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Review paper

# Piezoelectric oscillating cantilever fan for thermal management of electronics and LEDs — A review

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ABSTRACT

This review discusses piezoelectric fans and their feasibility in a cooling of electronics components and LEDs. The discussion will be restricted to fans based on an oscillating cantilever, the construction which is best known. Other possible piezoelectric fan constructions will be just shortly mentioned. Since the invention of a piezoelectric fan in late 1970s, at least hundreds of science papers have been published about them. A general level presentation of the subject and a summary of the research outcomes will be presented. The construction and operation principles of a piezoelectric fan will be presented. An introduction to piezoelectric materials will be given. The most important equations covering the oscillation of a cantilever beam and the equations for designing fan's geometry will be presented. The generated air flows of a single piezoelectric fan will be issued. This subject will be approached by executing some computational fluid dynamics (CFD) simulations. Use of an air nozzle can force the air vortices closer to laminar flow and improve the cooling effect. The rather weak air flow of a single fan motivates to use multiple fans. A large number of studies have been published about multiple fan constructions. A piezoelectric fan will be compared with a conventional radial fan. An introduction to the electrical parts of a piezoelectric fan will be given. An experimental work demonstrating the use of a piezo fan for electronics cooling will be executed.



**Contents**



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## 1. Introduction

A piezoelectric fan and its use for cooling electronics components have been known since the end of 1970s. Integration of electronics and increasing density of electronics packaging requires new solutions for cooling. Passive or active cooling is usually needed for processors, display drivers and many power electronics components. LED lighting is a new application area which grows fast. In order to maintain high light generation and long lifetime proper temperature management of individual LEDs or LED multichip modules must be arranged. Passive cooling is a common solution. This usually means using a heatsink. Heatpipe is a passive cooling method which nowadays is rather often used. If passive cooling is not efficient enough, active cooling methods must be used. Even nowadays, the most common active cooling arrangement is still the combination of a heatsink and a radial fan. The lifetime of a good quality radial fan is typically around 20,000 h. This is still much too short in comparison with the lifetime of high reliability electronics devices or typical LEDs. For many applications the power consumption of a fan is also much too high. In order to meet the requirements of a long lifetime, high cooling capability and efficiency, novel active cooling methods must be implemented. The piezoelectric fan, which features low power consumption, high reliability and long lifetime, low cost and low noise, can fit well in those requirements. All of these characteristics of a piezoelectric fan match well with present day LED technology. For these reasons piezoelectric fans are gaining more acceptance especially in LED lighting applications.

A piezoelectric fan (Fig. 1) which is based on a piezoelectric material patch and an oscillating cantilever attached to it. In literature different names are used for the cantilever. When speaking about fans, it is called either a blade, a shim or a beam. In this paper word beam will be used exclusively. The special characteristic of a piezoelectric material is that it is bending when an electric field is applied over it. The bending is caused by the expansion of the surface and contraction of the opposite surface. Although the used electric field is rather strong, bending is measured only in some micrometers. The bending itself cannot generate a significant air flow. A thin beam made of flexible material will be attached to the piezoelectric patch. This construction can be made oscillating if external energy is delivered into it. The structure will start to oscillate at its specific resonance frequency. There are numerous resonances, but the first fundamental resonance frequency is the best for fan operation. Beam oscillation with significant amplitude takes place just at the resonance. The oscillation attenuates quickly if the frequency of the external drive is even slightly shifted away. In the oscillation, electrical energy will be transformed to a mechanical energy which move the beam and at the resonance conditions this actualizes with the maximum efficiency. Typically a piezoelectric fan will be made to operate at low frequencies between 20 and 100 Hz or even below 20 Hz which is the practical limit of an audible sound. While operating, a piezoelectric fan is very silent or even non-audible. Sinusoidal waveform is the most often used for driving a fan as it results in the best efficiency.

A fan produces rotating air flows on both sides of the beam and the fan tip produces jet-like air stream which propagates ahead. All these air flows can be used for cooling. Considering the heat transfer capability all these flows provide the same magnitude of cooling enhancement [1]. Depending on the used air flow, there are two choices for the configuration. Either the beam locates above the plate to be cooled or the beam locates in front of the plate. In both cases, the beam can be either vertically or horizontally oriented. In case the beam locates above the plate, it can extend over the plate partly or entirely. Whatever arrangement is used, efficient cooling effect is possible only if the distance between the beam and the plate is no more than a few millimeters. Fig. 3 shows the typical fan orientations. In some cases cooling effect can be improved by a well-designed air nozzle. The most efficient solution might result when a fan is partly or totally integrated inside a heatsink (Fig. 2).

## 2. Early history of a piezoelectric fan

The first study about piezoelectric fans for electronics cooling was published by Minoru Toda and Susumu Osaka in 1978. The followed

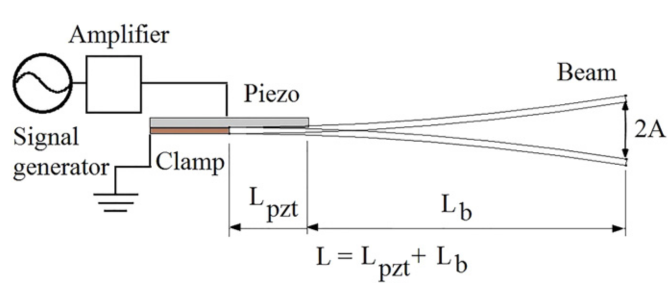


**Fig. 1.** Piezoelectric (unimorph) fan and its operation on the fundamental resonance frequency.

### Nomenclature

| | |
|---|---|
| $A$ | oscillation amplitude [m] |
| $A_n$ | amplitude of the nth natural frequency [m] |
| $D$ | piezoelectric fan width [m] |
| $E$ | Young's modulus [N m$^{-2}$] |
| $F$ | force [N] |
| $f_{osc}$ | resonance frequency of piezoelectric fan [Hz] |
| $h$ | convective heat transfer coefficient [W m$^{-2}$ K$^{-1}$] |
| $I$ | moment of inertia [kg m$^2$] |
| $K_{pf}$ | stiffness of cantilever beam |
| $L$ | length of fan [m] |
| $L_b$ | length of cantilever beam [m] |
| $L_p$ | spacing between fans in multifan configuration [m] |
| $L_{pzt}$ | length of piezo element [m] |
| $m$ | mass of cantilever beam [kg] |
| $m_{eff}$ | effective mass of cantilever beam [kg] |
| $n$ | order of natural frequency of vibrating cantilever |
| $P_{elec.}$ | electrical power, consumption [W] |
| $P_{stat.}$ | static pressure [Pa] |
| $Re$ | the Reynolds number |
| $R_{th}$ | thermal resistance [K W$^{-1}$] |
| $R_0$ | thermal resistance in natural convection conditions [K W$^{-1}$] |
| $T_{hs}$ | heatsink temperature [K] |
| $T_{amb}$ | ambient temperature [K] |
| $Q$ | heat flow [W] |
| Greek letters | |
| $\delta$ | distance from fan tip to hot surface [m] |
| $\eta$ | improved thermal performance of cooling system |
| $\rho$ | density [kg m$^{-3}$] |
| $\upsilon$ | kinematic viscosity |
| $\omega$ | angular frequency of oscillation |

papers revealed the basic characteristics and features of piezoelectric fans [2–4]. In [2] they piled up four 7 μm thick layers of piezoelectric material. The material they used was PVF2. The structure was driven by a square wave having ±150 V amplitude. Electrical power consumption was 14 mW and the measured speed of an air flow was 1.4 m/s. They compared the cooling efficiency with the efficiency of a conventional radial fan. The radial fan which was able to produce the same cooling efficiency consumed 95 mW electrical power. M. Toda and S. Osaka studied the theory of a piezoelectric fan and did experimental work. One major finding was that air volume the fan produced was dependent on the width of the beam and its density, but was independent of its length. Another fundamental finding was that energy efficiency of the fan was 50%, which means that half of the mechanical energy moving the beam converts to the energy of the air flows. It is better to mention that piezoelectric actuators (unimorph and bimorph) have been known much before the idea of a piezoelectric fan was presented. The innovation of piezoelectric actuators can be traced back to 1930s (piezoelectric microphone).

## 3. Piezoelectric patch

A piezoelectric fan is based on the use of piezoceramic material. An electric field over such a material causes transformation. It will expand on one side and shrink on the other side. In other words, it is bending. The structure is composed of two parts, the piezoceramic plate and the conducting layer on its side. Thickness of the piezoceramic plate can be from some micrometers to hundreds of micrometers. Thin structures can be piled up on top of each other to form a multilayer structure. Such a structure features larger bending than a single layer. Two kinds of basic structures are the most common in fans, unimorph or bimorph. The unimorph structure has one piezoelectric layer and an elastic beam attached to it. The bimorph structure has two piezoelectric layers and an elastic beam between them. There is also a conducting layer (for an electrode) between the piezoelectric layers [5–7]. The bimorph structure has higher mechanical strength and stiffness. It is often used in fans. In the unimorph structure, a metal electrode is mounted on one side of the piezoelectric material. Voltage is applied over the hole structure. In the bimorph structure the voltage can be applied over the hole structure (series) or voltages can be applied over the surface and the middle layer (parallel). In the latter case, the driving voltage can be reduced to the half for featuring the same bending deflection. Among the ceramic materials, lead zirconate titanate PZT, is the most often used. It is an intermetallic compound having chemical formula $Pb[Zr_xTi_{1-x}O_3]$, where $0 \le x \le 1$. Bending of the hole structure is still measured in micrometers and it cannot generate a significant airflow itself. A fan is created when a larger flexible, typically a rectangular, beam is attached to it.

