined fan operating in its first vibration frequency mode. The piezoelectric fan used in this study measures 12.7mm x 70mm and resonates at 92.5Hz in air. A custom built experimental facility was developed to capture the fan's flow field using phase locked Particle Image Velocimetry (PIV). The phase locked PIV results are presented in terms of vorticity and show the formation of a horse shoe vortex. A three dimensional $\lambda_2$ criterion constructed from interpolated PIV measurements was used to identify the vortex core in the vicinity of the fan. This analysis was used to clearly identify the formation of a horse shoe vortex that turns into a hairpin vortex before it breaks up due to a combination of vortex shedding and flow along the fan blade. The results presented in this paper contribute to both the fluid dynamics and heat transfer literature concerning first mode fan oscillation.

1. Introduction
Piezoelectric cooling devices are seen as a promising air moving technology that bridge the gap between natural convection heat sinks and axial fan forced convection heat sinks. The main advantages of piezoelectric fans are high reliability, low power consumption and minimal noise generation. A typical piezoelectric fan is comprised of a piezoelectric material bonded to a flexible cantilever beam or fan blade. The piezoelectric material expands and contracts when an AC voltage is applied to it causing the fan blade to deflect. The fan achieves its maximum deflection when it is rigidly secured at one end, for example to a metal pillar, and the electrical excitation frequency matches the resonant frequency of the fan blade and fluid. This oscillating motion induces an air flow that can subsequently be used to cool adjacent heated surfaces.

Different configurations of piezoelectric fans have been studied since 1979 when Toda and Osaka [1] first proposed their use for cooling applications. However, only in the last ten years has the technology gained popularity amongst the scientific and industrial community since device reliability, energy consumption, and miniaturisation have become critical design parameters. A number of articles found in the literature present experimental and modelled
data for confined piezoelectric fans. These confinements are used to simplify the complex fluid mechanics generated by a fan operating in its first vibration mode.

Kim et al. [2] studied a confined piezoelectric fan using phase-resolved Particle Image Velocimetry (PIV) and smoke visualisation techniques. The fan used in this study had a height to length aspect ratio of 1:1.2 and was confined by plates positioned on the lateral edges of the fan in an attempt to make the flow quasi-two-dimensional. They showed that a pair of counter-rotating vortices were generated at the fan tip with a maximum velocity almost four times that of the maximum fan tip velocity. They also showed that the velocity fields off-centre were considerably weaker than those in the centre, they attributed this to a three dimensional flow field resulting from the fluid interaction with the no-slip boundary condition at the confining planes. They postulated that this fluid interaction contributed to a breakdown in the vortex formation from the fan tip in these areas.

To gain further insight, Choi et al. [3] employed the experiments of Kim et al. [2] to validate a 2D numerical simulation of a piezoelectric fan. They numerically investigated the fluidic mechanism generating the vortices observed in experiments. They reported that there were four distinct vortex formation stages induced by the oscillation of the fan blade: initiation, development, separation, and propagation. A vortex is initiated when the fan blade begins to move causing high and low pressure zones on either side of the blade. The air surrounding the fan blade travels from the high pressure zone over the fan tip to the low pressure zone thus initiating a vortex. As the fan blade continues to advance, more air travels from the high pressure zone to the low pressure zone, thus developing the vortex. This vortex continues to develop until the fan blade reaches its maximum deflection and thus zero velocity. As the fan begins to accelerate in the opposite direction, another counter-rotating vortex is initiated causing the original vortex to separate away from the fan blade. As this secondary vortex develops it causes the primary vortex to propagate downstream. The two dimensional fluid flow analysis presented by Choi et al. [3] shows the basic fluid mechanics of an oscillating piezoelectric fan at its centre and does not account for strong out of plane vortex formation.

Kim et al. [4] performed Continuous Wavelet Transform and Proper Orthogonal Decomposition on a piezoelectric fan’s flow field to reveal data hidden by phase-averaging. They analysed the size, strength and distribution of the vortices generated by a fan confined along its lateral edges. They found from their instantaneous results that the size of all the vortices at each phase angle had a similar velocity magnitude, however, the location of the vortex cores were scattered suggesting a somewhat irregular motion of the vortex structures once they separate from the blade tip. This further supports the opinion that the fluid mechanics surrounding a piezoelectric fan are very complex and difficult to predict.

