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Robust Design of a Bimetallic Micro Thermal Sensor Using Taguchi Method

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Abstract In this study, a performance optimization process for a bimetallic micro thermal sensor using the Taguchi quality engineering method is described. Sensor performance is obtained by simulating the theoretical model, which shows the effect of the beam deflection on capacitance during changes in temperature. Optimal parameter combinations are determined using Taguchi experimental design method with at least 90 % confidence level. The level of importance of the parameters on the sensor's sensitivity is determined using the analysis of signal-to-noise ratio as well as analysis of variance. The improvement in S/N ratio is 29.47 dB, representing an increase of 29.74 times in sensitivity.

Keywords MEMS · Thermal sensor · Optimization · Taguchi · ANOVA

1 Introduction

Micro thermal sensors are one branch of micro sensors. One of the structure types used for micro thermal sensors is based on the bimetallic cantilever beam [1, 2]. Sensitivity of this sensor depends on several design factors. Taguchi method is used to investigate the effects of the design factors on sensitivity and to identify the performance characteristics under the optimal sensitivity parameters. The Taguchi method, developed at the beginning of 1950 by Genichi Taguchi, is a powerful tool for

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characterization, design and performance optimization. Taguchi experimental design method offers a wide range of applications, simple concept and use of method as well as variation reduction. Additionally, Taguchi method reduces cost of experiments by significantly reducing the number of needed experiments [3, 4]. The Taguchi method combines mathematical and statistical methods that are used in experimental studies. Using this method, an optimal condition with minimum experiments can be determined. The method treats variation as factor of signal to noise (S/N) ratio. Then, experimental conditions having maximum S/N ratio are viewed as optimal conditions [5]. The method ultimately leads to a robust product design by including noise factors and obtaining results that improves signal while reducing variations [6].

In this study, optimization of a bimetallic micro thermal (BMT) sensor is presented. The quantity used to measure the temperature is the capacitance variation due to tip deflection of a bimetallic cantilever beam. There are several existing bimetallic micro thermal sensor designs. A BMT sensor based on a comb drive was presented by Rezazadeh et al. [7]. This mechanism contains two capacitances in the form of a comb. The first comb is attached to the tip of the bimetallic strip, which lowers into the second comb attached to a fixed base. This mechanism is difficult to manufacture, which is why its optimization has not been studied. The BMT sensor presented in this paper contains a novel design structure with several design advantages over existing bimetallic micro thermal sensors. Primarily, it uses a simple capacitor plate. This difference is the primary reason why we propose and investigate optimization of the new sensor. The additional simplicity should ease manufacturability of the sensor. On the other hand, the governing equations of the proposed bimetallic micro thermal sensor, as a result of electrostatic forces, are more complicated than comb derive sensor. The design process of this novel sensor is submitted to the journal of Measurement [1]. Another BMT sensor based on tunneling current is presented by S. Nezhadian et al. [2], where tunneling-current modulation is used to convert the thermal changes of a cantilever bimetallic beam into an electrical signal. In its original design, the measurable range of temperature changes was relatively small. This problem was solved by adding an additional mechanism to extend the temperature range. However, the extra mechanism adds manufacturing complexity.

This paper is organized as follows. In Sect. 2, the bimetallic micro thermal sensor is described, and a theoretical model that relates temperature input and changes in capacitance output is presented. In Sect. 3, the theoretical model is simulated using material, and geometries used in typical MEMS applications. In Sect. 4, the Taguchi method is used to obtain optimal sensor performance. Next, the effect of the parameters and their level of significance on the sensitivity is statistically evaluated using analysis of variance. This section also includes prediction and verification experiments. Finally, concluding remarks are presented.

2 Sensor Properties

A simplified model of the proposed bimetallic thermal micro sensor is shown in Fig. 1(a). This system consists of a micro bimetallic cantilever beam and a capacitor joined at the tip of the cantilever beam. Because of the difference in coefficients

