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Effect of Different Wheatstone Bridge Configurations on Sensitivity and Linearity of MEMS Piezoresistive Intracranial Pressure Sensors

Mazita Mohamad[1*], Norhayati Soin[2,4,5], Fatimah Ibrahim[3,4,6]

[1]Faculty of Electrical and Electronic Engineering,
Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor, MALAYSIA

[2]Department of Electrical Engineering, Faculty of Engineering,
Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor, MALAYSIA

[3]Department of Biomedical Engineering, Faculty of Engineering,
Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor, MALAYSIA

[4]Centre for Innovation in Medical Engineering, Faculty of Engineering,
Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor, MALAYSIA

[5]Centre of Printable Electronics,
Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor, MALAYSIA

[6]University of Malaya, Centre for Innovation and Commercialization,
Universiti Malaya, 50603 Kuala Lumpur, MALAYSIA

*Corresponding Author

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Abstract: Monitoring of intracranial pressure for traumatic brain injured patients is very critical. Many intracranial pressure monitoring systems use the MEMS piezoresistive pressure sensor to measure the signal. The piezoresistive pressure sensor is very sensitive to temperature change. Hence, the Wheatstone bridge circuit is normally employed in this type of sensor to lessen the effect of temperature variation. This paper presents the effect of using different configurations of Wheat-stone bridge on the sensitivity and linearity performances of the piezoresistive intracranial pressure sensor. Six designs comprise of 3-turns meander shaped piezoresistors ranging from full-bridge to quarter-bridge were simulated using COMSOL Multiphysics. Based on the simulation results, the number and position of active piezoresistors were found to greatly influence the sensitivity of the sensor. The latter also influenced the sensors' linearity error. The active perpendicular piezoresistor produced the higher change in resistance which gave rise to higher sensitivity, while at the same time caused the higher nonlinearity performance. Overall, the piezoresistive intracranial sensor comprising of full-bridge Wheat-stone circuit produces the highest sensitivity and medium linearity.

Keywords: Pressure Sensor, MEMS, Wheatstone Bridge

Corresponding author: mazita@uthm.edu.my

1. Introduction

The application of MEMS piezoresistive pressure sensors could be found in the majority of fields including in the health sectors. According to Citerio and Andrews (2009) [1], the contemporary microsensors to measure the intracranial pressure are the piezoresistive and also the optical fibre types. Intracranial pressure is one of the signals used to monitor the brain health of those suffered from traumatic brain injury [2],[3]. Although the piezoresistive pressure sensors have low sensitivity performances compared to the capacitive type, they have good linearity performances. The cheaper cost and easy to fabricate are also the appealing factors, apart from the simple circuit required for the integration.

However, the operation of piezoresistive pressure sensor is prone to the temperature changes. This is because the properties of materials used to make piezoresistors are sensitive to temperature. Hence, the piezoresistors used in the sensor are normally arranged in a Wheatstone bridge configuration to compensate the effect [4]-[11].

This paper reports on the performances of MEMS piezoresistive intracranial pressure sensor of different Wheatstone bridge configurations, viz. quarter-bridge, half-bridge and full-bridge. The same piezoresistors are used in all circuit configurations. The simulation results in terms of sensitivity and linearity are compared and analysed here.