J.H. Yoo et al. [8–9] have described the sintering process which is used for manufacturing piezoceramic materials like PTZ-5. The raw material is in powder form. It will be pressed 30–90 min with 1 ton/$cm^2$ pressure and in 1300 °C temperature. In this process, the material will be transformed to a ceramic plate having 0.3–0.35 mm thickness. Electrical contacts will be made of silver paste. The paste will be spread over a ceramic plate at 600 °C temperature. In the final phase, the structure will be poled in silicone oil in the presence of a high electric field (3.3 kV/mm).

PZT contains lead, which is environmentally hazardous substance. Material science researchers are interested in lead-free piezoelectric materials. P. Zhang et al. [10] discuss piezoelectric composites, particularly combination of alkaline niobate (KNN) and polymer (PVDF). PVDF is polyvinylidene fluoride which has high mechanical flexibility and good dielectric characteristics. In the composite, these good characteristics are combined to the high piezoelectric coefficient of KNN ceramics.

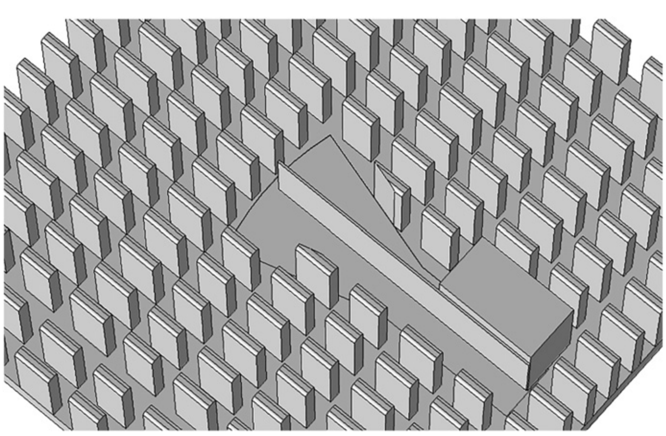

Fig. 2. A piezoelectric fan integrated into a heatsink.

## 4. Beam

### 4.1. Beam materials

Several materials have been used for fan beams. These are plastics like PVC, Mylar and PET, metals like stainless steel, brass, bronze, phosphor bronze, phosphor copper, aluminium and other materials like carbon fiber. The beam should be light and flexible. This is provided by a suiting density and Young's modulus of a material. Plastics which are available as foils suits for this purpose. Metals like stainless steel are heavier, but they can be processed to very thin plates. Finding out the best material and the right thickness for a beam requires a lot of experimental work. Comparison between beams is not a simple task as the resonance frequency changes according to the characteristics of the beam.

M. Kimber et al. [11–13] compared Mylar and stainless steel beams. The fan with Mylar beam was driven with 10–30 mW power at 60 Hz resonance frequency. The fan with a stainless steel beam was driven with 20–45 mW power at 113 Hz resonance frequency. Also the lengths of the beams were different. Because of these differences, the achieved amplitudes will not indicate the best beam material. The right criterion was the achieved air flow ($cm^3/s$). The flow was measured accurately using air pressure metering. The results indicated that there were no clear differences between these materials.

J. H. Yoo et al. [9] studied materials aluminium, brass and phosphor bronze suitability for a beam material. Experimental research indicated that they all suit well. Some differences between these materials were found. Comparison was made according to the achieved air speed. The beam made of brass produced an air speed of 1–1.4 m/s. With the aluminium beam, the speed was almost the same, 1–1.9 m/s. The highest speed 2–2.3 m/s, was measured with the beam made of phosphor bronze. There are no big differences in Young's modulus of these materials. Densities of brass and phosphor bronze are almost the same. Density of aluminium is the smallest. Although aluminium was not best, it is reasonable beam material because of its low price. On their other publication [8], materials like phosphor copper, bronze and aluminium were mentioned. According to them, phosphor copper is the best of these because its density and Young's modulus are the highest.

T. J-C. Liu et al. [7] compared PET plastics with stainless steel. Experimental results confirmed the general rule that a thinner beam features the biggest amplitude and generates the highest air flow. One exception was found. The thinnest beam was not the best. An explanation for this was not provided.

H.K. Ma et al. [14] compared PVC plastics with carbon fiber. They found significant differences between the two materials. The fan with carbon fiber beam featured lower thermal resistance. Reduction of the thermal resistance with the PVC beam was 64% and with the carbon fiber beam 74% compared to case of natural convection. This difference can be understood as Young's modulus of carbon fiber is over 40 times higher than PVC's. Density of carbon fiber is also somewhat higher

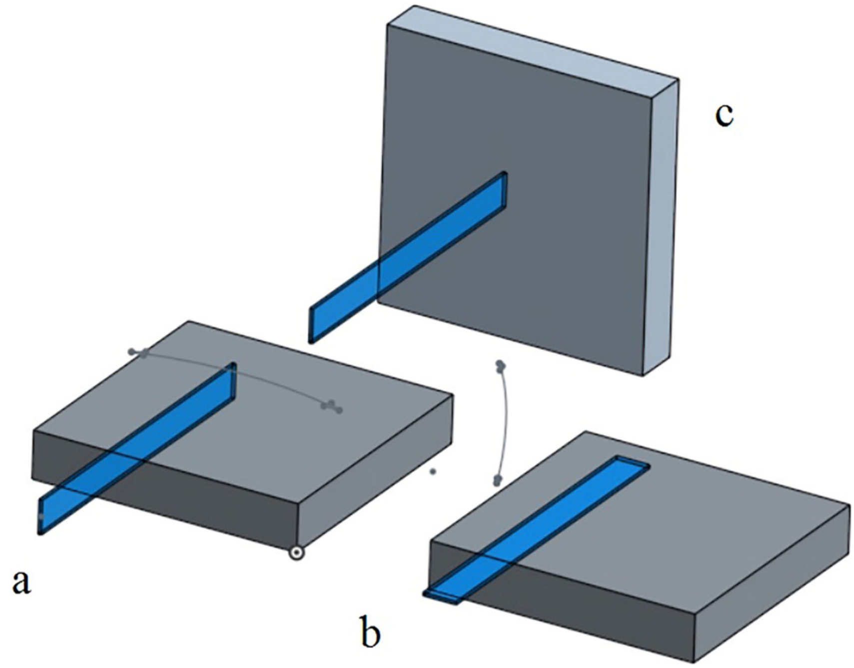


**Fig. 3.** The basic orientations of a piezoelectric fan. Vertical (a), horizontal (b), vertically in front of the surface to be cooled (c).

than PVC's. In their other publications [15] they mentioned phosphor copper and its excellent elastic properties.

*4.2. Beam bonding*

A beam is bonded on a piezoceramic patch normally by using glue. W-J. Sheu et al. [16] have pointed out the importance of the used glue and thickness of the glue layer between the patch and the beam. The layer of the glue has an effect on the piezoceramic stiffness and the structural damping of the vibration system. The authors have approached this subject by theoretical and experimental work. The results of their experiments show that vibration amplitude increases with decreasing the thickness of the glue due to the reduction in stiffness. On the other hand, by choosing a bonding material which has higher Young's modulus will increase the vibration amplitude. They made tests with two glue materials, black epoxy and RTV silica gel. In every case black epoxy was much better due its much higher Young's modulus. Mean time between a failure, MTBF, means the expected time duration until a failure occurs. In many cases it is the same as the expected lifetime of a device. Although the MTBF of a piezoelectric fan is high, beam bonding can be the weakest part of it. According to R.K.B. Schacht et al. [17] wrong bonding material can significantly reduce the MTBF of oscillating cantilever type structures.

*4.3. Material strength and noise*

It is difficult to estimate the MTBF of piezoelectric fans. Obviously this subject has not been studied large enough. It is quite clear that the MTBF will be high if the fan is operating within safety dynamic range. However, some endurance tests have been done. According to K.H. Tseng [18], piezoelectric fans have been set in an accelerated test in 60 °C temperature and 65% humidity while featuring oscillation with 30 mm amplitude at 60 Hz. Tested fans sustained over $10^9$ oscillations. The beam or its fixture can also be damaged by high inertia forces. The forces and strengths in the piezoelectric material are linearly dependent on the driving voltage (electric field).

Noise is generated mainly in the interaction between the beam and air. Some noise is generated in the piezoelectric patch and its fixture. In paper [18] noise generated by a piezo fan was measured. Noise level of 11 W fan, using 3 mm wide beam measured at 10 mm distance, was 24 dBA. Using 5 mm beam the noise was 29 dBA. J. Petroski et al. [19] have also measured noise levels. They managed to keep noise level below 25 dBA while using a piezoelectric fan with 10–20 mW power and frequency below 100 Hz. This level is hardly hearable by human ears. J.H. Yoo [8] made a notice that noise level is dependent on the width of a ceramic patch. In the experimental work, to be presented later in this text, it was found that the fan generated clearly audible rasping sound at high driving voltages. It was considered as an indication for exceeding the safety dynamic range.