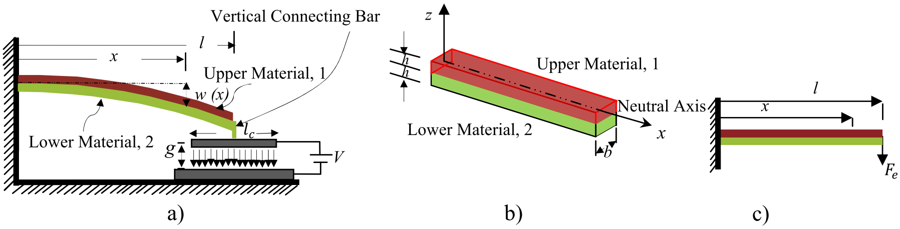

Fig. 1 (**a**) Schematic of the proposed thermal micro sensor, (**b**) element of bimetallic cantilever beam, and (**c**) electrostatic force applied to the tip of the cantilever

of thermal expansion in bimetal materials, changes in environmental temperature result in deflection of the cantilever beam. The tip deflection causes a change in the gap between the capacitor plates, and thereby affects the value of the system capacitance. Therefore, the influence of temperature on the capacitance can be measured. Figure 1(b) shows an element of the bimetallic cantilever beam. Assume two isotropic beams, each with length l, thickness h and width b. The upper and lower material in the bimetallic beam is designated by letter 1 and 2, respectively. The coefficient of thermal expansion and Young's modulus for upper and lower materials are α_1, α_2 and E_1, E_2, respectively. Using the Euler Bernoulli Theorem, the quantity h/l is assumed to be small enough to allow neglecting the shear deformation. The capacitor is attached to the cantilever beam using a short and narrow vertical connecting bar made of the lower beam material. Therefore, any deformation of the connecting bar, as well as its effect on the length of cantilever beam, is neglected. The axial force equilibrium condition along the x-axis of the beam and the bending moment $M(x)$ at a given section of a beam with the cross-sectional area A are [8]

$$\int \sigma \, dA = 0, \qquad \int z \, dA = M(x), \tag{1}$$

where σ is the stress at a given cross-section area of the beam.

As the two capacitor plates come in close contact with each other, charge exchange occurs. Charged objects exert a force on one another, which is called electrostatic force. As shown in Fig. 1(c), the moment for this beam at a given section as the result of the electrostatic force is

$$M(x) = F_e(l - x), \tag{2}$$

where F_e is the electrostatic force on the tip of the bimetallic cantilever beam generated by the two capacitor's plates [9], see Fig. 1(c):

$$F_e = \frac{\varepsilon_0 A_c V_b^2}{2(g_0 - w_t)^2}\left(1 + 0.65\frac{g_0 - w_t}{B_c}\right), \tag{3}$$

where ε_0, B_c, V_b, g_0 and w_t are permittivity of air, width of capacitor plate, bias voltage, initial gap and tip deflection of the cantilever beam, respectively. Additionally, A_c is the effective area of the capacitor plate ($A_c = l_c B_c$, where l_c is the length of the capacitor plate).

The relationship between the stress and the strain based on Euler–Bernoulli beam Theory and use of Hooke's law can be expressed as [10]

$$\sigma = Ez\frac{d^2w}{dx^2} - E\alpha\Delta T, \tag{4}$$

where $w(x)$, ΔT, z are deflection of the beam, temperature changes and the coordinate along the cross section with its origin at the neutral axis of cross section, respectively. The changes in temperature are measured relative to the initial temperature. By substituting (2), (3) and (4) into (1) and integrating both sides with respect to x, a general expression for the deflection of the bimetallic cantilever beam, as a function of temperature changes at any point along the beam, can be obtained as [1]

$$\begin{aligned} w(x) = {} & \frac{6\Delta T n(\alpha_1 - \alpha_2)}{h(n^2 + 14n + 1)}x^2 + \frac{6(1+n)\varepsilon_0 A_c V_b^2}{E_1 b h^3 (n^2 + 14n + 1)(g_0 - w_t)^2} \\ & \times \left(1 + 0.65\frac{(g_0 - w_t)}{B_c}\right)\left(\frac{lx^2}{2} - \frac{x^3}{6}\right), \end{aligned} \tag{5}$$

where $n = E_2/E_1$. Next the input temperature is related with output capacitance changes. The beam deflection, as the result of changes in temperature, causes a change in the gap between the capacitor plates, and thereby affects the value of the system capacitance. The expression for calculating the capacitance of this capacitor with respect to changes in temperature is given by

$$c = \frac{\varepsilon_0 A_c}{g_0 - w_t}, \tag{6}$$

where the tip deflection $w_t = w(l)$ results from (5).

