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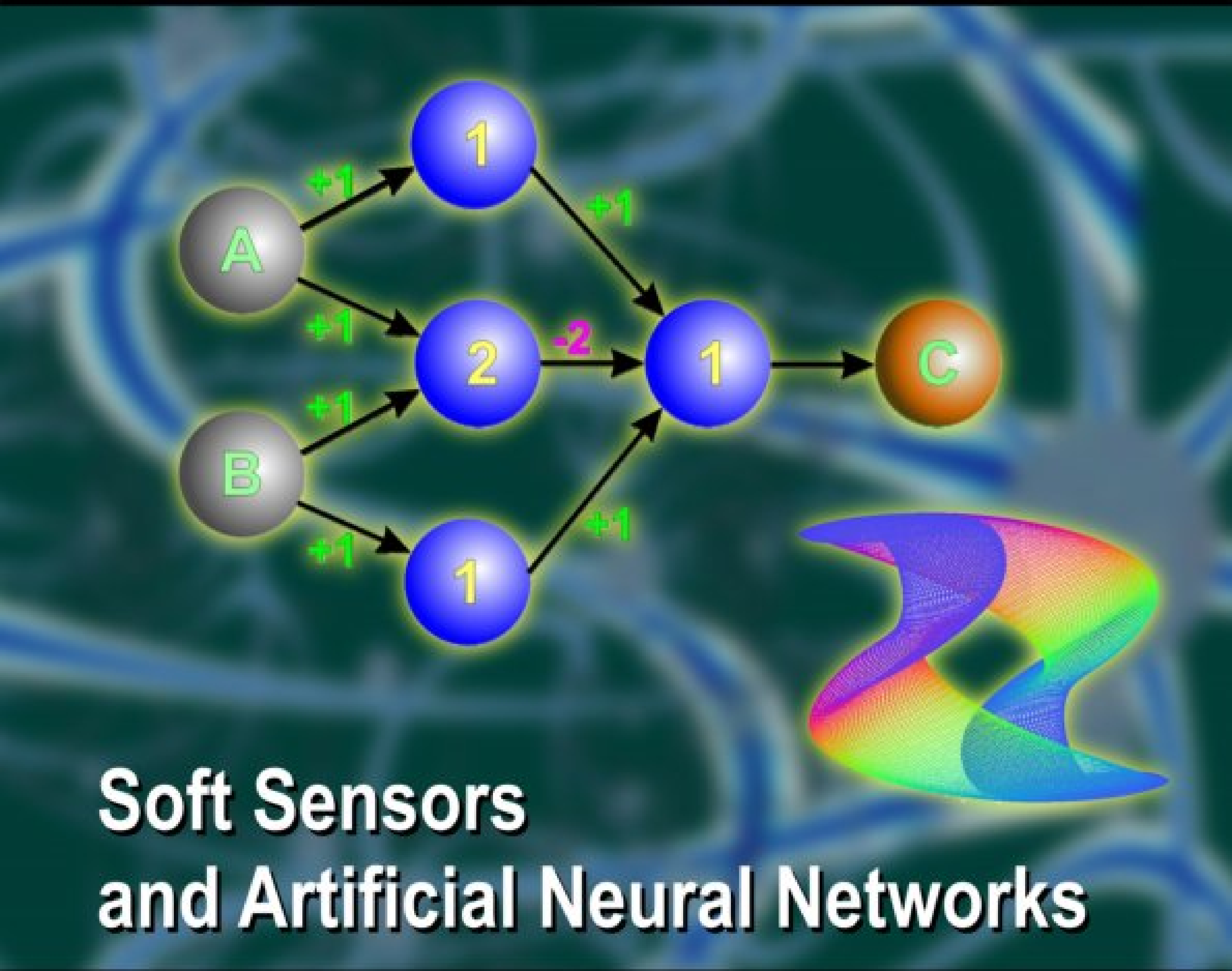

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MEMS Capacitive Thermal Sensor Sensitivity Investigation Using Full Factorial Design Method

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Abstract: In this paper a sensitivity of MEMS capacitive thermal sensors based on deflection of a bimetallic cantilever beam was investigated. Using design of experiment method, and applying a 2^5 factorial design the effect of factors in this sensor was calculated and main factors that affect on sensor's sensitivity were identified. Analysis of variance for the main factors of design and their interactions were studied for their significance.