## 5. Oscillation of a cantilever beam

*5.1. Oscillation of an uniform cantilever beam*

The structure of a piezoelectric fan is an oscillating cantilever beam which has been fixed on the end. The other end is allowed to move freely. Eq. (1) for the one end fixed and the free oscillating cantilever beam, is based on Bernoulli-Euler theory. The equation can be found numerous text books of mechanics. The transverse displacement is in the y direction and x is the longitudinal dimension of the beam. E · I stands for the flexural rigidity of the beam. E is Young's modulus and I is moment of inertia. This equation is for the case of stable oscillation when the damping factor has been set to zero.

$$\frac{d^2}{dx^2}\left\{EI(x)\frac{d^2y(x)}{dx^2}\right\} = \omega^2 m(x)y(x) \tag{1}$$

For a uniform free oscillating beam, the equation becomes Eq. (2).

$$\frac{d^4y(x)}{dx^4} - \frac{\omega^2 m}{EI}y(x) = 0 \tag{2}$$

The solution of Eq. (2) can be found in many textbooks of mechanics.

$$\begin{aligned} y(x) = {} & A_n(\sin(\beta_n L) - \sinh(\beta_n L)) \\ & \cdot(\sin(\beta_n x) - \sinh(\beta_n x)) \\ & + A_n(\cos(\beta_n L) - \cosh(\beta_n L)) \\ & \cdot(\cos(\beta_n x) - \cosh(\beta_n x)) \end{aligned} \tag{3}$$

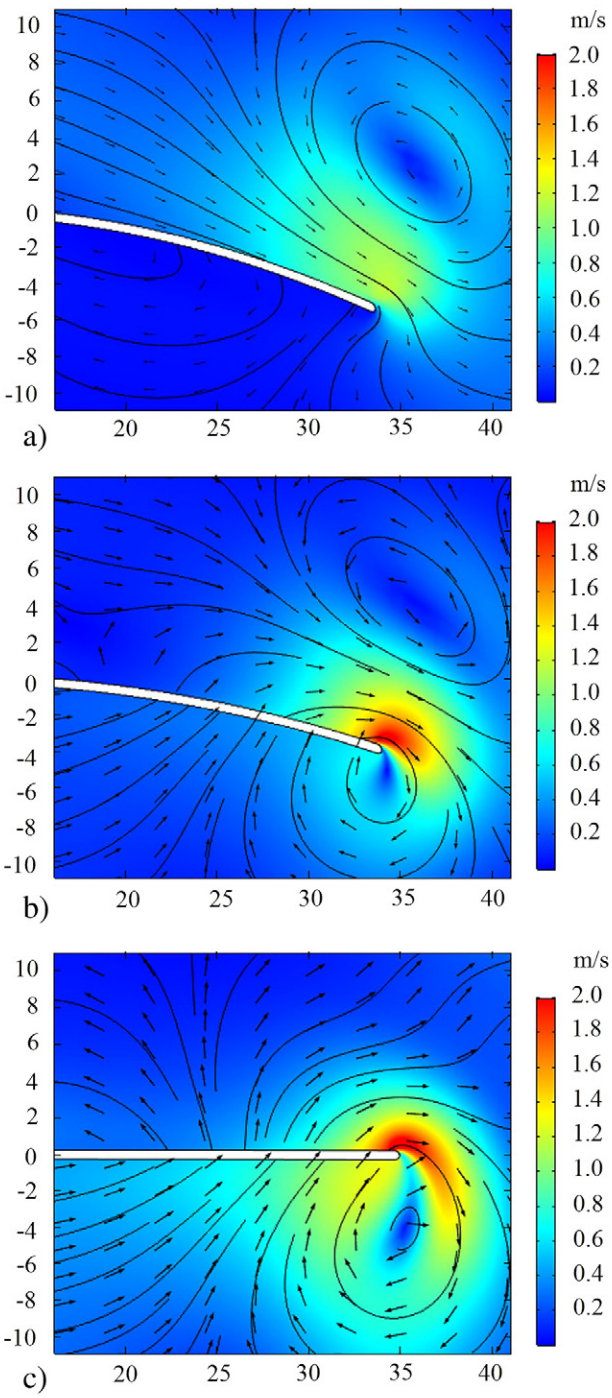


Fig. 4. 2D simulations (CFD) of the fan.

where $\beta_n L = n\pi$ and $A_n$ is the amplitude of nth natural frequency. L is length of the beam.

The oscillation may take place at natural frequencies. They can be calculated using Eq. (4).

$$f_{osc} = \frac{\alpha_n^2}{2\pi}\sqrt{\frac{EI}{mL^4}} = \frac{\alpha_n^2}{2\pi}\sqrt{\frac{K}{m_{eff}}} \tag{4}$$

In Eq. (4) I stands for the moment of inertia of the beam cross-section. In case of a rectangular beam, I can be calculated using Eq. (7) and its dimension is [$m^4$]. Coefficients $\alpha_n$ are unitless. $\alpha_1 = 1.875$ for the first natural frequency. $\alpha_2 = 4.694$, $\alpha_3 = 7.885$ for the second and

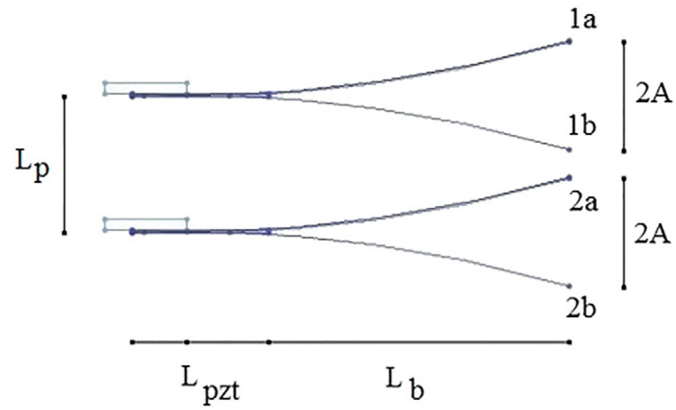


Fig. 5. In-phase and out-of-phase operation of two fans.

third natural frequencies. The first fundamental frequency is usually selected for a fan beam as it creates the largest forward going fluid flow. The alternative presentation of Eq. (4) has stiffness of the beam K and effective mass $m_{eff}$. The effective mass located at the fan tip features the same oscillation characteristics as the fan which has total mass m. Use of effective mass helps to analyze the case where some extra weight has been added on the fan tip.

The solution Eq. (3) for the oscillating cantilever might look rather complicated even in the case $n = 1$ and therefore approximations may be used. Authors of [20–22] have used an approximation Eq. (5) which is valid for the oscillation at the first natural frequency.

$$y(x,t) = A\left(\frac{x}{L}\right)^2 \sin(2\pi f_{osc} t) \tag{5}$$

Amplitude of an oscillating cantilever can be calculated using Eq. (6).

$$A = \frac{FL^3}{3EI} \tag{6}$$

I is the moment of inertia of the beam cross-section and F is the force which keeps on the oscillation. For a beam which has a rectangular shape, the moment of inertia of the beam cross-section can be

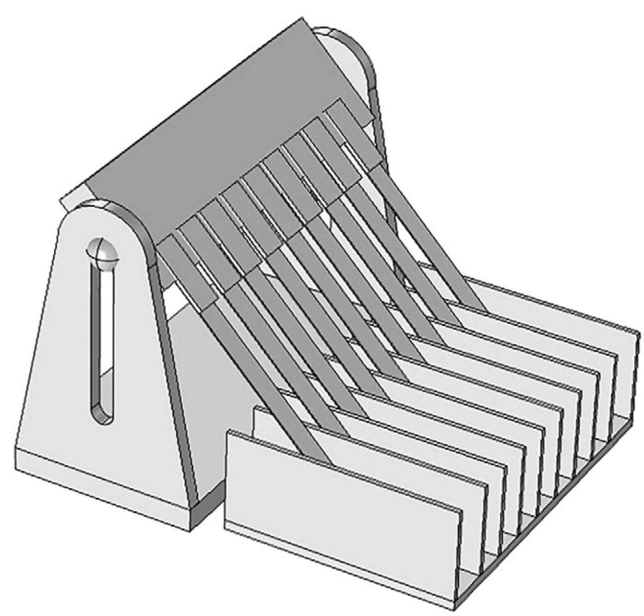

Fig. 6. Multiple piezoelectric fans with beams (horizontally oriented) locate partly between the fins of the heatsink.