3 Model Performances

In order to obtain an insight and a better understanding of the theoretical model performance, two materials with high difference in their thermal expansion coefficients are considered, i.e. gold and silicon. These two materials and geometrical dimensions of the bimetallic beam are similar to what is typically used in today's MEMS applications. The properties of cantilever beam and capacitor are: length of beam, l, is 100 µm, the width of beam, b, is 20 µm, the thickness of the beam, h, is 1.5 µm, the coefficient of thermal expansion for upper material, α_1, is $2.6 \times 10^{-6}\ \mathrm{K}^{-1}$, the coefficient of thermal expansion for lower material, α_2, is $14.3 \times 10^{-6}\ \mathrm{K}^{-1}$, Young's Modulus for upper material, E_1, is $122 \times 10^9\ \mathrm{N\,m}^{-2}$, Young's Modulus for lower material, E_2, is $78 \times 10^9\ \mathrm{N\,m}^{-2}$, the permittivity of air, ε_0, is $8.854 \times 10^{-12}\ \frac{c^2}{\mathrm{N\,m}^2}$, the width of capacitor plate, B_c, is 50 µm, the length of the capacitor plate, l_c, is 65 µm, the initial gap, g_0, is 3 µm and the bias voltage, V_b, is 24 V.

Because of the high difference in their thermal expansion coefficients, we expect our model to have a large deflection, and therefore a rather high sensitivity. To avoid the pull-in phenomenon [11], i.e. electrostatic instability, the bias voltage is selected

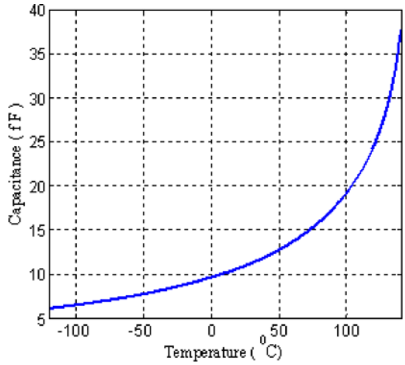

Fig. 2 Capacitance versus temperature

to be $V_b = 24$ volts. This value represents 20 percent of the pull-in voltage. The pull-in voltage represented by V_{pi} is approximated by

$$V_{pi} = \sqrt{\frac{24E_1 I_{eq} g_0^3}{27l^3 A\varepsilon_0}}, \tag{7}$$

where I_{eq} is the equivalent moment of inertia of the cross-section of the beam defined as

$$I_{eq} = \sum_{j=1}^{2} \frac{E_j}{E_1} I_j. \tag{8}$$

As shown in (5) and (6), as environment temperature changes, tip deflection changes cause changes in the capacitance of the proposed model. Using parameters outlined above, effect of temperature variations on capacitance is calculated and shown in Fig. 2. This figure shows that the capacitance increases nonlinearly due to increase of temperature. Furthermore, this figure provides us with an insight into our BMT sensor performance, which is necessary for the next step of our study to obtain optimal sensor performance.

4 Optimization Results Based on Taguchi Method

After obtaining a sensor model that relates temperature input with capacitance output, we can proceed to optimization of the sensor performance. In this paper, sensitivity represented by parameter y is defined as the ratio of capacitance variations in femtofarads (fF) to temperature variations in kelvins (K), i.e.

$$y = \frac{\Delta c}{\Delta T}. \tag{9}$$

To investigate the effects of parameters on sensitivity and to identify the performance characteristics under the optimal sensitivity parameters, the Taguchi quality engineering method (TQEM) is used [4, 5]. The objectives of the Taguchi method for robust parameter design are to establish an optimal design parameter combination which maximizes sensitivity, (9), by a minimum number of experiments. Taguchi method

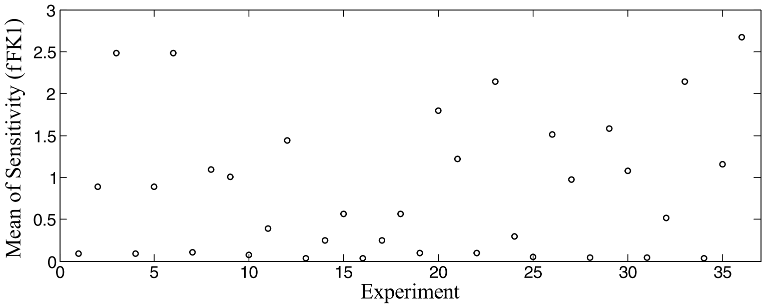

Fig. 3 Mean of sensitivity for each experiment

divides input parameters into two branches: control factors and noise factors. The control factors are used to find the optimal sensitivity in design process and noise factors influence the response of a process, but cannot be economically controlled. Taguchi method has seven steps: definition of a function that needs to be optimized, determination of controllable factors and their levels, selection of a suitable orthogonal array, performing the experiments and measuring output, calculation of S/N ratio and selecting the parameters corresponding to optimal conditions, analyzing the data and prediction of output in optimum case, and finally, as a last step, conducting the confirmation experiment [3, 4]. In the present study, five parameters are used as control factors, where some parameters have two, others have three levels.

