Static and Dynamic Modeling of a 3-Axis Thermal Accelerometer

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Abstract

A novel 3 dimensional model using a coupled fluidic-solid-interaction (FSI) approach is used to simulate the response of a 3-axis thermal accelerometer. The model is fully parametric, enables static and dynamic analysis and includes thermal dependent properties on both solid and fluidic domains. Unlike previous modeling approaches found in literature, the proposed model can be used to determine the power required for sensor operation, bandwidth and quality factor, and, due to the three dimensional approach, it is possible to use the total temperature variation along the temperature sensors (previous 2D models only give temperature differences in a single point) to simulate a more real sensor response. The model was applied to a polymer based 3-axis thermal accelerometer and simulation results using the proposed model show a power consumption of 23 mW and a sensitivity of 1 mV/g and 368 μV/g in the XY and Z directions respectively.

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Keywords: Fluid-structure-interaction; thermal accelerometers; sensor modeling.

1. Introduction

Fully integrated 3-axis thermal accelerometers have been recently introduced [1, 2] and since available models in literature have been used for 1 and 2 degrees-of-freedom (DOF) devices, they are unsuitable to model the response of 3-axis accelerometers. Both analytical and FEM modeling approaches have been reported in literature to model thermal accelerometers [3-9]. In [7], a two dimensional computational fluid dynamic (CFD) model is used to study the sensitivity of the device for different gases and pressures while in [8] analytical and CFD modeling is used to implement a system-level model, including dynamic effects, of a 1-DOF thermal accelerometer. These approaches are not suitable for a 3-DOF thermal

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accelerometer due to the sensor complexity and therefore a more comprehensive approach is required. The 3-dimensional (3D) thermoelectric-fluidic FEM model presented here includes all the physical domains involved in accelerometer operation (electric, thermal and fluidic), thermal dependent properties and enables both static and dynamic analysis. The model uses a coupled FSI approach and is used to predict the performance of a polymeric 3-axis accelerometer (details of the thermal accelerometer are found in [1]).

2. 3D thermoelectric-fluidic model

Thermal accelerometers operation involves the coupling of 3 physical domains: electric, thermal and fluidic. When current is applied to the heating element (electric domain) heat is generated by joule effect and the surrounding gas medium is heated (thermal domain). In the absence of any external acceleration the temperature profile does not change, however, if an external acceleration is present, free convection occurs and the temperature profile changes (fluidic domain). The changes of the temperature profile are proportional to the acceleration and inclusion on the device of temperature sensors enables the realization of a thermal accelerometer. The model introduced here includes a solid domain: the external polymeric body and the heater that includes both the supporting membrane and the active heating element, and a fluidic domain: the gas medium. The external polymeric body acts as a mechanical support for the membranes and as an encapsulation body for the gas medium. Fig. 1 shows the meshed 3D model while Fig. 2a shows the parametric dimensions used.

- Figure 1: Mesh and geometry of the model. a) Solid domain mesh, b) fluidic domain mesh and c) FSI surfaces.

- Figure 2: 3D accelerometer model. a) parametric model dimensions and b) model drawing showing the heater and X and Z temperature sensing resistors with typical temperature distribution on the resistors.
The implemented model is fully parametric enabling the simulation of the sensor response for several different configurations. The ANSYS Multi-field solver (MFX) is used to solve the coupled FSI model. Initially, a thermoelectric simulation is performed in ANSYS and the resulting temperature loads are transferred to the coupled fluidic domain. Next, CFX is used to perform a CFD analysis (fluidic domain) and computed wall heat flows are transferred back to the solid domain. This iterative process is stopped when the solutions on both domains converge. Key features of the proposed model are the use of thermal dependent properties (heater thermal conductivity and resistivity and gas viscosity, density, thermal conductivity and heat capacity) and the possibility to easily compute the temperature variations on the sensing temperature resistive sensors. In fact, the use of a 3D model allows checking the temperature variation on the full temperature sensor volume (see Fig. 2b), rather than the temperature changes on a single point (the only result available on 2D simulations).

3. Simulation results

Several simulations were performed using the dimensions shown in Table 1. Static and dynamic responses were computed and simulation results are presented in Fig. 3. Fig. 3a and 3b show the temperature differences of the temperature profile along the Z and X axis for the acceleration of 1g and for no acceleration. The results clearly show the optimum distance for sensors placement for maximum sensitivity. The dynamic response of the sensor for both the X and Z axis is presented in Fig. 3c and 3d. The lower time-response on the Z axis is related to the larger distance of the cavity in this direction.

Table 1. Geometric dimensions used for simulations.

| Dimension      | Value (μm) | Dimension      | Value (μm) |
|----------------|------------|----------------|------------|
| External height| 3880       | Gas width      | 1500       |
| External width | 2500       | Gas radius     | 750        |
| External radius| 1250       | Membrane height| 1400       |
| Gas height     | 2880       | Membrane thickness| 80        |

Fig. 2. Profile of temperature differences along a) X Line and b) Z Line between no acceleration applied and 1 g acceleration. Step response on the c) X axis and d) Z axis for an input acceleration of 10g.
4. Conclusions

A 3D thermoelectric-fluidic model was presented and used in this work to simulate the static and dynamic performance of a 3-axis thermal accelerometer. The expected electrical response of the accelerometer (considering a half active Wheatstone bridge connected to an instrumentation amplifier with a gain of 1000 as the readout circuit) was compared against other thermal accelerometers reported in literature (Table 2) and the proposed 3-axis accelerometer compares favorably with current state-of-the-art devices. The low power characteristics of the polymer device are also confirmed by the model results.

Table 2. Thermal accelerometers performance comparison.

| Reference | Power [mW] | Tmax [K] | Nº Axis | Sensitivity XY | Sensitivity Z |
|-----------|------------|----------|---------|----------------|---------------|
| [3]       | 87         | -        | 1       | 600mV/g        | -             |
| [4]       | 45         | -        | 1       | 6.6mV/g p      | -             |
| [5]       | 54         | 511      | 1       | 2.5mV/g        | -             |
| [6]       | 166        | -        | 1       | 1300nA/g       | -             |
| [7]       | 75         | 523      | 1       | 7°C p          | -             |
| [8]       | 27         | 598      | 1       | 200µV/g        | -             |
| [9]       | 12.5       | 473      | 2       | 13mV/g         | -             |
| [2]       | 2.5        | -        | 3       | 66µV/g         | 25µV/g        |
| This Work | 23         | 490      | 3       | 1mV/g          | 368µV/g       |
|           | 4.8        | 342      | 3       | 82µV/g         | 27µV/g        |

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