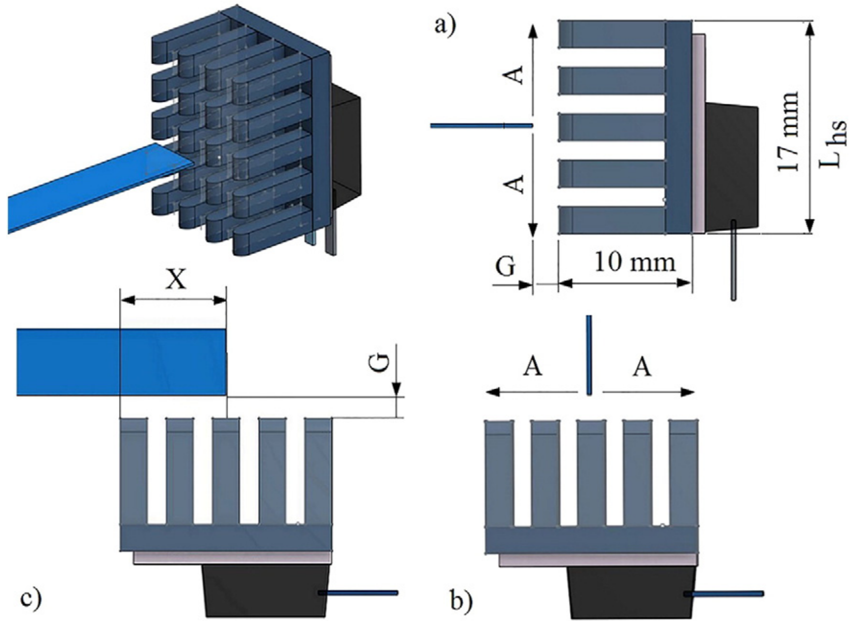


**Fig. 7.** Piezoelectric fan cooling experiment.

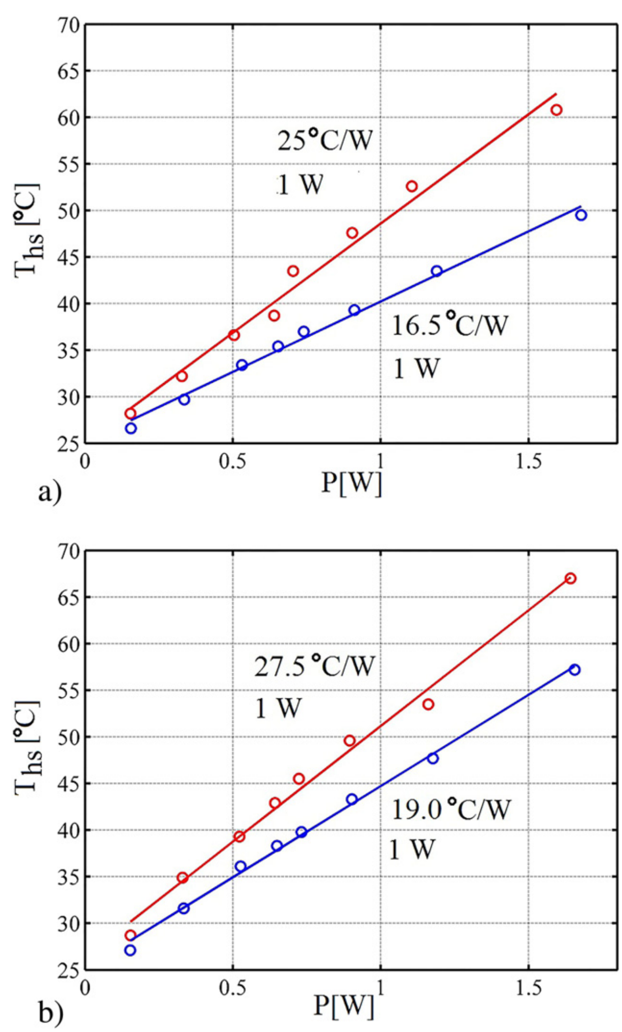


**Fig. 8.** Heatsink temperature (bottom) and the thermal resistance (case to ambient). Natural convection (red) and forced convection (blue). Cases a and b.

calculated using Eq. (7). D is width of piezoelectric fan beam.

$$I = \frac{LD^3}{12} \tag{7}$$

Eqs. (4) and (6) give the basic information to a fan designer. They also show the contradictory effect fan length has. Amplitude A can be increased by increasing fan length L, but this reduces the oscillating frequency and therefore also air speed and volume. In generally there is no clear design procedure to follow while optimizing the fan construction [7].

### 5.2. Oscillation of a piezo element with an attached beam

Eq.(3) is valid for a uniform single element beam which cross-section is constant along the hole length of the beam. Typically a piezoelectric fan has two separate, different, but uniform (not tapered) elements, the piezo patch and the beam. The solution for this combination can be found in various sources. S.S. El-Din et al. [23] have presented solution

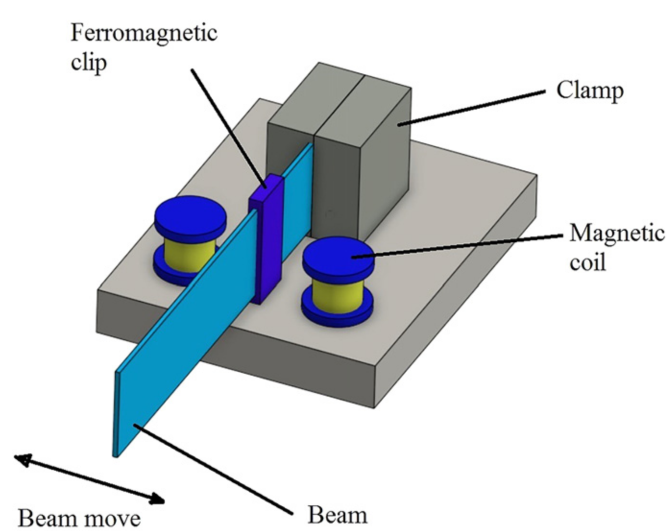


**Fig. 9.** An electromagnetic oscillating cantilever fan.

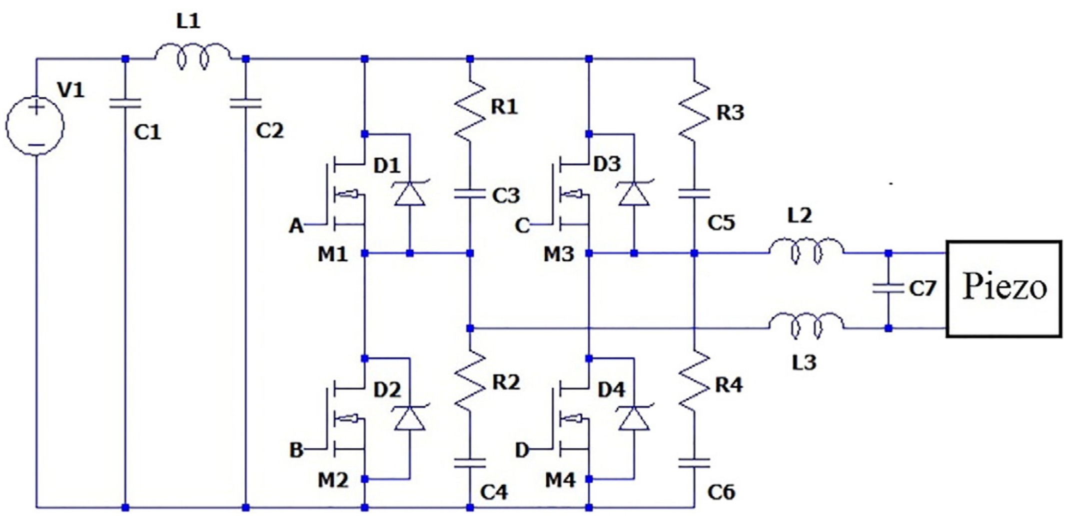


**Fig. 10.** H-bridge for driving a piezo element. PWM controls A, D and B, C have the opposite phases and sufficient dead zones to prevent simultaneous conducting.

for the vertical displacement of the beam. The same equation, but with two sets of coefficients, one for the piezo patch and the other for the beam.

$$\begin{aligned} y(x) &= a_1 \cos(b_1 x) + a_2 \cosh(b_1 x) \\ &\quad + a_3 \sin(b_1 x) + a_4 \sinh(b_1 x) \\ &\qquad \text{when } 0 \le x \le L_1 \end{aligned} \tag{8}$$

$$\begin{aligned} y(x) &= a_5 \cos(b_2 x) + a_6 \cosh(b_2 x) \\ &\quad + a_7 \sin(b_2 x) + a_8 \sinh(b_2 x) \\ &\qquad \text{when } L_1 < x \le L_2 \end{aligned} \tag{9}$$

$$y(x,t) = \mathrm{Real}\left(y(x)e^{i\omega x}\right) \tag{10}$$

T. Açikalim et al. [24] presented the Eqs. (8)–(9) in context of piezoelectric fans. They have written the Eq. (8) to a slightly different form by using exponential functions for $\cos(b_1x)$ and $\cosh(b_1x)$. A similar presentation is also given by S. Basak [25]. Neither of these papers shows a way for defining the coefficients of the equation.

Eqs. (3), (8), and (9) describe only the motion of the beam, but they do not show how the mechanical force, which keeps the beam oscillating, can be linked with the case. This has been addressed by some theoretical studies, like [26–28], just to mention a few of them. It is quite impossible to shortly discuss these studies or to reproduce the results, which are rather complex. However, the work of P. Bürmann et al. [29] is worth mentioning. They have presented the general second order differential function describing the motion of a fan in a steady state condition. For the solution, they have included some material characteristics and dimensions and a frequency dependent presentation of the force.

### *5.3. Air flow visualizing*

In the past only experimental methods could be used for visualizing an air flow generated by a piezoelectric fan. This could be done by using a high-speed camera and smoked air [19]. An alternative method uses water droplets in the air [29]. A method which utilizes imaging methods for detecting the particle move in a flow is called PIV (particle image velocimetry). It is a contact-free nonintrusive optical measurement technique based on the use of added trace particles in a fluid, laser illumination and fast imaging technology. This method has been used by many authors [30–32]. Somewhat more detailed description of the needed facilities is given by [31] while describing their experimental setup.

The increasing availability of CFD simulation tools has made it possible to study air flows much easier and more accurately than ever before. Full 3D simulation is numerically heavy, but often a 2D simulation can reveal the most important characteristics of an air flow.

If only air flows are concerned, the fan can be modelled by defining the motion of the beam mathematically. For defining the motion in the y-direction, Eq. (5) is normally accurate enough. Equation for the move in the x-direction can be found by using some trigonometric dependencies. CFD simulations may require the use of a turbulent flow model. Air can be assumed to be non-compressed. Fluid-solid interaction physics must be included. The beam can be defined as an elastic material, but this has not much importance, as the move of the beam is now defined by the equation. In 2D simulation, it is impossible to model the possible rotation of the beam along the x-axis. The gravity force will not be included if its direction is normal of the xy-plane. This is the case the fan is vertically oriented.

The following results of 2D-simulations have been calculated by using Comsol Multiphysics (v. 5.2) with its fluid module (Fig. 4). The used flow model was k-ε turbulent model. This model is widely usable for various flow conditions and for wide range of the Reynolds number. Used k-ε model is rather robust and less memory intensive as k-ω model, which in some cases can be more accurate. For a piezoelectric fan the Reynolds number, just in the vicinity of the bean, is calculated as fluid volume multiplied by characteristic length divided by the kinematic viscosity of a fluid Eq. (11). The calculated value helps in making decision weather turbulent modelling is needed. Particularly in CFD simulations it is important to set the boundary and initial conditions properly. Flow near walls was modelled with wall functions. The mesh has been optimized for a fluid dynamics case. Boundary layer meshing has been defined for the beam and the walls. In time dependent simulations with defined displacement of the beam, deformed mesh is created automatically by the software whenever it is needed.

$$Re = \frac{\omega A D}{\upsilon} \tag{11}$$

The oscillating beam generates two vortices, one on the pressure side and the other on the suction side, near the tip of the beam. The vortices rotate in opposite directions. The rotating directions are defined by the initial direction of the beam. While the beam moves, the vortex on the pressure side gets smaller and the vortex on the suction side gets larger. Finally, the vortex on the pressure side disappears. At that moment, the highest air speed is just in front of the pressure side of the beam. When approaching the maximum amplitude, air speed in front of the pressure side will reduce quickly. Air speed just behind the suction side starts increasing quickly. At the moment of maximum amplitude, the direction of the beam move changes. The pressure side becomes the suction side and the cycle repeat itself. In Fig. 4a, the beam has just reached the maximum amplitude and changed the moving direction. In Fig. 4b, the beam direction is the same (upwards) and both vortices are clearly visible. In Fig. 4c, the vortex on the pressure side has almost totally disappeared. In the simulations, the beam length is 35 mm and the frequency is 30 Hz. Surface velocity magnitude is indicated by colors and velocity fields by streamlines and arrows. Units in x- and y-axis are millimeters.