To date the literature has predominantly reported on confined fans restricted by a number of confinement plates in an attempt to simplify the fan’s flow structures. However, there is a gap in the literature reporting on the fluid mechanics resulting from an unconfined fan in free space. For this reason it is important to understand how an unconfined fan generates air flow. This paper aims to help fill this gap in the literature by assessing the fluid mechanics of an unconfined fan. A custom measurement facility was built to non-intrusively measure the fluid mechanics of the fan using PIV. The flow field measurements obtained with the PIV system are used to explain how the oscillating fan interacts with the surrounding fluid.

2. Experimentation

This paper primarily examines the aerodynamic effects of a piezoelectric fan operating in its first mode of oscillation. In order to achieve this objective, a rigorous regime of PIV measurements were carried out at different planes to obtain a phase averaged 3D flow field in a volume surrounding the fan. The complete apparatus used in this work is discussed in greater detail by Jeffers et al. [5], nevertheless this section discusses the experimental apparatus and details
Figure 1. A schematic of the piezoelectric fan used in this investigation.

pertaining to this study.

Figure 1 illustrates the piezoelectric fan used in this investigation. The device is adapted from a commercially available fan in order to aid with PIV measurements. The opaque mylar blade was replaced with a transparent 300µm acetate blade to allow the PIV laser to pass through unobstructed. The new blade was thicker, stiffer and 6mm shorter resulting in a shift in the first harmonic from 60Hz to 92.5Hz in light of the observations of Kimber and Garimella [6] who found that elevated frequency had a greater influence on heat transfer rates compared to fan tip amplitude. Additionally the peak fan tip deflection amplitude was reduced from 25mm to 16.5mm. The power consumption of the modified fan was 100mW which is 70mW higher than the unmodified fan. The fan is driven with a 110V (rms) sine wave produced by a TTi TG1000 function generator and a linear amplifier model. The fan was fixed to a three-axis stage to allow precise positioning.

The PIV measurement apparatus used in this study is the same as that used by Jeffers et al. [5] apart from the TSI PowerView Plus 4MP PIV Camera used in this work. The camera and the laser were on two traversing stages mechanically held perpendicular to each other, allowing precise placement of the camera and laser in the x, y and z directions.

To obtain the 3D flow field surrounding the oscillating fan, measurements were acquired in two perpendicular planes as illustrated in figure 2. In configuration A, the laser is positioned perpendicular to the fan and the PIV camera records images in the x – y plane. Measurements were taken at 5mm increments from 5mm beyond the blade tip towards the blade root. Configuration B positions the laser parallel to the fan’s major axis and the PIV camera records images in the x – z plane. The five planes taken were located 3mm below and above the long side of the fan, one at each of the fan’s edges and one in the centre of the fan.

The periodic sine wave used to drive the fan facilitates the use of phase locked PIV measurements. Here, PIV images are acquired at precise times, synchronised with the blade’s deflection. For the present measurements, a total of 11 positions along a half period of the fan’s input signal were acquired as illustrated in figure 3. By assuming symmetry, half of a fan’s oscillation is sufficient to describe the flow fields for a full oscillation. In the uppermost plot of figure 3, open circles show the measured fan deflection at equally spaced phases of the fans oscillation while closed circles represent those positions plotted herein. For the present data the
Figure 2. PIV measurement plane configurations. Configuration A comprises measurements spaced at 5mm increments in $x - y$ planes from 5mm in front of the fan toward the root. Configuration B comprises measurements in the $x - z$ plane corresponding to 3mm above and below the fan geometry and at the extrema and centreline of the fan.

Figure 3. Illustration of the phase locked measurements. (top) Measured fan tip deflection and the driving sine wave, the closed circles represent the data presented herein; (bottom) deflection of the fan for a half period.
fan moves from right to left, i.e. from \( \pi/2 \) to \(-\pi/2\). At these extrema the fan has zero tip velocity accelerating to its peak velocity at the midpoint and back to zero again.

The PIV test procedure used to produce the results in this paper was the same as that used by Jeffers et al. [5]. 300 image pairs were acquired at each phase and spatial position ensuring that the ensemble averages of velocity magnitude and vorticity had sufficiently converged towards a representative time-average. A full-field analysis, as described by Stafford et al. [7], was conducted on the flow fields generated by this piezoelectric fan. As the sampling rate constitutes random sampling of unique flow structures, standard error estimates were used to determine the uncertainty in the ensemble average velocity magnitude compared to a time-average flow field. The current sample size results in an uncertainty in the full-field first order data of less than 6.5%. Therefore, the velocity data presented in this paper sufficiently represents the time-average flow fields.