Keywords: MEMS; Bimetallic cantilever; Full factorial design; Sensitivity; Thermal Sensor

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1. Introduction

MEMS technologies for fabricating tiny sensors and actuators are being developed successfully throughout the world. The field of MEMS is large and growing, with numerous means reported for both sensing and actuation on-chip. Compared to conventional systems, MEMS are more lightweight, smaller and less power consuming. All these qualities make MEMS very promising devices for space applications. However, to be space compatible, they need a robust behavior towards harsh environmental conditions, such as vacuum, temperature cycles, and irradiation. Thermal sensors are one of the most applications of the MEMS sensors and MEMS capacitive thermal sensor based deflection of bimetallic cantilever beam is the one of the last type of it. These microsensors were used to measure the temperature rising due to the change of a comb drive capacitance. Bimetallic microbeams can provide sensitive structure for fabrication of temperature sensors that cover the wide range of temperature based on these structures [1]. Sensitivity of this sensor depends on several factors. Effect of each factor on sensitivity may be not equal. With investigation of these factors effect the sensitivity of thermal sensors can be optimized. Several methods can be used for calculate the effect of each factors on sensitivity of this thermal sensor. One of the most applied methods for these purposes is Full Factorial Design method (FFD) that is used to seek the active factors, which affect on the system performance, and aid decision making in such a way that the optimum solution can be found. The traditional approach to experimental work is to vary one factor at a time and to hold all other factors fixed. This method does not produce satisfactory results in a wide range of experimental settings. If interaction exists between the factors, there is no guarantee that the final set of operating conditions will be the optimum [2]. Box and Meyer [3] stated that highly factorial designs are powerful tools for identifying important factors to improve the system performance. Madu [4] had already applied 2^{4-1} fractional factorial experiment design to analysis the management of maintenance floats. Murugabaskar and Huang [5] had worked on the application of full factorial design or fractional factorial design. They concluded that it is an efficient tool for analyzing the system performance.

In this article sensitivity of MEMS capacitive thermal sensors based on tip deflection of bimetallic cantilever beam was investigated. Using 2^5 full factorial designs with five main factors and two levels for them, the effect of factors and their interaction that affect on sensitivity of thermal sensor were studied.

2. MEMS Capacitive Thermal Sensor Structure

Fig. 1 shows a thermal sensor whose sensitivity was studied in this work. Bimetallic cantilever beam was deflected because of different temperature expansion coefficient of selected materials due to temperature rising. Due to the tip deflection of bimetallic cantilever beam, the effective surfaces of comb drive plates and its equivalent capacitance was changed. Which means the influence of temperature on the capacity of the system can be easily measured [1]. This model is a Micro Electro Mechanical System that consists of a bimetallic cantilever beam and one comb drive that is jointed at the tip of the cantilever beam. This system acts as a MEMS capacitive thermal sensor.

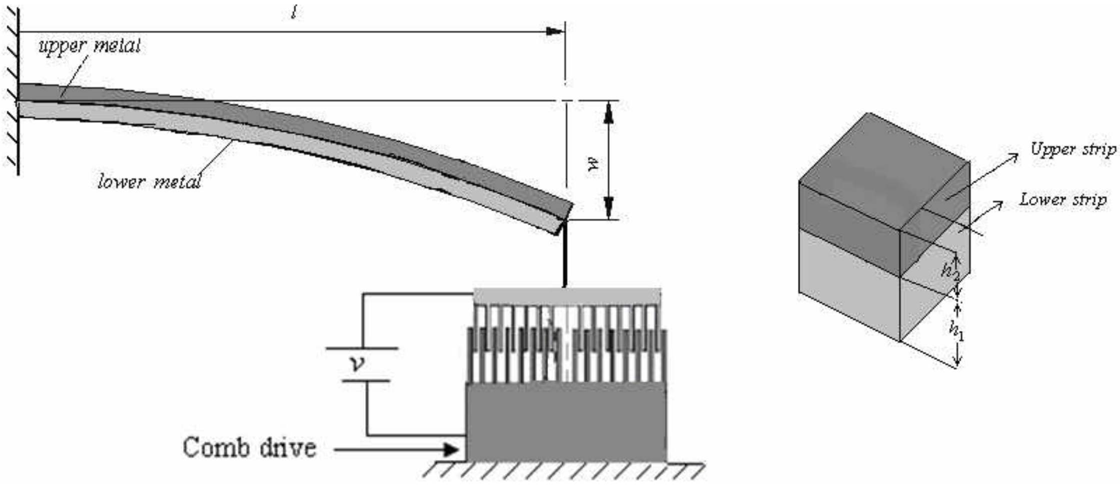

Fig.1. MEMS capacitive thermal sensor [1].