In the simulation above, sidewalls have been far enough not to have any significant effect on the air flows. It has been demonstrated that the effect of sidewalls becomes significant if the distance of the fan tip and a sidewall is only in size of a couple of millimeters. Such a short distance can have both beneficial and detrimental effects on the operation of the fan. A. Eastman et al. [33] discussed these effects. They measured a small enhancement in the air thrust in a case where the distance was <2 mm. However, the wall effect with such distances decreases the amplitude of the oscillation. To maintain constant amplitude, extra power must be supplied for the fan. An interesting discovery they made is that in case the fan tip reaches and extends over the sidewall edge, the power dissipation increase can be avoided and some improvement in thrust can still be achieved.

### 5.4. Air nozzle

The energy a fan releases divides between the air vortices around the vibrating beam and the flow directed forward along the cantilever. Simulations show that the forward directed component of the air flow is significant only in range of approximately 5 to 10 mm. The hot surface to be cooled should locate within that range. A fan used for cooling should generate a strong and laminar air flow. This is not the case with piezoelectric fans, but a well-designed air nozzle can improve the situation.

It is quite obvious that an optimal nozzle would have two outlets due to the structure and operation of the fan. The air flow of each outlet has a sinusoidal waveform, but the flows are in opposite phases. The solution with two outlets seems to be common to all published nozzle designs. The optimal design will have optimized walls which turn the vortices forwards with minimal pressure losses. There are basically two kinds of solutions. The fan with a nozzle can be separated from the heatsink or the fan, the nozzle and the heatsink can be integrated together. The integrated solution sounds not only more efficient, but maybe also the most compact and economical solution.

J.Petroski et al. [19] optimized an integrated fan + a nozzle + a heatsink combination. In optimization, they used 2D simulations. They verified the solution by experimental work and 3D simulations. In their design, many fins locate near the inlet where they are also directing the air flow. At the outlet, the restricting walls bend outwards to create reduced air pressure which helps to form the flow closer to laminar at two outlets. The bottom plate of the structure will be directly mounted on the surface which will be cooled.

K. Zhang et al. [34–35] studied an air nozzle with one inlet and two outlets. Their solution is a separate nozzle which can be attached to heatsinks of various shapes. The inlet has size 20 mm × 20 mm and outlets size 35 mm × 5 mm. The outlets locate quite far, approximately 50 mm, from each other. They simulated the nozzle for resolving the air speed and the air volume rate at the inlet and the outlets. They also presented a practical cooling design for an LED luminaire using four fans.

## 6. Multiple fan constructions

### 6.1. Multifan

The relatively low air flow generated by a single piezoelectric fan leads to an idea of using multiple fans. A setup of multiple fans is normally driven by a single piezo driver. The driver must be designed to drive the total capacitance of the fans, but this is not a tight requirement for the driver. The major difficulty in using multiple fans with a single driver is related to the mismatch of resonance frequencies. The resonance is very narrow and a small deviation in the driving frequency, typically <1 Hz, will diminish the oscillation. Mismatch in the resonance frequency of fans is caused by manufacturing tolerances, small differences in fan lengths, weights, orientation, piezo patch fixture and mounting at the fixed end. Depending on the fan construction and the used beam material, it might be possible to trim each fan to specific resonance frequency. This could be done by cutting the beam step by step to the right length. The other approach could be the use of multiple drivers. Each fan could have its own tunable driver, but in that case the synchronization between fans will be lost.

Synchronization between fans is one subject widely studied in many papers. Principally the phase difference between fans can be arbitrary. Usually, there are two choices for synchronization, in-phase ($\Phi = 0$) and out-of-phase ($\Phi = 180$) operation. Considering the cases shown in Fig. 5 where the fans are located face to face. Fig. 5 shows the in-phase case (1a–2a or 1b–2b) and the out-of-phase operation (1a–2b or 1b–2a). In the out-of-phase case a separation between fans must exist in order to avoid the collision of the beams. Air between fans causes a flexible mechanical coupling between the fans. This coupling, depending on the mode of synchronization, affects on the oscillation amplitude of both fans. Amplitudes will be either slightly increased (in-phase) or decreased (out-of-phase operation). The coupling between the fans also affects on the resonance frequency. Decreasing the spacing shifts the resonance frequency slightly upwards [36]. S.F. Sufian et al. [37] reported a significant change, but <1 Hz, difference in resonance frequency while using two fans. Air fluid interaction with the beam is the mechanism based on the coupling. It reduces the amplitude by causing viscous drag for the beam. It is obvious that by reducing air pressure, the drag will be reduced and the oscillation amplitude will be increased. This has been demonstrated by M. Kimber et al. [38] who set fans in a vacuum. In a vacuum, the amplitude was nearly twice compared with the amplitude in normal atmospheric pressure. In a vacuum the coupling between the fans had disappeared.

The efficiency of cooling can be valuated by using either the improvement of thermal transfer ratio or the reduction of thermal resistance. The efficiency of cooling is compared with the case of natural heat convection. Optimal distance between the fan tip and the hot surface is mainly dependent on the size of the cooling surface. In the optimal case, the airflow reaches the hole surface but does not exceed it. Cooling effect can be improved by increasing the number of fans. However there seems to be an optimum fan spacing. M. Kimber et al. [11] made experiments and found that the optimal spacing compared with the amplitude, the aspect ratio, was $L_p/A = 1.5$. H.K. Ma et al. [39–40] found the optimum $L_p/A \approx 0.23$. However, the construction of their multifan was different. Use of two fans no doubt improved heat transfer. M. Kimber et al. [38] found that using two fans instead of one, heat transfer coefficient increased by 19–21%. Compared with the natural convection the heat transfer coefficient improved by factor 6.5. These values are for the in-phase operation. The out-of-phase operation featured somewhat smaller improvement.

S.F. Sufian et al. [37] studied the case of two fans and found that heat transfer coefficient was 3.1 times higher (in-phase operation) and 2.9 times higher (out-of-phase) case compared with the case of natural convection. They also measured the enhancement of heat transfer versus distance between the fan tip and the hot surface. The enhancement reduces if the distance increases. In another study [41] they used piezoelectric fans for cooling multi-LED packages. They reported about an improvement of the heat transfer coefficient by factor 1.8 in the case of one fan and by factor 2.3–2.4 in the case of two fans compared with the natural convection. They also expressed the results as equivalent reductions in thermal resistance.

S.F. Sufian et al. [37] have given a detailed description of fluid flows in the case of two fans locating near each other. While the fans are operating in-phase, the flow field is similar to the flow field of a single fan. While the fans are operating out-of-phase, there will be a vortex between the fans. This vortex rotates the opposite direction compared with the vortices on the outer sides of the beams. The vortex between the beams causes a drag which reduces the amplitudes.

### 6.2. Magnetically coupled fan beams

H.K. Ma et al. [15] has introduced a novel structure of a multifan which uses a single piezoelectric beam and multiple magnetically coupled beams. In this structure permanent magnets are mounted at fan tips in such a way that magnetic repulsive forces affect on the adjacent beam. In this way, the piezoelectric driven fan beam pushes adjacent beams forwards. This coupling is to some extent flexible. Obviously the driving fan faces a larger load due to the coupling and its amplitude will be reduced to some extent. However, the authors claim that the combination of one piezoelectric fan and four magnetically coupled fans feature four times larger amplitude and therefore significantly increased air flow compared with a single fan. In another publication [42] they also claim that the multifan consumes approximately the same or somewhat less electrical power than a single piezoelectric fan. The authors have published many papers about this fan structure which they call with name m-MPMF (micro multiple piezo electric magnetic fan). H. C. Su et al. [20] introduced the T-shape multiple-vibrating fan (T-shaped m-MPMF). T-shaped m-MPMF has been discussed in many of their publications and the improvement of thermal resistance has been experimentally demonstrated. Using the fans with 0.15–0.25 W power, the optimum aspect ratio of the fan spacing $L_p/L$ was 0.233 and the optimum of the gap ratio (the gap is between the fan tip and the heatsink) G/L was 0.05 [40]. These results are for a fan with one active fan beam and two coupled passive fan beams. The largest reduction of thermal resistance while using MPMF was around 80%. MPMFs can be constructed with a variable number of fan beams. So far it looks like no other research group has studied the magnetically coupled multifan structure.

### 6.3. Embedded piezoelectric fan

Several authors have investigated embedded type piezoelectric fans. These are constructions where the beam locates partly or entirely between heatsink fins. The beam is able to move air very close to the surfaces of a heatsink. By doing so the forced convection is the most efficient. H. Ma et al. [21] made experiments to find out how deeply the bean should extend between the fins. They measured the maximum drop of heatsink temperature in the case, where the beam length between fins was 0.3–0.5 of the hole length. They also noticed that the optimal beam location was as close as possible to the surface of heatsink base and the surfaces of fins. The idea of an embedded fan can be used in multifan construction. K. H. Tseng [18] experimented a fan with multiple beams (raked piezoelectric fan). It is quite similar to the embedded multifan in Fig. 6 below.