Choi et al. [3] utilised vorticity, \( \omega = \nabla \times \mathbf{v} \), to identify vortices in their data. This is a common and simple technique to identify vortices in flow fields in the literature. However it is also susceptible to error in the presence of strong shear and can vary significantly in magnitude along the length of a vortex in 3D flow fields hindering structure identification.

Jeong and Hussain [8] proposed a technique for vortex structure identification, commonly referred to as the \( \lambda_2 \) criterion, as a good estimate to capture circulation in a vortex core. Here the velocity gradient tensor \( \nabla \mathbf{u} \) is split into symmetric and anti symmetric parts corresponding to the strain rate tensor \( \mathbf{S} = \frac{1}{2}(\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \) and the rotation tensor \( \mathbf{\Omega} = \frac{1}{2}(\nabla \mathbf{u} - (\nabla \mathbf{u})^T) \) so that \( \lambda_2 \) is the second eigenvalue of \( \mathbf{S}^2 + \mathbf{\Omega}^2 \). Selecting a negative value of \( \lambda_2 \) and computing an isosurface can reveal the vortical structure of a flow field. Both identification methods will be used herein.

In order to compute \( \lambda_2 \) for the 2D PIV measurements the data were interpolated into a 3D field using linear interpolation owing to the high spatial density of velocity vectors. This made available the phase averaged velocity gradient tensor and thus \( \lambda_2 \) for each phase measured.

3. Results and Discussion

This section presents and discusses the fluid mechanics of a piezoelectric fan in free space. Figure 4 shows the phase averaged flow field contoured with vorticity normal to the measurement plane surrounding the fan. Two views of the fan blade’s deflection are shown: the front view which is taken 5mm from the fan tip in the \( x - y \) plane; and the top view that is taken in the centre of the fan in the \( x - z \) plane. The dashed line in each subplot indicates the intersection of these two measurement planes. At \( \pi/2 \) the fan velocity is zero. As the fan accelerates to \( 3\pi/11 \) the front view shows two vortices are formed on the top and bottom of the trailing side of the fan blade. The simulations of Choi et al. [3] have shown that the formation of these vortices is caused by the fan blade generating positive pressure on its leading surface and a negative pressure on its trailing surface. This pressure differential and the shear with the ambient is what drives the vortex formation at both top and bottom of the fan blade.

Simultaneously the top view shows that a vortex rolls up over the fan tip while the fan is accelerating, resulting in a vortex detached via a shear layer. This comma shaped structure appears to result from the vortex separating from the rapidly accelerating fan tip. This is analogous to vortex shedding over a bluff body. As the piezoelectric fan is effectively a flapping cantilever, it has zero displacement at one end (the fixed end) and maximum displacement at the other (the free end). Therefore the rate of acceleration, and therefore velocity, increases from the fixed to free end. As a result of this, it is expected that the flow behaviour will change with distance along the fan blade from root to tip (consider how the flow over a bluff body changes as the Reynolds number increases). The measurements in the \( x - y \) plane are located 5mm before the blade tip, therefore the local blade velocity at this position is lower than the blade tip velocity. The results show that vortices in close proximity to the fan are entrained behind the blade as it moves through a half oscillation and they resist detachment. However, in the \( x - z \)
Figure 4. Phase locked PIV measurements for the vorticity of an unconfined fan in free space corresponding to the filled circles in figure 3. The left column shows measurements in the $x-y$ plane while the right column shows measurements in the $x-z$ plane. The dashed lines show the intersection of the $x-y$ and $x-z$ planes.
plane, the vortex formed behind the blade is shed due to the higher velocity and thus remains in approximately the same $x - z$ location ($x \approx 37\text{mm}$, $z \approx 20\text{mm}$). This is to be expected from observation of the flow over bluff bodies; as the Reynolds number increases, vortices form behind the body that eventually begin to detach and shed downstream. This behaviour is similar to the observations of Kim et al. [4] and Choi et al. [3] for confined fans, however their results only consider a two dimensional $x - z$ plane.

The influence of the top and bottom vortices on this unconfined configuration can be better understood by looking at the 3D flow field, in particular isosurfaces of $\lambda_2$, as shown in figure 5. As discussed in section 2, the $\lambda_2$ criterion is used to visualise the vortical structures in the phase locked data. The colours plotted in figure 5 represent distance from the blade root in the positive $z$ direction. Four phases are shown in figure 5 between $3\pi/11$ and $-\pi/2$ as the fan moves from right to left ($\pi/2$ is omitted for clarity). As the fan accelerates from zero velocity to $-3\pi/11$, a horse shoe type vortex is formed from both sets of vortices previously described and illustrated in figure 4. Figure 5 illustrates that for all phases, sections of the vortex remain close to the fixed end of the blade, these are coloured blue in the figure. Moving along the length of the fan in the $z$ direction, towards the blade tip, the vortex core increasingly lags behind the blade throughout its motion.