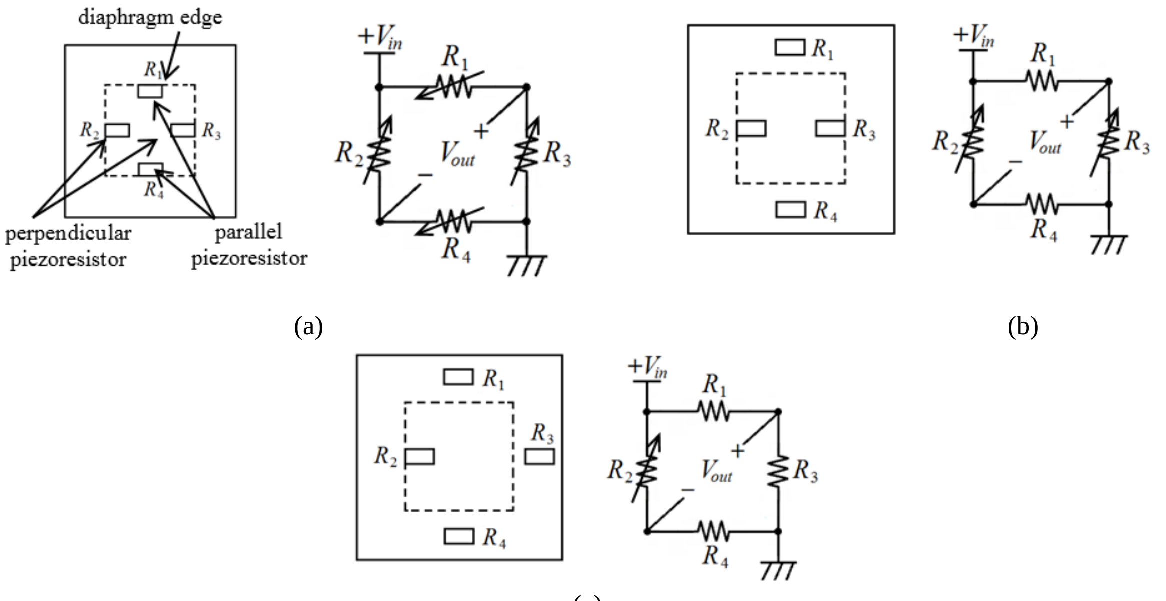
2. Wheatstone Bridge Circuit of Piezoresistive Pressure Sensor

For a diaphragm-based pressure sensor, the stress effect of piezoresistive materials put on the diaphragm has been manipulated as resistors. These piezoresistors are arranged in the Wheatstone bridge circuit as depicted in Fig. 1(a)-(c) for full, half and quarter-bridge configurations. The numbers of active resistors on each configuration are 4, 2 and 1, respectively. When no pressure is applied, the output voltage, V_{out} is 0 V as all the piezoresistors are equal to $R_0(1+\alpha\Delta T)$. When the pressure is applied, the diaphragm is under stress. The active piezoresistors, which are positioned in the high stress regions on the diaphragm are strained, hence change their values to $R_0(1+\alpha\Delta T+\pi_l\Delta\sigma_l+\pi_t\Delta\sigma_t)$ where α is the temperature coefficient of resistance. π_l and π_t are the longitudinal and transverse piezoresistive coefficient, respectively. Meanwhile ΔT, $\Delta\sigma_l$, and $\Delta\sigma_t$ are the changes in temperature, longitudinal stress and transverse stress, respectively [4,8].

The active perpendicular resistors (R_2 and R_3) experience the longitudinal stress and the active parallel resistors (R_1 and R_4) undergo the transverse stress [10,12]. A longitudinal tensile stress increases the resistivity of p-type resistors, while a transverse stress has the opposite effects [4]. Hence, the V_{out} changes accordingly due to these changes. Assume that $\Delta R_1=\Delta R_4$ and $\Delta R_2=\Delta R_3$, thus, the V_{out} expressions for the full-bridge (Fig. 1(a)), half-bridge (Fig. 1(b)) and quarter-bridge (Fig. 1(c)) are shown in (1), (2) and (3), respectively.

$$V_{out(FB)}=V_{in}\left(\frac{\pi_l\Delta\sigma_l-\pi_t\Delta\sigma_t}{2(1+\alpha\Delta T)+\pi_l\Delta\sigma_l-\pi_t\Delta\sigma_t}\right) \tag{1}$$

$$V_{out(HB)}=V_{in}\left(\frac{\pi_l\Delta\sigma_l}{2(1+\alpha\Delta T)+\pi_l\Delta\sigma_l}\right) \tag{2}$$



(a)

(b)

(c)

Fig. 1 - Schematic and its equivalent circuit of piezoresistive sensor of different Wheatstone bridge circuit configuration (a) Full-bridge Wheatstone circuit: All four piezoresistors are placed at the diaphragm edges, acting as the sensing elements, i.e. active piezoresistors; (b) Half-bridge Wheatstone circuit: Two piezoresistors at the diaphragm edges are active elements. The other two piezoresistors are passive elements; (c) Quarter-bridge Wheatstone circuit: Only one piezoresistor is active element. The rest are passive elements

$$V_{out(QB)} = V_{in}\left(\frac{1}{2} - \frac{1+\alpha\Delta T}{2(1+\alpha\Delta T)+\pi_l\Delta\sigma_l}\right) \tag{3}$$

Differentiating the V_{out}/V_{in} with respect to stress and assuming $\alpha\Delta T << 1$, $\pi_l\Delta\sigma_l << 1$ and $\pi_t\Delta\sigma_t << 1$, the sensitivity of three Wheatstone bridge circuits are summarised in Table 1.