## 7. Piezoelectric fan experiment

An experimental piezoelectric fan was build using piezoceramic material PZT and PVC sheet for the beam. Complete piezoelectric fans have become available as commercial products. At the moment of this work was initialized (Sept. 2015), just a few suppliers existed and the prices, including also the electrical parts, were around USD 180 for a single unit. Since then, fans without electrical parts have become available for more affordable unit prices (USD 10). For this study, the fans were build using commercial piezoelectric buzzer components. Used buzzers have a circular piezoelectric patch, diameter 23 mm and thickness 100 μm. The backplate was made of brass and had thickness 200 μm. Half of the backplate was etched away. The beam was attached to the patch with epoxy glue. PVC sheet having thickness of 200 μm and mass 200 g/m$^2$ was used for the beam. Beam length $L_b$ was 50 mm and width D was 7 mm. Length $L_{pzt}$ was chosen to be the radius of the piezoelectric patch. With these parameters, the resonance frequency sets to 14 ± 0.2 Hz.

A variable sine wave oscillator was build based on analogue Wien bridge circuitry. The oscillator was followed by a class B HV-amplifier. The amplifier used ±60 V supply voltages. A flyback step-up converter was build for producing these voltages from a single input voltage ranging from 5 V to 15 V. These fans were driven safely up to 80 V peak-to-peak, corresponding the maximum 13 mW power consumption. With that power, the oscillation amplitude was 22 mm. In the following experiments, peak-to-peak voltage was 58 V and the power consumption 7 mW.

Fig. 7 shows the experiment setups. Heat source is two diodes connected parallel (BYV32) in TO-220 package. Diodes were driven with a current source supplying up to 2 A. The benefit of choosing diodes for a heat source is that they can also be used as temperature sensors. The junction temperature can be measured in the same way as the junction temperature of LEDs is measured according to standard JEDEC JESD51-51 [43]. Type K thermocouple measured temperature at the bottom of the heatsink. The power dissipation of the diodes was calculated using the diode current and the voltage over the diodes.

Cooling effect was measured in terms of temperature drop of the heatsink. Maybe a better way to express the effect is to specify the reduction of the thermal resistance $R_{th}$ (Eq. (12)). The improved thermal performance of the cooling system compared with the case of natural heat convection is η (Eq. (13)).

$$R_{th} = \frac{T - T_{amb}}{Q} \tag{12}$$

$$\eta = \frac{R_{th} - R_0}{R_0} \tag{13}$$

An alternative measure often used is the heat transfer coefficient.

$$h = \frac{Q}{A(T - T_{amb})} \tag{14}$$

In the case shown in Fig. 7a the heatsink is horizontally mounted and the beam vertically oriented. In the case shown in Fig. 7b, the fins are pointing upwards and the fan blows downwards. In the case shown in Fig. 7c, the beam is vertically oriented and the beam overlap over the heatsink $X/L_{hs}$ is set to 0.5. This has been found to be the optimum at least for a case of smooth hot surface [1]. Should the beam be horizontally oriented optimum $X/L_{hs}$ would be 0.25 [1]. Gap G was set at value as small as possible (0.5–1 mm). The measurements indicated that the case shown in Fig. 7a was better than the cases shown in Fig. 7b and c. The cases shown in Fig. 7b and c were equally good. In Fig. 8 red line shows the thermal resistance in natural heat convection and blue in forced heat convection. Thermal resistances between the case and the ambient at 1 W heat power are shown on the figures. Thermal resistance between the junction and the case was measured to be 3 °C/W. Fig. 8 shows that the reduction of the thermal resistance is somewhat over 30% when the fan (7 mW) is used. To say it in other words, the fan enhanced the heat transfer coefficient by a factor of approximately 1.3 compared with the natural convection. Using fins shorter than 10 mm or thermal isolation on the other side of the component, the enhancement would be even larger.

## 8. Comparison between a piezoelectric fan and a radial fan

A piezoelectric fan is clearly more efficient than a radial fan. A piezoelectric fan features the same cooling effect while consuming much less electrical power. Use of multiple piezoelectric fans further improves the thermal resistance. The biggest limitation of a piezoelectric fan is the small air volume it generates and therefore the comparison must be made to a small radial fan. A radial fan also has limitations. The airflow it generates is very turbulent and therefore its cooling effect isn't the best. Due to the electrical motor, there is no air flow around the center of the rotation. Other drawbacks are related to the mechanical structure. Friction causes the wear-out of the bearings and reduces the lifetime which is much shorter than the lifetime of modern electronics components and LEDs. A piezoelectric fan has no bearings or other easily wearable parts and therefore its lifetime is longer. Noise level of piezoelectric fan is low, often non-audible.

H. K. Ma et al. [39] compared the cooling efficiency of their piezoelectric multifan (MPMF) with a small radial fan. With the used heatsink and 1.8 W radial fan, the thermal resistance was 0.25 °C/W. With the used heatsink and the MPMF, the thermal resistance was 0.63 °C/W, but consumed electrical power was only 150 mW. K.H. Tseng et al. [18] measured 11 mW electrical power for a piezoelectric fan. A radial fan, which generated the same cooling effect, consumed 220 mW. R.K.B. Schacht et al. [17] compared a mini radial fan with a piezoelectric fan. The radial fan is better only in the form factor, in static pressure generation and at this moment in price. In all other criteria, it is worse. The present-day limited use of piezoelectric fans keeps their prices high. Table 1. shows a comparison between a conventional radial fan and a piezoelectric fan. The efficiency is the product of static pressure and the air volume flow rate divided by the power consumption Eq. (15). The form factor means the same as the size (Table 1).

$$\text{efficiency} = \frac{P_{\text{stat.}} \dfrac{dV_{\text{air}}}{dt}}{P_{\text{elec.}}} \tag{15}$$

A radial fan is normally characterized by specifying its pressure-flow rate relationship. M. Kimber et al. [13] have compared piezoelectric fans with radial fans in terms of pressure, the flow rate and the consumed electrical power. Piezoelectric fans were set in different size enclosures in order to study the wall effects. The authors discussed the different ways to measure the efficiency. They have used the definition Eq. (15). The highest efficiency was measured with the largest enclosure. All the piezoelectric fans were commercial products. They found that the piezo fans were nearly ten times more efficient than the referenced radial fans. The maximum efficiency was reached at power level 0.5–0.7 of the maximum. Maximum static pressure 6 Pa and flow rate 30 l/min were measured.

## 9. Other types of piezoelectric fans and related fan constructions

### 9.1. Vibrating fins with piezoelectric actuator

The idea of using a fan with a heatsink is that stagnant air between heatsink fins will be made moving. This improves the heat convection. The same effect can be caused by moving the fins instead. [5] discusses this cooling method. In their study, heatsink fins are made of piezoelectric material and coated with a thin copper layer. The structure resembles much the multifan piezoelectric fan. They found using simulations, that the performance of the vibrating fins is strongly affected by the dimensions, the vibrating frequency, the spacing, and the amplitude of fins. By increasing the vibrating frequency while keeping amplitude fixed, effectiveness increases rapidly after a certain corner frequency. On their second paper [44] the authors introduced a fan which utilizes one piezoelectric patch and 10 magnetically connected fins. This is a similar solution the authors have previously introduced with multifans. For vibrating fins, this idea sounds particularly good as it allows the passive fins and their mounting to be designed primary for considering maximum heat transfer. In their experiment, the vibrating fins are made of copper and have size 0.3 mm × 55 mm × 20 mm. However, the power consumption is 0.2 W, much more than the power consumption of a single piezoelectric actuator. The authors rise up the question of thermal expansion of the fins. This is essential as the fins now conduct significant amount of heat and their temperature may be high. Thermal expansion increases the length of the fin and the stiffness of the fin. This results in resonance frequency change. The authors made experiments for searching the optimum spacing. They found the improvement of thermal resistance $\eta$ was 38.5% while using the optimum 10 mm spacing.

S. Dey and D. Chakrborty [45] approached the subject of oscillating fins by simulations. They were interested in the dependency of the Nusselt number *Nu*, the Reynolds number *Re*, frequency and amplitude of the oscillation. They found that *Nu* and the cooling efficiency start increasing fast after certain corner frequency has been exceeded.

**Table 1**
Comparison with a radial fan and a piezoelectric fan.

| | Radial fan | Piezoelectric fan |
|---|---|---|
| Form factor | Lower | Higher |
| Weight | Higher | Lower |
| Power dissipation | Higher, typ. 10× | Lower |
| Supply voltage | Lower, typ. 12 V | Higher, typ. 10× |
| Static pressure | Higher | Lower |
| Air volume flow rate | Lower | Higher, typ. 30× |
| Efficiency | Lower | Higher, typ. 100× |
| Noise level | Higher | Lower |
| MTBF | Lower, typ. <20,000 h | Higher |
| Price | Lower | Higher |

### 9.2. Piezo pumps, impinging jets and micro blowers

Other piezoelectric fans which do not use the oscillating cantilever are based on structures called pumps, jets or micro blowers. They exist in various sizes, also micromechanicals structures. Typical characteristics of them are high flow velocities, but small flow volumes. As micromechanical structures, they often operate at ultrasound frequencies. In cooling applications, they can be located very near the hot surface or be connected to miniature air channels integrated into a larger structure. A piezo pump typically has a round piezoelectric foil which expands and contracts causing the air inside a cavity to flow back and forth. Often two mechanical flaps are included. They function as valves and let the air to flow only in one direction.