Factor A is the coefficient of thermal expansion for lower material. $14.3 \times 10^{-6}\ \mathrm{K}^{-1}$ and $23.6 \times 10^{-6}\ \mathrm{K}^{-1}$ are chosen as first and second levels of factor A, respectively. Factor B is the coefficient of thermal expansion for upper material. $2.6 \times 10^{-6}\ \mathrm{K}^{-1}$ and $4.5 \times 10^{-6}\ \mathrm{K}^{-1}$ are chosen as first and second levels of factor B, respectively. The length of beam, is selected as factor C. 100 μm, 300 μm and 500 μm are chosen as first, second and third levels of this factor, respectively.

Factor D is thickness of the beam. 1.5 μm, 3 μm and 5 μm are chosen as first, second and third levels of factor D, respectively. Factor E is the width of beam. 20 μm, 60 μm and 100 μm are chosen as first, second and third levels of this factor, respectively.

Knowing the number of factors and their levels, a suitable orthogonal array can be selected. These arrays were created by Taguchi method and each variable and setting can be tested equally. Utilizing the Taguchi method, a L_{36} $(2^2 \times 3^3)$ orthogonal array robust design with 36 rows is implemented for the controllable factors (Table 1). Each row corresponds to three experiments in which the controllable factors are held constant, but the noise factor is changed in its range. The bias voltage depends on circuit properties, which is why it is treated as noise factor and assumed to have three levels: 23.5, 24 and 24.5 volts. In order to calculate the sensitivity, (9), of the BMT sensor, we assume in (5) and (6) a temperature variation $\Delta T = 20$ K and a constant initial gap $g_0 = 3$ μm. According to Table 1, totally 108 runs are simulated (three times for each experiment) using our theoretical model, (5) and (6). The mean values of sensitivities for each row of the L_{36} table are illustrated in Fig. 3.

Table 1 Design matrix

Ex.	Level of factors					Ex.	Level of factors				
	A	*B*	*C*	*D*	*E*		*A*	*B*	*C*	*D*	*E*
1	1	1	1	1	1	19	2	1	1	2	1
2	1	1	2	2	2	20	2	1	2	3	2
3	1	1	3	3	3	21	2	1	3	1	3
4	1	1	1	1	1	22	2	1	1	2	2
5	1	1	2	2	2	23	2	1	2	3	3
6	1	1	3	3	3	24	2	1	3	1	1
7	1	1	1	1	2	25	2	1	1	3	2
8	1	1	2	2	3	26	2	1	2	1	3
9	1	1	3	3	1	27	2	1	3	2	1
10	1	2	1	1	3	28	2	2	1	3	2
11	1	2	2	2	1	29	2	2	2	1	3
12	1	2	3	3	2	30	2	2	3	2	1
13	1	2	1	2	3	31	2	2	1	3	3
14	1	2	2	3	1	32	2	2	2	1	1
15	1	2	3	1	2	33	2	2	3	2	2
16	1	2	1	2	3	34	2	2	1	3	1
17	1	2	2	3	1	35	2	2	2	1	2
18	1	2	3	1	2	36	2	2	3	2	3

4.1 Optimization and Analysis of Experimental Results

The target of the Taguchi method is to reduce cost and time of experiments, where a loss function is used to put the cost of deviation from target into perspective. The loss represents a summation of rework, repair, warranty cost plus customer dissatisfaction, bad reputation, and eventual loss of market share for the manufacturer. Taguchi defines the difference between the target value, y_0, of the performance characteristic of a process and the measured value y as a loss function. There are three categories of loss function based on the quality characteristics of the response: the lower the better (LB), nominal is best (NB), and the higher the better (HB) [12]. In this paper, the higher sensitivity is the indication of better performance. Therefore, the loss function of N repeated experiments can be calculated as

$$L_{\mathrm{HB}} = \frac{1}{N}\sum_{m=1}^{N}\frac{1}{y_m^2}. \tag{10}$$

The loss function is then transformed into a signal-to-noise (S/N) ratio, which provides a measure of the impact of noise factors on performance

$$\eta = -10\log(L_{\mathrm{HB}}). \tag{11}$$

The S/N ratio for each row of the L_{36} table is shown in Fig. 4. The larger S/N, the more robust the product is against noise. By averaging the S/N ratios for each factor