By assumption that the width of bimetallic cantilever beams are same, the equation which indicates the relationship between tip deflection of bimetallic cantilever beam with respect to temperature rising is derived as follow [1]:

$$w = \frac{3nh_1h_2(h_1 + h_2)(\alpha_1 - \alpha_2)\Delta T}{h_1^{\ 4} + n^2h_2^{\ 4} + nh_1h_2(6h_1h_2 + 4h_1^{\ 2} + 4h_2^{\ 2})} l^2 \tag{1}$$

where n, $h_1, h_2, \alpha_1, \alpha_2, \Delta T, l$ are ratio of young's modulus of upper layer on young's modulus of lower layer, height of lower layer, height of upper layer, thermal expansion coefficient of lower material, thermal expansion coefficient of upper material, temperature rising and length of bimetallic cantilever beam. To calculate the capacity of the comb drive due to change of its surfaces, the following equation can be used [1]:

$$C = 2N\frac{\varepsilon_0 B}{g}(d_0 - \frac{3nh_1h_2(h_1 + h_2)(\alpha_1 - \alpha_2)\Delta T}{h_1^{\ 4} + n^2h_2^{\ 4} + nh_1h_2(6h_1h_2 + 4h_1^{\ 2} + 4h_2^{\ 2})} l^2), \tag{2}$$

where N is the number of combs, g is the gap, B is the width of plates of comb drive capacitor and d_0 is the initial effective height of comb drive plates (figure2). Here sensitivity can be defined as a function of capacitance and temperature as below:

$$S = \frac{C}{\Delta T} \tag{3}$$

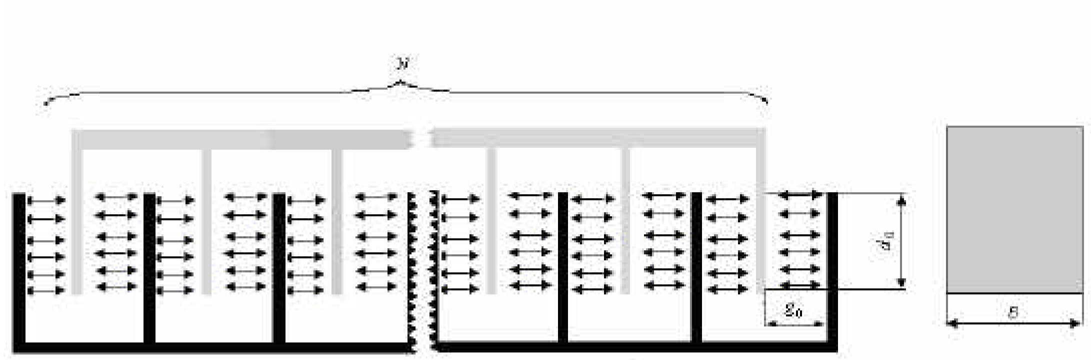

Fig.2. Schematic of the sensor's comb drive.

Dimensional parameters of sensor's comb drive are $d_0 = 10\mu m, g = 25\mu m, B = 15\mu m, N = 14$. These parameters are the same as those for the sensor that designed in [1].

3. Full Factorial Design

Factorial design is an optimization process, which is used for preliminary evaluation of the experimental variables of a system. It allows the determination of their effects and significances [6]. In this article experiments were carried out using 2^5 factorial design. Maximum and minimum selected levels of each factor were shown in Table1.

Table1. Factors and their levels used in the factorial design.

Variable	Low level (-)	High level (+)
(A): a_1 - Thermal expansion coefficient of lower material (k^{-1})	2.6	4.6
(B): a_2 - Thermal expansion coefficient of upper material (k^{-1})	14.3	23.6
(C): h_1 - height of lower strip (mm)	1.8	4.0
(D): h_2 - height of upper strip (mm)	1.8	4.0
(E): l- Length of bimetallic cantilever beam (mm)	300	500

In this work all possible combination of factor levels were investigated. For this purpose, 32 run using Eq. (3) by applying given values of factors showed in Table 1 were done in order to calculate the sensor sensitivity. The results of experiments and their corresponding sensitivity are shown in Table 2.

Table 2. Design matrix and the results of sensitivity.

