

A novel accelerometer design has recently been developed [1]. This design features a heater centrally placed within a fluid-filled cavity. The heater is maintained a constant Temperature  $\Delta T$  above the temperature of the wall of the enclosure, producing a radial temperature gradient. When an acceleration is applied, the heated fluid is displaced by buoyancy forces. The resulting temperature asymmetry,  $\delta T$ , is detected by temperature sensors symmetrically placed around the heating element and the acceleration deduced. This description can be realized in one of two forms: as a single-axis accelerometer, in which the heater and enclosure are concentric parallel cylinders or parallelepipeds; or as a multi-axis accelerometer, in which the heater and enclosure are concentric spheres or cuboids.

Equations (1)–(4) were represented in the CFD package FLOTRAN. Accurate modeling of the accelerometer performance required exceptional care, as the quantity of interest,  $\delta T$ , is a small difference between two almost equal temperatures. Full details of the modeling process are provided in [3]. To validate the modeling method, the equations were first solved for two geometries for which closed-form solutions exist.

We were supplied with a number of accelerometer chips designed for use with air as a working fluid. A cross-section of one of these chips is shown in Fig. 1. The device consists of a cavity etched in silicon, spanned by a silicon bridge 20.6 microns wide and 3 microns deep, which is used as a heater. The cavity is 970 microns across in the direction parallel to the long axis of the heater, and 915 microns across in the orthogonal direction. Eight silicon bridges extend from each of the two sidewalls of the cavity to the edge of the heater. The cross-section of these bridges is approximately 3  $\mu\text{m}$  by 20  $\mu\text{m}$ . Each bridge carries a thermocouple at a distance of 300 microns from the cavity wall. The thermocouples are an integral part of the chip, and consist of aluminum films deposited on silicon, having a sensitivity of approximately 100  $\mu\text{V}/\text{K}$ . The chip is designed to measure accelerations acting in the plane containing the heater and thermocouples, orthogonal to the heater.

The depth of the etched cavity below the plane of the heater and detectors was 230 microns. The chip was packaged in a TO-100 metal can package, leaving the cavity unsealed above the heater plane, but covered by a metal cap giving about 1000 microns clearance above the heater plane.

To allow us to determine the temperature at the heater during operation, we placed the chip in an environmental chamber and heated it by stages from 20  $^{\circ}\text{C}$  to 120  $^{\circ}\text{C}$ , measuring the resistance of the heater at each stage. The resistance was found to, increase as a linear function of temperature. In using this correlation to interpret experimental measurements, we note that in operation, though not in the environmental chamber, the heater loses heat by axial conduction to the cavity walls. This results in a non-uniform temperature profile, which can be calculated as follows:

The FLOTRAN model calculates the time taken for the temperature at a given radial location to reach 63% of its final value. The actual response time of the accelerometer will exceed this by the time taken for the thermocouples to register that change in temperature.

To measure the transient response of the chip, it was mounted on a Brüel and Kjær PM Vibration Exciter Type 4808 and subjected to a sinusoidally varying acceleration at a frequency gradually increasing from 1 Hz to 1 kHz. For both air-filled and isopropanol-filled chips, the chip output signal followed the imposed acceleration, but its amplitude fell off after a certain point.

In addition to the magnitude of the response to acceleration, we are also concerned with the time taken for this response to develop. We again suppose that the response time of the device can be estimated by solutions for the cylindrical and spherical geometries. However, this problem differs from the transient cases discussed in the prior literature, both for the cylindrical case ([13]–[16]) and the spherical case ([13], [17], [18]), in that the transient develops due to the suddenly imposed acceleration rather than the heating of one bounding surface. We have therefore undertaken a series of FLOTRAN studies to establish correlations for response time.

Given the current rate of progress in the MEMS field, it is difficult to set a lower limit on the size of accelerometer that can be constructed. However, a hard lower bound is set by the kinetics of the working gas: if the temperature of the gas is measured with a sufficiently small detector over a short time interval, a relatively small number of gas molecules will come into contact with the detector, and the mean kinetic energy of this small sample may differ from the mean kinetic energy of the gas as a whole. This will introduce noise into the measurements, and the noise will be greater as the size of the detector decreases.

A cylindrical detector made of silicon, radius 0.1  $\mu\text{m}$ , length 500  $\mu\text{m}$ , has a thermal mass of about  $10^{-10}$  J/K. This corresponds to an ensemble of  $2 \times 10^{12}$  air molecules. The fluctuations measured by the detector will therefore be about  $10^{-6}$  times smaller than the temperature fluctuations of a single air molecule, that is, 0.1 mKelvin or smaller. For comparison, the temperature differential between the detectors of the accelerometer described in the following section is about 0.1 K for a 1-g acceleration when the working fluid is air, and about 10 K for a liquid (isopropanol).

The capacitive accelerometer senses an acceleration by the deflection of a set of beams. Larger accelerations will cause larger deflections, and eventually failure. There is thus a trade-off between device sensitivity and device robustness. Because it lacks a solid proof mass, the convective accelerometer does not face this trade-off. Thus, it is well-suited to applications in which the instrument must measure small accelerations, while surviving high accelerations, for example, the accelerations of spacecraft launch or re-entry.

The most salient weakness of the thermal convective accelerometer is its slow response time, and this is exacerbated when we consider a liquid as the working fluid. However, the design relationships derived in the previous section suggest a possible solution to this problem: it has been shown that the isopropanol-filled chip is approximately 1000 times as sensitive as the air-filled chip, but also approximately 40 times slower to respond to an acceleration. If we reduce  $r_i$  and  $r_o$  for this chip by a factor of 10, the Rayleigh number will be reduced by a factor of 1000, as will the differential temperature signal. The response time of the shrunken isopropanol chip will be reduced by 100 times as a result of the shrinkage, which will make it more than twice as fast than the air-filled chip.

On the basis of published expressions for convection in enclosed fluids, we have conjectured that it is possible to construct liquid-filled micromachined accelerometers having sensitivities up to three orders of magnitude greater than previously reported. FLOTRAN modeling supports this conclusion, and suggests that the response time of the liquid-filled accelerometer will be increased by about a factor of 40. An isopropanol-filled accelerometer has been constructed. Its sensitivity has been found to be about seven hundred times that of the same chip filled with air, in line with prediction. Its response time is at least an order of magnitude greater than that of the air-filled chip, though not two orders of magnitude greater, as theory would imply. A residual response to high-frequency acceleration is seen, the reasons for which are not understood.

Equations have been given that can be used to predict the effects of working-fluid properties and heater temperature on device sensitivity and response time. Upper and lower bounds on device size have been established. The liquid-filled accelerometer has been compared with other micromachined accelerometers: its strength is its combination of high sensitivity with great robustness, while its chief weakness is its slow response time.

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