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Dynamic modelling for thermal micro-actuators using thermal networks

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A B S T R A C T

Thermal actuators are extensively used in microelectromechanical systems (MEMS). Heat transfer through and around these microstructures are very complex. Knowing and controlling them in order to improve the performance of the micro-actuator, is currently a great challenge. This paper deals with this topic and proposes a dynamic thermal modelling of thermal micro-actuators. Thermal problems may be modelled using electrical analogy. However, current equivalent electrical models (thermal networks) are generally obtained considering only heat transfers through the thickness of structures having considerable height and length in relation to width (walls). These models cannot be directly applied to micro-actuators. In fact, micro-actuator configurations are based on 3D beam structures, and heat transfers occur through and around length. New dynamic and static thermal networks are then proposed in this paper. The validities of both types of thermal networks have been studied. They are successfully validated by comparison with finite elements simulation and analytical calculations.

1. Introduction

The thermal actuation is widely present in active microsystems, either by inherent design or combining two or more energy domains such as optical, mechanical or electrical [1–3].

One of the earliest (1970's) and most commercially successful application of thermal microelectromechanical systems (MEMS) is the ink-jet printer head [4]. Recent applications including microlens [5,6], microprobes [7,8], microsensors [9–13] and micro-actuators, are rapidly gaining importance too. For example, a thermal microlens tunes its focal lens by temperature, which is easily controlled via managing the current input of the heater [6]. An on-wall in-tube flexible thermal sensor is able to measure the flow rate under both developing and fully developed flow conditions. The resistance of the sensor linearly changes with temperature [13].

Thermal micro-actuators are a very popular actuation technology in MEMS. They commonly exploit differential thermomechanical expansion of materials, known as the thermomechanical effect, resulting generally from Joule heating. The common actuation geometries of this kind of micro-actuators are multimorph [14–16], U-shape [1,17–21] and V-shape [17,22–25]. In all of them, the prevalent geometry is the beam.

Properties of thermal micro-actuators strongly depend on their geometry structure and material properties, as well as the applied current. It is therefore important to model the thermal micro-actuator in order to improve or optimize its design. Thermal micro-actuators are used in microgrippers [16,19,25–27], microheaters [28,29], micromotors [30], microrobots [31], micromirrors [14], ice gripping [32], etc. Direct applications of these devices are electrics, optics, electronics, mechanics and biomedicine [30,33]. Thermal actuators are usually rather slow, due to thermal time constants typically in the upper millisecond range [34]. In smaller structures, however, it has been shown that substantially higher speeds can be attained, because thermal time constants scale linearly with decreasing surface [30,35]. Compared to their counterparts such as electrostatic or piezoelectric actuators, thermal actuation provides larger forces [36]: for typical configurations, thermal actuation provides 4 orders of magnitude higher energy density than electrostatic actuation (450 μN mm^{-2} for thermal actuation, and 20 μN mm^{-2} for electrostatic actuation [22]), and 1–2 orders of magnitude higher energy density than piezoelectric actuation [1,30]. Thermal micro-actuators have a high reliability and are also easier to control, compared to shape memory alloy actuators. In addition, they are usually simpler to be fabricated, contrary to magnetic actuators, for instance, that may require special materials in the fabrication process [22]. Some of the thermal micro-actuators have been made on silicon, polysilicon, and nickel structural components. Metal-based electrothermal micro-actuators provide a larger output displacement with a smaller input voltage. However, they generally suffer from mechanical deficiencies, such as fatigue and aging [33].

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Nomenclature

a	height, m
b	width, m
C_p	specific heat (constant pressure), J/kg K
C_{th0}	thermal capacitor, J/K
d	characteristic size, m
h	heat transfer coefficient, W/m^2 K
i	current, A
k	thermal conductivity, W/m K
l	length
P	lateral perimeter, m
Q_h	heat convection, W
Q	heat flux, W
R_{c0}	conduction thermal resistance, K/W
R_{v0}	convection thermal resistance, K/W
S	lateral surface, m
t	time, s
T	temperature, K
V	voltage, V
x, y, z	Cartesian coordinates, m
Z	thermal impedance