Beyond the tip of the fan, as it moves through zero deflection (0 to $-3\pi/11$), the vortex structure is observed to pull away from the blade more aggressively than along the blade edges. This region corresponds to the detached vortex and shear layer observed on the right side of
figure 4 and appears to result from an inertial resistance to entrainment behind the retreating blade. As the fan decelerates to its point of maximum deflection (from $-3\pi/11$ to $-\pi/2$), the source of this inertia becomes apparent. The fluid behind the blade has momentum from the acceleration phase and as a result it is deflected towards the fan tip by the slower moving, decelerating fan. This results in an ejection of fluid outwards form the blade tip. The direction of this fluid is at about twice the deflection angle of the blade tip measured relative to the $z$-axis. The competing entrainment of the retreating blade and the inertia of this ejection drive the development of the strong tip vortex.

At $-\pi/2$ the fan is at maximum deflection, the vortex structure indicated by the $\lambda_2$ isosurface in figure 5, appears to be split in half at the tip. Unlike the measurements of Kim et al. [2] and the simulations of Choi et al. [3] where a train of counter-rotating vortices are ejected from the tip of the fan, the upper and lower edge vortices appear to twist the tip vortex in line with their rotation. This can also be inferred in figure 4 as the vortex appears to suddenly vanish from the $\omega_y$ colormap at $-\pi/2$.

4. Conclusions

This paper presents the fluid mechanics of a piezoelectric fan operating in its first vibration mode. Phase locked PIV flow visualisation measurements for one half oscillation of the fan are presented. Using this data, three dimensional $\lambda_2$ isosurfaces were constructed from interpolated PIV data. These results showed a horse shoe type vortex initially forming around the unconfined fan blade as it accelerates from zero velocity at maximum deflection. As the fan blade advances beyond $-3\pi/11$ the horse shoe vortex begins to separate from the tip of the fan and a hairpin vortex is formed.

The segment of the vortex structure entrained along the upper and lower edges of the fan blade appears to remain attached to the fan blade unlike the region at the tip. This attachment is due to the strong coherence of the structure extending from the fan root along its length. The momentum of the flow resulting from the observed region of strong angular flow is enough to cause a strong rollup of the flow that resists entrainment to the retreating fan blade. This has the effect of peeling the edge vortices away from the blade with increasing $z$ position. When the fan blade completes one half period of oscillation, the vortex structure ruptures and the two separated halves become aligned with the edge vortices expelling fluid outwards in the process.

The experimental results presented in this paper have provided new insights into the flow physics of piezoelectric fans. However, assessing the influence of fan geometry, confinement, frequency, and displacement is necessary to determine the best piezoelectric fan configuration.

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References

[1] M. Toda and S. Osaka, “Vibrational fan using the piezoelectric polymer pvf2,” Proceedings of the IEEE, vol. 67, no. 8, pp. 1171–1173, Aug 1979.

[2] Y. H. Kim, S. Wereley, and C. H. Chun, “Phase-resolved flow field produced by a vibrating cantilever plate between two endplates,” Physics of Fluids, vol. 16, no. 1, pp. 145–162, Jan 2004.

[3] M. Choi, C. Cierpka, and Y.-H. Kim, “Vortex formation by a vibrating cantilever,” Journal of Fluids and Structures, vol. 31, no. 0, pp. 67 – 78, 2012.
[4] Y. H. Kim, C. H. Chun, and S. Wereley, “Flow field around a vibrating cantilever: coherent structure eduction by continuous wavelet transform and proper orthogonal decomposition,” *Journal of Fluid Mechanics*, vol. 669, pp. 584–606, 2011.

[5] N. Jeffers, J. Stafford, and B. Donnelly, “Heat transfer and fluid mechanics from a piezoelectric fan operating in its second resonant frequency mode,” 2014, to be published.

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

[7] J. Stafford, E. Walsh, and V. Egan, “A statistical analysis for time-averaged turbulent and fluctuating flow fields using particle image velocimetry,” *Flow Measurement and Instrumentation*, vol. 26, pp. 1–9, 2012.

[8] J. Jeong and F. Hussain, “On the identification of a vortex,” *Journal of Fluid Mechanics*, vol. 285, pp. 69–94, 1995.