T. Fukue et al. [46] introduced a novel piezoelectric micro blower, size 20 mm × 20 mm × 3.5 mm and a small size heatsink attached to it. Locating between acrylic plates on both sides of the blower, a narrow air channel will be formed. The micro blower is able to generate flow speed 20 m/s and volume 600 ml/min. The blower can be an efficient cooler device for electronics, especially for portable computers and smartphones.

B.A. English et al. [47] introduced a piezoelectric actuator integrated into a multi-layer PCB. This actuator is a simplified version of a piezoelectric pump. It does not have valves and air is in constant fort and back move. The idea is to locate the exhaust hole very close to the surface to be cooled. At that point, the air flow can have an efficient cooling effect although the air does not have a constant flow direction. The blower operates with 10 V supply and up to 1 kHz frequency.

### 9.3. Related fan constructions

#### 9.3.1. Electromagnetic driven frictionless beam fan

R.K.B. Schacht et al. [48] have presented an electromagnetic driven oscillating beam fan. It does not have a piezoelectric patch, but otherwise it is much the same fan discussed so far in this paper. Without piezoelectric drive, the main benefits, like the excellent energy efficiency and the minimal EMI interference are lost. The beam will be moved by driving magnetizing currents in the coils on both sides of the beam.

The driving currents are in opposite phases. However this type of fan still features high MTBF as its operation is in the same manner frictionless as is piezoelectric fan's. Some benefits over a piezoelectric fan are available. The fan, for example, can be driven with a low voltage, just 2–3 V. The other benefit is the price which is much lower than piezoelectric fans. One difference in operation is that as the piezoelectric fan operates at the first natural resonance, the second natural resonance is more favourable for this kind of fan. Fig. 9 shows the structure of the electromagnetic driven fan.

On their second paper [17] the authors optimized the fan structure and achieved improvement in all characteristics. The form factor was reduced, the air volume flow rate, the static pressure level and the efficiency was increased. The power loss was reduced. However, the air volume flow rate was just the half and the power loss eight times higher than piezoelectric fan's. They also find that in this type of a fan, a polymer like Mylar is much better beam material than steel. In generally this fan can be seen as an intermediate fan type between a conventional radial and a piezoelectric fan.

## 10. Driver electronics of the piezoelectric fan

Very few papers discuss the electrical parts needed in piezoelectric fans. It is obvious, that rather conventional electronics can drive a piezoelectric fan. However, if the small physical size and maximum efficiency of the driver electronics are needed, attention has to paid on the electronics as well. The simplest driver circuitry uses the direct voltage of a grid line. In that case diver voltage is either 230 or 110 Vrms and 50 or 60 Hz respectively. In the general case a dedicated high voltage power supply, an oscillator and a HV-amplifier are needed. These can be constructed by using rather cheap discrete components. The design may become inexpensive, but rather large by its physical size. The most challenging applications of piezoelectric devices may require the driver electronics to locate very near the piezo element and inside a very limited space. Such applications can be found for example in microrobotics and in microactuators. For those applications, an integrated solution can be the only considerable one. Y. K. Yong and J. Fleming [49] present a driver electronics which have been integrated in size 7–12 $mm^2$. The electronics include a step-up power supply and one or two HV-amplifiers. By using two amplifiers as a bridge, the voltage over the load can be doubled. To say it otherwise, the power supply voltages of the amplifiers can be reduced to the half. The authors obviously use class B amplifiers as the efficiency of amplifiers is specified to be around 75%. The maximum efficiency of a class B amplifier is 78.5% and can be achieved with maximum output amplitude. It is worth to mention that the capacitance of a piezo element is voltage dependent and has some amount of hysteresis. This must be considered in designing the HV-amplifier. For improving the power efficiency, authors [49] proposed the use of H-bridge.

The optimization of piezo fan driver electronics has not been discussed adequately in publications. The efficiency can be improved by using class D amplifiers which are driven by a pulse-width modulation signal. A typical driver uses a half bridge or a full bridge stage (H-bridge) followed by a low-pass LC-filter. The filter utilizes the capacitance of the piezo element. The efficiency of a class D amplifier is high. At high output levels, the efficiency is well over 90%. There must be a low-pass filter at the output for removing the high frequency content. On circuit of Fig. x, the low-pass is formed by using L2-3 and C7. Snubber circuits (the RC-circuits in Fig. 10) are mandatory to cut the overvoltage spikes. The impedance of a piezo is mainly capacitive. However when approaching the resonance frequency it becomes resistive. After the resonance frequency, the impedance is inductive until at higher frequencies it becomes capacitive again. Capacitance of a piezo element is both temperature and voltage dependent. The capacitance is increasing if the voltage over the piezo element or the temperature increases. Voltage sensitivity causes distortion, which could be reduced by negative feedback.

## 11. Summary

This paper discussed the subjects listed already in the abstract. The nature of this paper was a review on the subject of a piezoelectric oscillating cantilever fan and its use for electronics cooling. This paper was largely an introduction to the subject with the most important issues presented at a rather general level of understanding. Approximately 100 research papers have been studied in details and a good selection of the best papers have been referenced. The author's own contribution to this subject was given in the form of some CFD simulations, which exhibited the air flows generated by a piezoelectric fan. Another contribution of the author was the cooling experiment, which utilized an experimental piezoelectric fan. The fan was used to cool dual power diodes in TO-220 package mounted on a small heatsink. The results indicated that a significant cooling effect, over 30% reduction of the thermal resistance, can be obtained with minimal 7 mW of consumed power.

## References


[1] S.-F. Liu, R.-T. Huang, W.-J. Sheu, C.-C. Wang, Heat transfer by piezoelectric fan on a flat surface subject to the influence of horizontal/vertical arrangement, Int. J. Heat Mass Transf. 52 (2009) 2565–2570, http://dx.doi.org/10.1016/j.ijheatmasstransfer.2009.01.013.

[2] M. Toda, S. Osaka, Vibrational fan using the piezoelectric polymer PVF2, Proc. IEEE 67 (8) (August 1979) 1171–1173.

[3] M. Toda, Theory of airflow generation by resonant type PVF2 bimorph cantilever vibrator, Ferroelectrics 22 (1979) 911–918.

[4] M. Toda, Voltage-induced large amplitude bending device-BDF2 bimorph – its properties and applications, Ferroelectrics 32 (1981) 127–133.

[5] H.K. Ma, B.R. Chen, H.W. Lan, K.T. Lin, C.Y. Chao, Study of an LED device with vibrating piezoelectric fins, 25th IEEE Semiconductor Thermal Measurement and Management Symposium (SEMI-THERM) 2009, pp. 267–272, http://dx.doi.org/10.1109/STHERM.2009.4810774.

[6] T.J.-C. Liu, Y.-S. Chen, H.-Y. Ho, J.-T. Liu, C.-C. Lee, Notes on vibration design for piezoelectric cooling fan, World Academy of Science, Eng. Technol. Int. J. Mech., Aerosp, Ind., Mechatron. Manuf. Eng. 7 (2) (2013) 93–97.

[7] T.J.-C. Liu, Y.-S. Chen, H.-Y. Ho, J.-T. Liu, C.-C. Lee, Notes on vibration design for piezoelectric cooling fan, Int. J. Mech., Aerosp., Ind., Mechatron. Manuf. Eng. 7 (2) (2013) 93–97.

[8] J.H. Yoo, J.I. Hong, C.Y. Park, Characteristics of piezoelectric fails using PZT ceramics, Proceedings of the 5th International Conference on Properties and Applications of Dielectric Materials, May 25–30, Seoul, Korea 1997, pp. 1075–1081, http://dx.doi.org/10.1109/ICPADM.1997.616634.

[9] J.H. Yoo, J.I. Hong, W. Cao, Piezoelectric ceramic bimorph coupled to thin metal plate as cooling fan for electronic devices, Sensors Actuators 79 (2000) 8–12, http://dx.doi.org/10.1016/S0924-4247(99)00249-6.

[10] P. Zhang, M. Wang, J. Zhu, X. Zhu, Lead-free piezoelectric composites with high piezoelectric performance and high dielectric constant caused by percolation phenomenon, J. Mater. Sci. Mater. Electron. 25 (2014) 4225–4229, http://dx.doi.org/10.1007/s10854-014-2153-2.

[11] M. Kimber, S.V. Garimella, Cooling performance of arrays of vibrating cantilevers, ASME J. Heat Transf. 131 (11401) (November 2009) 1–8, http://dx.doi.org/10.1115/1.3153579.

[12] M. Kimber, S.V. Garimella, Measurement and prediction of the cooling characteristics of a generalized vibrating piezoelectric fan, Int. J. Heat Mass Transf. (52) (2009) 4470–4478, http://dx.doi.org/10.1016/j.ijheatmasstransfer.2009.03.055.

[13] M. Kimber, K. Suzuki, N. Kitsunai, K. Seki, S.V. Garimella, Pressure and flow rate performance of piezoelectric fans, IEEE Trans. Compon. Packag. Technol. 32 (4) (December 2009) http://dx.doi.org/10.1109/TCAPT.2008.2012169 (pp. 766–755).

[14] H.K. Ma, S.K. Liao, Y.T. Li, Y.F. Li, C.L. Liu, The application of micro multiple piezoelectric-magnetic fans (m-MPMF) on LEDs thermal management, 30th IEEE Annual Semiconductor Thermal Measurement and Management Symposium (SEMI-THERM) Symposium 2014, pp. 159–163, http://dx.doi.org/10.1109/SEMI-THERM.2014.6892233.

[15] H.K. Ma, H.C. Su, W.F. Luo, Investigation of a piezoelectric fan cooling system with multiple magnetic fans, Sensors Actuators A 189 (2013) 356–363, http://dx.doi.org/10.1016/j.sna.2012.09.009.

[16] W.-J. Sheu, R.-T. Huang, C.-C. Wang, Influence of bonding glues on the vibration of piezoelectric fans, Sensors Actuators A Phys. 148 (2008) 115–121, http://dx.doi.org/10.1016/j.sna.2008.06.028.