	Factors					Sensitivity (S)		Factors					Sensitivity (S)
Experiment	A	B	C	D	E	($fF/^{\circ}C$)	Experiment	A	B	C	D	E	($fF/^{\circ}C$)
1	-	-	-	-	-	0.620	17	+	-	-	-	-	0.531
2	-	-	-	-	+	1.201	18	+	-	-	-	+	0.946
3	-	-	-	+	-	0.485	19	+	-	-	+	-	0.465
4	-	-	-	+	+	0.817	20	+	-	-	+	+	0.763
5	-	-	+	-	-	0.453	21	+	-	+	-	-	0.380
6	-	-	+	-	+	0.729	22	+	-	+	-	+	0.527
7	-	-	+	+	-	0.443	23	+	-	+	+	-	0.403
8	-	-	+	+	+	0.701	24	+	-	+	+	+	0.589
9	-	+	-	-	-	0.866	25	+	+	-	-	-	0.727
10	-	+	-	-	+	1.903	26	+	+	-	-	+	1.502
11	-	+	-	+	-	0.644	27	+	+	-	+	-	0.626
12	-	+	-	+	+	1.302	28	+	+	-	+	+	1.201
13	-	+	+	-	-	0.554	29	+	+	+	-	-	0.437
14	-	+	+	-	+	1.000	30	+	+	+	-	+	0.684
15	-	+	+	+	-	0.553	31	+	+	+	+	-	0.491
16	-	+	+	+	+	1.000	32	+	+	+	+	+	0.834

where *A, B, C, D* and *E* respectively are the experimental factors that represent a_1, a_2, h_1, h_2 and *l*. The main effect for each factor and their interaction effects can be calculated using the Table 2 and using this concept that the effect of each factor is the change in response by a change in the level of the factor [7]. Based on this concept, the effect of a factor can be calculated as:

$$\text{Effect of a factor} = \frac{\sum \text{responses at high levels} - \sum \text{responses at low levels}}{\text{half the number of runs in the experiment}} \tag{4}$$

Considering signs and results in Table 2, main effect and interaction effects of factors can explain in figure 3. In this figure the effects of all of the factors and their interactions were shown.

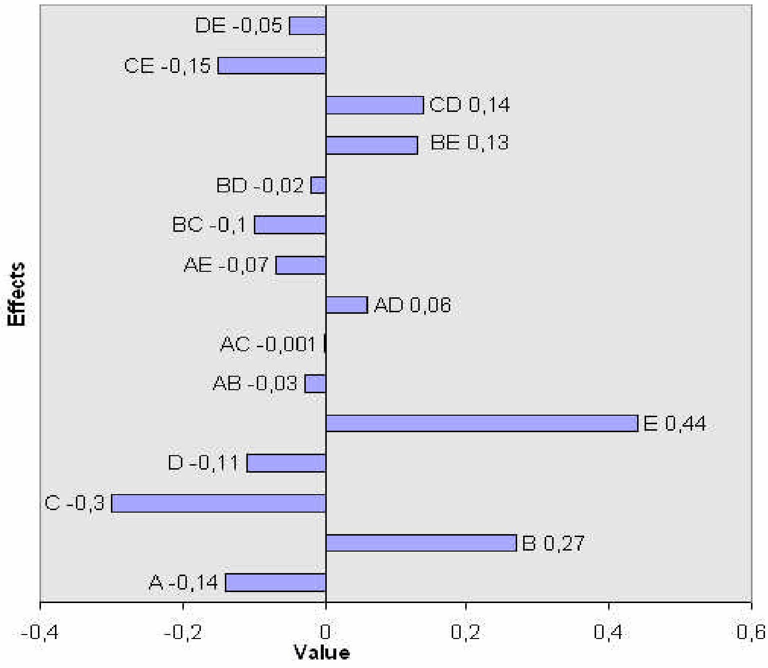

Fig.3. The effect of factors and their interactions on sensitivity.

As an example figure 4 illustrates that there is an interaction effect between the thermal expansion coefficient of lower strip ($\boldsymbol{a}_1$) and the height of upper strip (h_2) on sensor sensitivity.

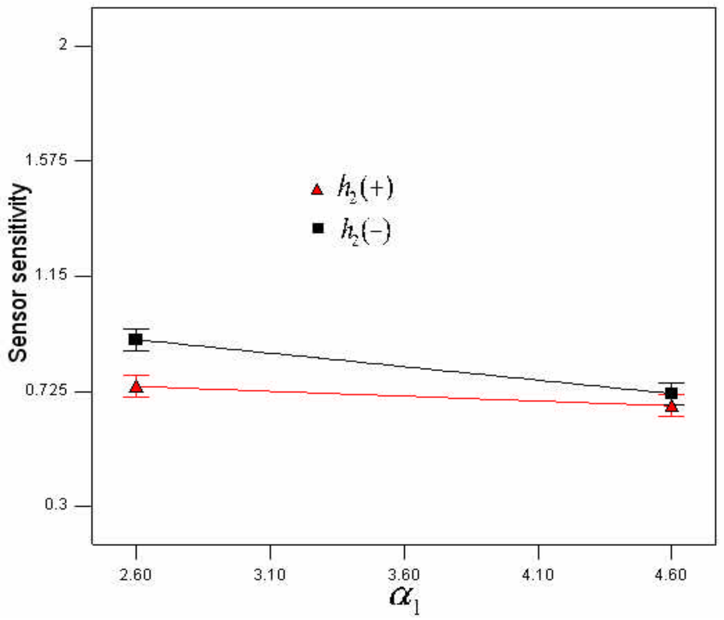

Fig.4. Interaction effect of Thermal expansion coefficient of lower strip ($\boldsymbol{a}_1$) and height of upper strip (h_2).

