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# A review of piezoelectric fans for low energy cooling of power electronics

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## HIGHLIGHTS

- The need for low energy thermal management solutions is introduced.
- Piezoelectric fan design, operation and optimisation processes are analysed.
- Existing limitations in the development process are outlined.
- Methods to widen the field of piezoelectric fan applications are considered.

## ARTICLE INFO

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## ABSTRACT

Power consumption from electrical devices increases year upon year, and as a result thermal management of power electronics is becoming ever more relevant. This review summarises the advancements made in the piezoelectric fan optimisation since their invention in the late 1970s. Energy consumption is highly relevant, and is an underlying theme throughout. Emphasis is placed on the methods undertaken to optimise designs for many different applications, and critical analysis of these processes is included. Comparison of data taken from different studies highlights the well-established rules of piezoelectric fan design and, more importantly for future advancements, also identifies the aspects of design which are not fully understood. Numerical modelling has become an essential tool for piezoelectric fan design optimisation since 2010, and the large majority of publications since have included computational methods to some degree. The optimisation of a single piezoelectric fan for a hot spot cooling application is well understood and, whilst always fundamental to the research field, does not pose the greatest potential for development in real life applications, as a single piezoelectric fan cannot replace a cooling system of any great size. Rather, the development of multiple fan arrays, which could ultimately replace alternative power electronic thermal management systems, should be strongly considered in the coming years.

## 1. Introduction

The cooling requirements of electronic systems call for new cooling technologies with low power consumption. Unlike traditional convection fans, piezoelectric (PE) fans are ultra-low power air movers, made up of a fan blade, a lead zirconate titanate (PZT) actuator and a clamp. In operation, a small amount of geometric expansion and contraction is generated in the actuator by an alternating electrical current. The actuator induces resonance in the blade, and the high oscillation amplitude and frequency disturbs the surrounding air sufficiently for vortex formation and to create significant downstream wind velocities. The basis of research in the field, therefore, is the optimisation of all aspects of a piezoelectric fan design to create maximum turbulence and vorticity, in the case of near field hot spot cooling, or maximum directional flow rate, in the case of bulk airflow generation.

PE fans were first considered at the end of the 1970s. Toda's publication [1] marks the beginning of PE fan development in the academic domain, whilst Kolm and Kolm were the first to patent a PE fan device, through *Piezo Electric Products Inc.* in 1985 [2]. Interest and research was driven by the need for a small, low power cooling device for use in electronic equipment, as other components shrank and assemblies became more compact. The original works are still very relevant, showing the field has undergone a process of continual optimisation, rather than a complete overhaul. This is testament to the quality of the original design.

Maaspuro published a review of the field in 2016 [3], which reported, in particular, on the design and construction of PE fans. These topics are covered, but this review will focus specifically on the potential for a reduction in the energy demanded by thermal management systems across the entire spectrum of power electronics. A thorough

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**Nomenclature**

| | |
|---|---|
| $A$ | amplitude, m |
| $A_{XC}$ | PE fan blade cross-sectional area, $m^2$ |
| $D_c$ | driving coefficient [dimensionless] |
| $E$ | Young's modulus, $N\,m^{-2}$ |
| $f$ | frequency, Hz |
| $f_r$ | resonant frequency, Hz |
| $g$ | side wall gap, m |
| $G$ | empirical factor for plate bending theory [dimensionless] |
| $I$ | second moment of area, $m^4$ |
| $K_{mag}$ | PE fan array apparent stiffness, $m^{-3}$ |
| $L$ | PE fan length, m |
| $L_{FIN}$ | heat sink fin length, m |
| $L_{PZT}$ | PE actuator length, m |
| $m$ | PE fan blade mass, kg |
| $N$ | number of PE fan blades in an array [dimensionless] |
| $P$ | pitch between PE fans, m |
| $S$ | length of heated surface, m |
| $t$ | time, s |
| $t_{BL}$ | PE fan blade thickness, m |
| $W$ | PE fan blade width, m |
| $W_{PZT}$ | PE actuator width, m |
| $x$ | PE fan coverage of heated surface, m |
| $y$ | PE fan blade displacement, m |
| $Y$ | PE fan blade displacement at maximum amplitude, m |
| $\beta$ | PE fan blade characteristic coefficient, $(kg\,N^{-1}\,m^{-3}\,s^{-1})^{0.25}$ |
| $\delta$ | blade tip to heat source separation distance, m |
| $\varepsilon$ | blade tip extension beyond side wall, m |
| $\rho$ | density, $kg\,m^{-3}$ |
| $\sigma$ | Poisson's ratio [dimensionless] |

technical understanding is required to optimise PE fans, and the methods undertaken by researchers in the field to achieve this are analysed in detail.