[17] R.K.B. Schacht, A. Hausdorf, B. Wunderle, S. Rzepka, B. Michel, Efficiency optimization for a frictionless air flow blade fan – design study, 14th IEEE Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITHERM) 2014, pp. 1019–1026, http://dx.doi.org/10.1109/ITHERM.2014.6892393.

[18] K.H. Tseng, M. Mochizuki, K. Mashiko, T. Kosakabe, E. Takenaka, K. Yamamoto, R. Kikutake, Piezo fan for thermal management of electronics, Fujikura Technical Review 2010, pp. 39–43.

[19] J. Petroski, M. Arik, M. Gursoy, Optimization of piezoelectric oscillating fan-cooled heat sinks for electronics cooling, IEEE Trans. Compon. Packag. Technol. 33 (No. 1) (March 2010) 25–31, http://dx.doi.org/10.1109/TCAPT.2009.2023859.

[20] H.C. Su, C.L. Liu, T.J. Pan, H.K. Ma, Investigation of a multiple-vibrating fan system for electronics cooling, 29th IEEE Semiconductor Thermal Measurement and Management Symposium (SEMI-THERM) 2013, pp. 110–115, http://dx.doi.org/10.1109/SEMI-THERM.2013.6526814.
[21] H.K. Ma, C.L. Liu, H.C. Su, W.H. Ho, Study of a cooling system with a piezoelectric fan, 28th IEEE Semiconductor Thermal Measurement and Management Symposium (SEMI-THERM) 2012, pp. 243–248, http://dx.doi.org/10.1109/STHERM.2012.6188855.
[22] H.K. Ma, H.C. Su, C.L. Liu, W.H. Ho, Investigation of a piezoelectric fan embedded in a heatsink, Int. Commun. Heat Mass Transfer 39 (2012) 603–609, http://dx.doi.org/10.1016/j.icheatmasstransfer.2012.03.003.
[23] S.S. El-Din, A.A. Mahmoud, M.A. Nasser, Free vibrations of stepped beam with two uniform and/or tapered parts, Mechanics Mech. Eng. Int. J. 4 (2) (2000) 166–181.
[24] T. Açikalim, A. Raman, S.V. Garimella, Two-dimensional streaming flows induced by resonating, thin beams, J. Acoust. Soc. Am. 114 (4, Pt. 1) (October 2003) 1785–1795, http://dx.doi.org/10.1121/1.1610453.
[25] S. Basak, A. Raman, S.V. Garimella, Dynamic response optimization of asymmetrically configured piezoelectric fans, ASME 19th Biennial Conference on Mechanical Vibration and Noise, Chicago, Illinois, September 2–6, 2003 http://dx.doi.org/10.1115/DETC2003/VIB-48529.
[26] Q.-M. Wang, L.E. Cross, Performance analysis of piezoelectric cantilever bending actuators, Ferroelectrics 215 (1998) 187–213, http://dx.doi.org/10.1080/00150199808229562.
[27] K. Yao, K. Uchino, Analysis on a composite cantilever beam coupling a piezoelectric bimorph to an elastic blade, Sensors Actuators A 89 (2001) 215–221, http://dx.doi.org/10.1016/S0924-4247(00)00552-5.
[28] S. Basak, A. Raman, S.V. Garimella, Dynamic response optimization of piezoelectrically excited thin resonant beams, ASME J. Vib. Acoust. Vol, 127 (2005) 18–27, http://dx.doi.org/10.1115/1.1857921.
[29] P. Bürmann, A. Raman, S.V. Garimella, Dynamics and topology optimization of piezoelectric fans, IEEE Trans. Compon. Packag. Technol. 25 (4) (December 2003) 592–600, http://dx.doi.org/10.1109/TCAPT.2003.809111.
[30] T. Açikalin, S.V. Garimella, Analysis and prediction of the thermal performance of piezoelectrically actuated fans, Heat Transf. Eng. 30 (6) (2009) 487–498, http://dx.doi.org/10.1080/01457630802529115.
[31] G.M. Gilson, S.J. Pickering, D.B. Hann, C. Gerada, Piezoelectric fan cooling a novel high reliability electric machine thermal management solution, IEEE Trans. Ind. Electron. 60 (11) (November 2013) 4841–4850, http://dx.doi.org/10.1109/TIE.2012.2224081.
[32] T. Wu, P.I. Ro, Heat transfer performance of a cooling system using vibrating piezoelectric beams, J. Micromech. Microeng. 15 (2005) 213–220, http://dx.doi.org/10.1088/0960-1317/15/1/030.
[33] A. Eastman, M.L. Kimber, Flow shaping and thrust enhancement of sidewall bounded oscillating cantilevers, Int. J. Heat Fluid Flow 48 (2014) 35–42, http://dx.doi.org/10.1016/j.ijheatfluidflow.2014.04.001.
[34] K. Zhang, D.G.D. Xiao, X. Zhang, H. Fan, Z. Gao, M.M.F. Yuen, Novel cooling solutions for LED solid state lighting, 12th International Conference on Electronic Packaging Technology & High Density Packaging (ICEPT-HDP) 2011, pp. 1–5, http://dx.doi.org/10.1109/ICEPT.2011.6067026.
[35] K. Zhang, D.G.D. Xiao, X. Zhang, H. Fan, Z. Gao, M.M.F. Yuen, Thermal performance of LED packages for solid state lighting with novel cooling solutions, 12th International Conference on Thermal, Mechanical and Multiphysics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE) 2011, pp. 1–7, http://dx.doi.org/10.1109/ESIME.2011.5765839.
[36] M. Kimber, S.V. Garimella, A. Raman, Local heat transfer coefficients induced by piezoelectrically actuated vibrating cantilevers, ASME J. Heat Transf. 129 (September 2007) 1168–1176, http://dx.doi.org/10.1115/1.2740655.
[37] S.F. Sufian, M.Z. Abdullah, J.J. Mohamed, Effect of synchronized piezoelectric fans on microelectronic cooling performance, Int. Commun. Heat Mass Transf. 43 (2013) 81–89, http://dx.doi.org/10.1016/j.icheatmasstransfer.2013.02.013.
[38] M. Kimber, S.V. Garimella, A. Raman, An experimental study of fluidic coupling between multiple piezoelectric fans, Thermal and Thermomechanical Phenomena in Electronics Systems (ITHERM) 2006, pp. 333–340, http://dx.doi.org/10.1109/ITHERM.2006.1645361.
[39] H.K. Ma, Y.T. Li, L.K. Tan, C.L. Liu, S.K. Liao, Thermal performance of multiple piezoelectric–magnetic fans, 30th Semiconductor Thermal Measurement and Management Symposium (SEMI-THERM) 2014, pp. 100–104, http://dx.doi.org/10.1109/SEMI-THERM.2014.6892223.
[40] H.K. Ma, L.K. Tan, Y.T. Li, C.L. Liu, Optimum thermal resistance of the multiple piezoelectric–magnetic fan system, Int. Commun. Heat Mass Transf. 55 (2014) 77–83, http://dx.doi.org/10.1016/j.icheatmasstransfer.2014.04.006.
[41] S.F. Sufian, Z.M. Fairuz, M. Zubair, M.Z. Abdullah, J.J. Mohamed, Thermal analysis of dual piezoelectric fans for cooling multi-LED packages, Microelectron. Reliab. 54 (2014) 1534–1543, http://dx.doi.org/10.1016/j.microrel.2014.03.016.
[42] H.K. Ma, W.F. Luo, H.C. Su, A multiple vibrating-fan system using interactive magnetic force and piezoelectric force, 28th IEEE Semiconductor Thermal Measurement and Management Symposium (SEMI-THERM) 2012, pp. 238–242, http://dx.doi.org/10.1109/STHERM.2012.6188854.
[43] JEDEC JESD51-51, Implementation of the electrical test method for the measurement of real thermal resistance and impedance of light-emitting diodes with exposed cooling, JEDEC Solid State Technology Association, 2012.
[44] H.K. Ma, S.K. Liao, Y.T. Li, Study of multiple magnetic vibrating fins with a piezoelectric actuator, 31st IEEE Thermal Measurement, Modeling & Management Symposium (SEMI-THERM) 2015, pp. 309–3013, http://dx.doi.org/10.1109/SEMI-THERM.2015.7100178.
[45] S. Dey, D. Chakrborty, Enhancement of convective cooling using oscillating fins, Int. Commun Heat Mass Transf. Vol. 36 (2009) 508–512, http://dx.doi.org/10.1016/j.icheatmasstransfer.2009.01.018.
[46] T. Fukue, K. Hirose, H. Terao, Cooling performance of impinging jet from piezoelectric micro blower mounted in narrow flow passage, Electronics Packaging and iMAPS All Asia Conference (ICEP-IAAC) 2015, pp. 605–610, http://dx.doi.org/10.1109/ICEP-IAAC.2015.7111086.
[47] B.A. English, M.R. Whitley, M.S. Kranz, T. Hudson, J. Rock, Integrated PCB active cooling with piezoelectric actuator, IEEE Aerospace Conference 2012, pp. 1–7, http://dx.doi.org/10.1109/AERO.2012.6187089.
[48] R. Schacht, A. Hausdorf, B. Wunderle, B. Michel, Frictionless air flow beam fan for thermal management of electronics, Thermal and Thermomechanical Phenomena in Electronics Systems (ITherm), 13th IEEE Intersociety Conference 2012, pp. 1320–1326, http://dx.doi.org/10.1109/ITHERM.2012.6231573.
[49] Y.K. Yong, A.J. Fleming, Piezoelectric actuators with integrated high-voltage power electronics, IEEE/ASME Trans. Mech. Vol. 20 (2) (April 2015) 611–617, http://dx.doi.org/10.1109/TMECH.2014.2311040.