4. Analysis of Variance (ANOVA)

In the 2-level factorial designs, normal plot can be used in order to choose significant effects of factors. If the effects represent a sample from a normal population, we would expect to see them form an approximate straight line on a normal probability plot of the effects. Usually only a few effects turn out to be important. They show up as outliers on the normal probability plot. The ordered effects plotted on half normal probability plot are shown in Figure 5. It is seen that more effects and interactions lie approximately along a straight line, while all main factors and their interactions that involve AD, AE, BC, BD, CD and CE are not in the direction of the crossed straight line and can be significant factors.

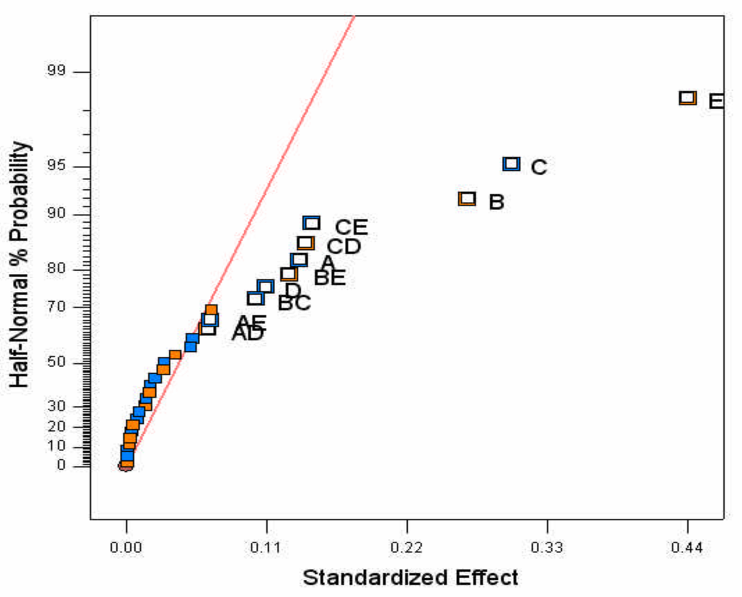

Fig.5. Half normal plot of the effects.

These ANOVA are based on reduced models was carried out by first fitting the full model according to the constraints of the design and eliminating non-significant terms. Analysis of variance for this model is shown in Table 3.

Table 3. ANOVA result for sensitivity effected factors.

Source	Sum of Squares	Degree of freedom	Mean Square	F-value	P-value
Model	3.680	11	0.330	57.04	< 0.0001
A- a_1	0.150	1	0.150	24.96	< 0.0001
B- a_2	0.570	1	0.570	97.15	< 0.0001
C- h_1	0.730	1	0.730	123.78	< 0.0001
D- h_2	0.095	1	0.095	16.18	0.0007
E- l	1.540	1	1.540	262.52	< 0.0001
AD	0.032	1	0.032	5.53	0.0291
AE	0.034	1	0.034	5.86	0.0251
BC	0.082	1	0.082	13.89	0.0013
BE	0.130	1	0.130	22.05	0.0001
CD	0.160	1	0.160	26.79	< 0.0001
CE	0.170	1	0.170	28.69	< 0.0001
Residual	0.120	20	0.059	-	-
Total	3.800	31	-	-	-

The Model F-value of 57.04 implies that the model is significant and there is only a 0.01 percent chance that a critical F-value could occur due to noise. Also P-values less than 0.05 indicate model terms are significant so in this case all selected main factors and AD, AE, BC, BE, CD, CE interactions is significant that effect on the sensitivity.

5. Conclusions

In the present work sensitivity of MEMS capacitive thermal sensors was studied, and by applying the FFD method effective parameters that affect on sensor sensitivity were identified. It was seen that E factor which represents length of bimetallic cantilever beam has maximum effect and height of upper strip has minimum effect on sensor sensitivity. In addition CE interaction that represents the interaction of length of bimetallic cantilever beam and height of lower strip has maximum effect on sensor sensitivity between other interactions. Using ANOVA for obtain the significant factors it was identified that the all main factors and some interactions have significant effect on sensor sensitivity.

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