It is evident that the demand for power electronics has outgrown advances in thermal management systems in the last 30 years [4,5]. In regard to energy consumption, the critical point has been reached where rapid innovation of air-moving technology is essential to avoid a slowing in the development and optimisation of power electronics. This is firstly due to the expansion of the industry sector: the worldwide electrical energy consumption increased threefold between 2000 and 2010 [6,7], and has continued to increase at the same rate since [8]. In certain technological fields, one third of this energy is being put towards cooling [9].

PE fans are very relevant for innovation in the immediate future, because of the complexity and economic cost of the current energy management solutions that implements liquid cooling or heat dissipation through phase change materials [5,10,11]. As a result, this technology is not widely implemented across a range of large industry areas, where air-cooling is heavily relied upon. For example, air-cooling is still used in 95% of computer technology worldwide [12]. Airflow is very often generated by axial fans which, amongst the other drawbacks considered in Section 6, demand a great deal of energy [13,14]. At present, the PE fan is a viable alternative for certain applications involving moderate heat flux components [12], where they are easy to retrofit and provide comparable cooling capabilities for 50% of the power demand [15–17]. The challenge faced is the development of the technology to widen the field of possible applications, and this is a key theme throughout the review. There is great potential to dramatically reduce the worldwide energy consumption of thermal management systems with intelligent innovation in this field.

The demand for alternative air-moving technology has sparked an increase in published literature concerning PE fans in the last decade, and the considerable advancements in computational and numerical modelling over the same period has allowed researchers to understand the field in far more details than previously possible. This review will summarise such advancements and also expand on the areas which must still be investigated. The ratio of power consumed to heat transfer generated is an underlying theme throughout the review, as this will ultimately govern the degree of PE fan implementation in electrical components in the coming years.

A single, simple PE fan can be seen as a clamped cantilever beam of uniform width, $W$, and thickness, $t$, being driven, typically from a power source of 1–10 mW, to oscillate at a certain frequency. The PE fan actuator is a strip of lead zirconate titanate (PZT). The blade is driven from the clamped end, and the strip most often covers its entire width. A typical PE actuator is 24–35 mm in length, covering 35–50% of the fan blade. The phenomenon of resonance is essential to the driving of a PE fan blade. The blade's fundamental resonant frequency, $f_r$, which is discussed in Section 3.1, must be matched by the AC power supplied to the actuator, in order to incite resonance in the blade. The result is an oscillation amplitude that can be thousands of times greater than the actual expansion and contraction induced in the actuator. Blades, typically, are 50–100 mm in length, and oscillate at 50–100 Hz to an amplitude of 1–15 mm.

In Section 2, the fundamental aspects of a single PE fan blade are set out. PE fan operational and geometric characteristics, and the results of blade confinement are covered in Section 3. The use of multiple blades is considered in Section 4, along with specific novel designs. In Section 5, the implementation and validation of numerical models is discussed. Finally, Section 6 discusses the potential energy saving benefits of PE fan technology in specific applications, and the competition to the technology in the present day.

## 2. Piezoelectric fan oscillation

It is essential to understand the fundamentals of piezoelectric fan design: variable parameters, blade motion characteristics and airflow generation. These principles are fundamental to the research field and will drive innovation. Fig. 1 outlines the geometric and operational parameters of a single PE fan (Section 3) and a PE fan array (Section 4).

The mode shape of a PE fan, as it deflects, is theoretically defined by Eq. (1) [18], where $Y$ is the amplitude of deflection at any distance, $x$, along a beam of length $L$. $A_{XC}$, the cross-sectional area of the blade. The coefficient $\beta$ is defined in Eq. (2) [18], where $m$,$I$ and $f_r$ are the mass, second moment of area and first resonant frequency of the blade, and $E$ is the blade material's Young's modulus. In reality, the PZT actuator affects the blade shape, limiting the deflection in this region. Empirical functions have been defined in the literature to better describe $Y$, which are used in numerical models and discussed in Section 5.1.

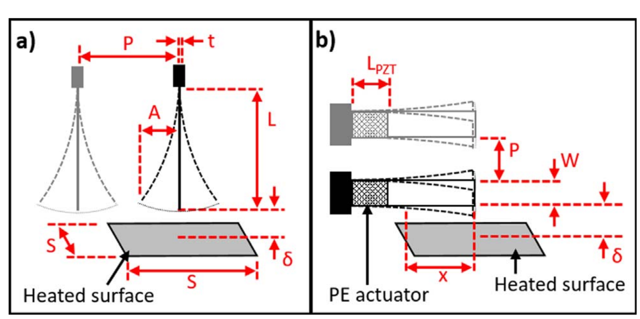


**Fig. 1.** PE fan parameters and characteristics for (a) face-to-face and (b) edge-to-edge orientation.