Greek symbols

δ	static validity criterion
ν	dynamic validity criterion
ω	angular frequency, rad/s
φ	heat Laplace transform, W
ρ	mass density, kg/m^3
θ	temperature Laplace transform, K

Subscripts

1	lateral face, at $x = 0$
2	lateral face, at $x = l$
ext	external
lin	linear
st	static

Fabrication techniques of thermal micro-actuators are well-known microtechnologies such as bulk micromachining, wet and dry etching processes, surface micromachining and LIGA processes, including laser micromachining [1,2,6,14,24,37]. Managing thermal phenomena in thermal micro-actuators is a key factor for future progress in their optimization. Modelling heat transfers through the actuator and its surroundings are fundamental for understanding, predicting and controlling the temperature distribution, and consequently the device response characteristics. This paper deals with this problem and proposes a dynamic thermal analysis using electrical analogy. This last is generally used to model heat transfers occurring through the thickness of structures with geometries as walls, where height and length are considerable in relation to width. Here, we develop equivalent electrical models of long structures, which are currently found in thermal micro-actuators. In these thermal structures, heat transfers are present through and around the length.

Being the analysis presented in this paper useful for the MEMS community dealing with thermal problems, in Section 3 we present different approaches to model these problems, particularly in micro-electronics and thermal micro-actuators. The beam geometry, currently found in thermal micro-actuators, is analysed dynamically in Section 4 via electrical analogy. In Section 5 we determine the validity of the proposed equivalent electrical models, and they are validated by comparing them with finite elements simulations and analytical calculations in Section 6.

2. Thermal modelling in microdevices

Thermal effects have an obvious impact in the performance and reliability of electronic systems and thermal devices [38]. Efforts to model the electrothermal actuators and thermal effects in electronic systems have been focused on analytical modelling, finite-element methods, lumped parameters based on electrical analogy, and model order reduction. Several examples of these techniques are presented in this section.

2.1. Analytical modelling

In practice, an analytical solution provide very accurate models, and it may easily consider constraints. Liao et al. theoretically modelled an electrothermal micro-actuator for bidirectional motion to forecast the relationship between applied voltage and displacement [1]. A one-dimensional conductive heat transfer analysis of two types of thermal actuators (U-shaped and V-shaped) are presented by Hickey et al. [17]. Thermal time constants were predicted using this model. Robert et al. predicted the shape of a thermal and electrostatic micro-actuator versus the temperature [3]. An algorithm has been also developed in order to evaluate the damping behavior of a microswitch taking the micro-actuator deflection into account. Li and Uttamchandani analysed a modified asymmetric micro-electrothermal actuator [18]. The aim of this analysis was to calculate the optimum dimensions of the hot arm of the actuator to maximize the deflection of the actuator before the onset of thermal failure. A theoretical model of the actuation stress of a polymeric (SU-8) thermal micro-actuator with embedded silicon microstructure has been realized by Lau et al. [39]. The analytical model of Boutchich et al. predicted the dependence of the restoring force on the input electrical power and topology of a thermal actuator [15]. A two-step analytical model of a four-hot arm U-shape electrothermal actuator that can achieve bidirectional motion in two axes has been developed by Elbuken et al. [40]. Finally, Mayyas and Stephanou obtained closed-form solutions for the thermal modelling of a general 5 non-homogeneous, lineshape microbeam's actuator using 1-D steady state heat equations under both heat conduction and convection [41].

Finite element (FE) based simulations [1,17,40,41] or experimental measurements [3,15,17,18] were usually performed to validate analytical models. Analytic solutions for describing thermal problems are only available for simple geometries. For complex geometries, either numerical methods or approximations may be used.

2.2. Finite element modelling

Electrothermal devices are traditionally simulated with finite element method (FEM) due to the complex coupling of the electrical, thermal and mechanical problem [42]. FEM analysis is principally used to demonstrate the feasibility of the design and to simulate the behaviour; for example, the relationship between the applied voltage and the displacement [1,37,43,44], or the effects of geometrical and material stiffness variations on the performance [45].

The principal drawbacks of implementing analytical and FEM analysis in electrothermal microdevices are regarded to the long simulation time, and the time required to build-up the model in the FEM software. Faster methods become necessary.