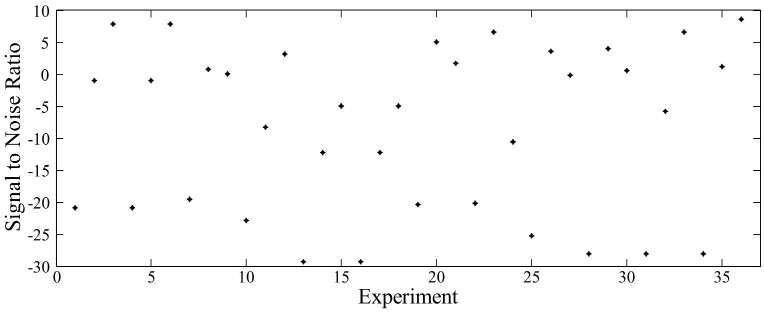

Fig. 4 The S/N ratio *for each experiment*

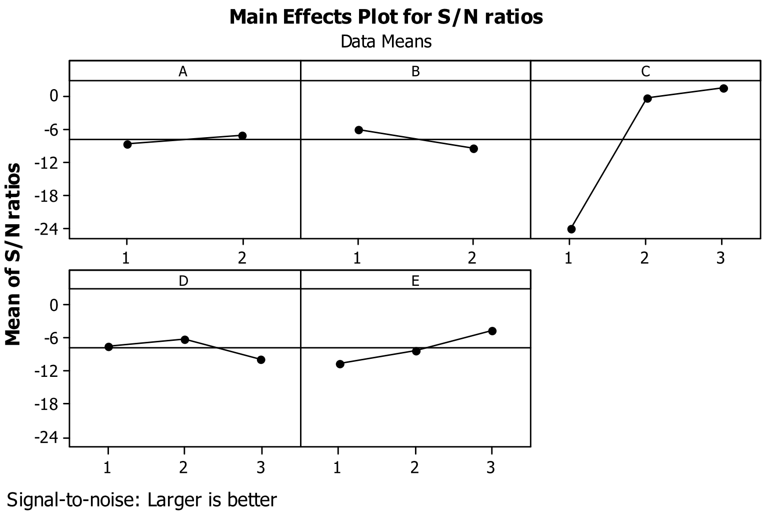

Fig. 5 The effect of parameters on sensitivity

level, we get a response graph for S/N shown in Fig. 5. For instance, the average S/N for A_1 is calculated by averaging S/N ratio for rows 1 to 18, where the level of factor A is at level 1 [3].

As mentioned above, the better performance is indicated by greater values of S/N ratio. Thus, the optimal performance for the sensitivity is obtained at second level of factor A, i.e. the thermal expansion coefficient of lower material ($\alpha_2 = 23.6 \times 10^{-6}\ \mathrm{K}^{-1}$), first level of thermal expansion coefficient of upper material ($\alpha_1 = 2.6 \times 10^{-6}\ \mathrm{K}^{-1}$), third level of beam length (500 μm), second level of height of each strip (3 μm), and third level of beam width (100 μm).

In the next step, the relative importance of the input parameters with respect to the sensitivity is studied. To do this, analysis of variance (ANOVA) is used and the optimal combinations of input parameters are determined more accurately. It also provides the percent contribution of the input parameters on the sensitivity of the bimetallic micro thermal sensor.

The results of analysis of variance analysis for the sensitivity at 90 % confidence level (risk $\alpha = 0.1$) are presented in Table 2. In this table, Adj MS_i designates Adjusted mean sum of squares for factor i and is defined as

$$\mathrm{Adj}\,MS_i = \frac{\mathrm{Adj}\,SS_I}{DF_I} \tag{12}$$

where Adj SS_i and DF_i are adjusted sum of squares and degree of freedom for factor i, respectively. A detailed explanation of these statistical terms is presented in [13]. Additionally, DF_i is defined for each factor i separately and is equal to number of the levels minus one. Degree of freedom, DF, for error is the difference between total DF and sum of the DF_i for all input factors. The total degree of freedom is defined as the required number of comparisons between design factors to determine which level is better [14].

