Journal of Fluids and Structures 70 (2017) 450–463

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Visualization of three-dimensional structures shed by an oscillating beam

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A R T I C L E I N F O

Keywords:
Vortical structures
Flow visualization
Piezoelectric beam
Particle image velocimetry
Computational fluid dynamics

A B S T R A C T

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 associated with a piezoelectric fan are similar to that for a flapping bird wing, which are known to be complex. This paper is the first to investigate the three-dimensional fluid mechanics of an unconfined fan operating in its first vibration frequency mode. A custom built experimental facility was developed to capture the fan's flow field using two-dimensional phase locked Particle Image Velocimetry (PIV). The fluid-structure interaction was also captured through unique two-way coupled three-dimensional simulations of an oscillating beam in which the beam is actuated by a shear force at its resonant frequency and interacts with the surrounding air. This forgoes the need for temporal beam displacement data from experiments as in previous studies, allowing the numerical technique to be used independently. A finite element method is used for the simulations which allows the two-way coupling while maintaining computational efficiency. A three dimensional λ_2 criterion constructed from interpolated PIV measurements as well as numerical data was used to identify a horse shoe vortex in the vicinity of the fan and its evolution into a hairpin vortex before it breaks up due to a combination of vortex shedding and flow along the fan blade. The experimental and numerical data are comparatively in agreement, confirming that the methods presented are valid for capturing the complex flow fields generated by this fluid-structure interaction. The results provide both a fundamental understanding on the formation and break-up of vortices from an oscillating beam, and demonstrate a validated approach which can be applied in the development of high efficiency piezoelectrically driven air moving devices and extended to the study of flapping bird and UAV wings.

1. Introduction

Piezoelectric cooling devices are seen as a promising air moving technology that bridge the gap between natural convection heat sinks and conventional rotating fan forced convection heat sinks. The main advantages of piezoelectric fans are high reliability, low power consumption and minimal noise generation (Açikalin et al., 2007). 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 oscillating system comprised of the cantilever beam immersed in the ambient fluid. This oscillating motion induces an air flow that can subsequently be used to cool adjacent heated surfaces.

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http://dx.doi.org/10.1016/j.jfluidstructs.2017.02.013
Received 25 August 2016; Received in revised form 27 January 2017; Accepted 28 February 2017
0889-9746/

Different configurations of piezoelectric fans have been studied since Toda and Osaka (1979) 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 computational data for confined piezoelectric fans. These studies mimic the confinement expected in current real-world applications of such fans.

Kim et al. (2004) studied a confined piezoelectric fan using phase-resolved Particle Image Velocimetry (PIV) and smoke visualization 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. (2012) employed the experiments of Kim et al. (2004) 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* down stream. The two dimensional fluid flow analysis presented by Choi et al. (2012) 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. (2011) 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 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.

The importance of understanding the aerodynamics of the flow structures in an unconfined configuration can be understood from studies on bird wings. Experimental (Lua et al., 2015) and computational (Ramamurti and Sandberg, 2007) studies while investigating the aerodynamics of flapping wing creatures and have found that negligible changes in parameters such as flapping speed and frequency result in vastly different flight. This implies that there is vast potential for the use of piezoelectric fans in electronics cooling, with the possibility of changes in flow through variation of the oscillation parameters. To date the literature on piezoelectric fans has predominantly reported on confined fans restricted by a number of confinement plates. While such fans are likely to be deployed in a confined space, knowledge of their full potential in an unconfined environment would drive research towards innovative recovery of the performance lost due to confinement. There is therefore a gap in the literature which needs to be addressed given the complex aerodynamics that exist, and which have evidently been shown to have a significant role in other areas of research including bird and insect flight.

This paper aims to understand the fluid mechanics of an unconfined oscillating fan through the analysis of the three-dimensional flow structures surrounding the fan. A custom measurement facility was built to non-intrusively measure the fluid mechanics of the fan using PIV. The three-dimensional flow field measurements obtained with the PIV system are used to explain how the oscillating fan interacts with the surrounding fluid. Further, three-dimensional simulations of an oscillating beam in air are performed using a unique technique to reduce computational complexity, the results of which were compared to the experimental data for validation. The comparison sets up the numerical technique presented to be used independently as a reliable method of assessing the performance of oscillating beams as cooling devices.

2. Experimental and simulation setup

This paper primarily examines the aerodynamic effects of a piezoelectric fan operating in its first mode of oscillation. The general solution for oscillation frequency of a freely vibrating cantilever beam can be obtained from to Euler-Bernoulli beam theory. A cantilever beam is said to be in its first mode of operation when it oscillates at the first natural frequency obtained from the solution. 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. Kim et al. (2011) state that phase-averaging results in an underestimation of the peak velocity and vorticity field as the vortex core shifts in each cycle. The flow structures shed from the oscillating beam are however similar during each oscillating cycle which justifies this approach for the current study in which the aim is to visualise the 3-D structures. The complete apparatus used in this work is discussed in greater detail by Jeffers et al. (2014), nevertheless this section discusses the experimental apparatus and details pertaining to this study. Three-dimensional simulations were then performed of a comparable setup and validated using the experimental results. The numerical method used is described in the following section.