In ANOVA, *F-test* by means of F_value can be used to test if the estimates are significantly different using a desirable confidence level [5]. F_value for factor i is defined as

$$F_\text{value} = \frac{\mathrm{Adj}\,MS_i}{\mathrm{Adj}\,MS_E}, \tag{13}$$

where Adj MS_E is adjusted mean sum of squares for error. The degree of significance of the computed F_value can be determined by looking up F-tables. The greater F_value shows that the variation of the parameter has a larger impact on the output performance characteristics. Therefore, when the F_value of a parameter is greater than F_{α,ν_1,ν_2}*-value* provided by the confidence table, then we conclude that the parameter is significant. The variables α, ν_1 and ν_2 are risk, degrees of freedom (DF) associated with input factor, and error, respectively.

Percent contribution indicating the relative power of a factor on the output factor is also reported. The percent contribution is a function of the adjusted sums of squares for each significant item and is defined as

$$\rho(\%) = \frac{\mathrm{Adj}\,SS_i - DF_i \times \mathrm{Adj}\,MS_E}{SS_T} \times 100, \tag{14}$$

where SS_T is the total sum of square. A small variation will have a large influence on the output for factors which have high percent contribution [15, 16].

The adequacy of the experiment can also be estimated by the percent contribution due to error. The percent contribution due to error is 13.91 %. This value is rather low and therefore, it is assumed that no important factors are omitted from the experiment [17].

Referring to Table 2, controllable factors can be ranked as C, E, B, A and D. Thus, the most significant factor affecting the sensitivity is the length of the cantilever beam (82.03 %) followed by width of the cantilever beam (3.49 %) and coefficient of thermal expansion for the upper material (1.35 %). According to the F_value of the remaining factors, the percent contribution of the thermal expansion coefficient of lower material and height of each strip are not significant.

4.2 Prediction and Verification Experiments

The last step in Taguchi experimental design requires validation of the conclusions drawn during the analysis by performing confirmation studies. A new experiment is

Table 2 ANOVA test results for sensitivity

Parameters	DF_i	Seq SS_i	Adj SS_i	Adj MS_i	F-value	Contribution (ρ%)
A	1	22.81	22.81	22.81	1.03	0.01
B	1	87.66	87.66	87.66	3.94[a]	1.35
C	2	4049.71	4022.3	2011.15	90.39[a]	82.03
D	2	6.81	15.16	7.58	0.34	−0.79
E	2	214.23	214.23	107.11	4.81[a]	3.49
Error	21	467.23	467.23	22.25		13.91
Total	29	4848.44				100

[a]???

performed using the optimum conditions provided by the earlier Taguchi analysis. The response under these conditions is also predicted. Using the optimal levels of the parameters, the predicted S/N ratio for the optimal case is

$$\eta = \eta_m + \sum_{i=1}^{p} (\bar{\eta}_i - \eta_m), \tag{15}$$

where $\bar{\eta}_i$ is the mean of S/N ratio at the optimum control factor settings, η_m is mean of S/N ratio and p represents the number of control factors [4]. The comparison between the predicted and the experimental value of the sensitivity using the optimal parameters shows that improvement in S/N ratio from the initial settings (–20.84 dB) to the optimal settings (8.63 dB) is 29.47 dB. Also The BMT sensor sensitivity is increased by a factor of 29.74. It can be claimed that the sensitivity is significantly improved using this approach. Hence, the Taguchi methodology is quite effective and has enabled significant design improvement. It should also be mentioned that the 29.74 times improvement uses a baseline for comparison where all input parameters are set to their lowest level (A_1, B_1, C_1, D_1, E_1). Using the lowest values is common when additional information or limitations are not known. However, if there is prior information on any parameter and its effect on the output, then one may actually use those settings as the baseline. It is extensive practical experience of the authors that Taguchi method seems to always identify parameter settings that significantly improve output compared to those selected based on best educated guess.

5 Concluding Remarks

The rapid growth in MEMS industries has enabled great advancement in the field of micro sensors. In this study, optimization of a bimetallic micro thermal sensor using Taguchi design method is presented. The BMT sensor is a simple structure, where the deflection of a cantilever beam, as result of input temperature change, corresponds to output capacitance change. First, the theoretical expression for the relation between input temperature and output capacitance change is shown. Model simulation shows that the capacitance increases nonlinearly with the increase in temperature.

This model is then used with the Taguchi method to obtain the optimal design of the BMT sensor with respect to the S/N ratios. Analysis of variance is also conducted and found that the most important parameter affecting sensitivity is the length of bimetallic cantilever beam. The thermal expansion coefficient of the lower material, as well as the height of the two beams, is not statistically significant. The conclusions drawn during the analysis step are also validated with a confirmation experiment. Using the optimum settings, the S/N ratio improves by 29.47 dB, which corresponds to an increase of 29.74 times in the sensitivity.

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