Meanwhile, differentiating the V_{out}/V_{in} with respect to temperature and using the assumptions above, one could see that the sensitivity is independent to temperature variation. Since $\pi_l \approx -\pi_t$ for p-type piezoresistor, therefore the output of the full-bridge circuit is approximately equivalent to the single resistor but with improve temperature variation.

3. Methodology

To study the effect of number of sensing elements in the intracranial pressure sensor, the six designs summarised in Table 2 were used in the project. All the designs used the 3-turns piezoresistors regardless active or passive resistors. The resistors were oriented in <110> direction with the piezoresistive bars of p-type and the connecting bars of Al. The diaphragm and substrate were of (100) n-type. Geometric parameters of the resistor and diaphragm are depicted in Fig. 2.

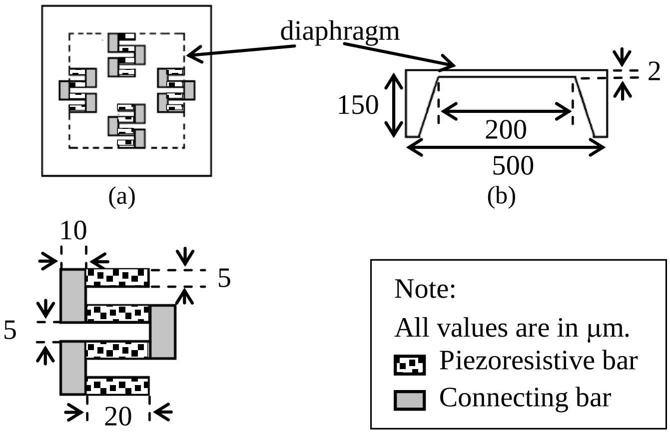
COMSOL Multiphysics was used to simulate the sensors. Tetrahedron and quad shapes were applied for the meshes. As the sensor's application is to measure the intracranial pressure, the operating range of pressure set in the simulation was 0 – 100 mmHg. Parametric Sweep function was used to obtain the sensing outputs in multiple of 10 mmHg pressure per step. The input voltage, V_{in} was set to 1 V.

Table 1 - Summary of the approximated $d(V_{out}/V_{in})/d\sigma$

Wheatstone Bridge	Approximated Expression
Full-bridge	$\frac{1}{2}(\pi_l - \pi_t)$
Half-bridge	$\frac{1}{2}\pi_l$
Quarter-bridge	$\frac{1}{4}\pi_l$

Table 2 - Designs of Piezoresistive Intracranial Pressure Sensors

Model Name	Description
FB	Full-bridge
HB-A	Half-bridge (Active: R_2 and R_3 i.e. perpendicular resistors) (Passive: R_1 and R_4 i.e. parallel resistors)
HB-B	Half-bridge (Active: R_1 and R_4 i.e. parallel resistors) (Passive: R_2 and R_3 i.e. perpendicular resistors)
HB-C	Half-bridge - combination (Active: R_3 and R_4) (Passive: R_1 and R_2)
QB-A	Quarter-bridge (Active: R_2, i.e. perpendicular resistor) (Passive: R_1, R_3 and R_4)
QB-B	Quarter-bridge (Active: R_1, i.e. parallel resistor) (Passive: R_2, R_3 and R_4)



(a) (b) (c)

Fig. 2 - (a) Arrangement of piezoresistors for full-bridge Wheatstone circuit; (b) Dimension of diaphragm; (c) Geometric parameters of piezoresistors

4. Results and Analysis

4.1 Analysis of Sensitivity of Different Wheatstone Bridge Configurations

Fig. 3 shows the output voltage, V_{out} of six different configurations of intracranial pressure sensors. The steeper line indicates the higher sensitivity. The full-bridge has the highest sensitivity, 0.114 mV/V/mmHg, followed by the half-bridge with active perpendicular piezoresistors (HB-A), i.e. 72% of FB. Meanwhile, the quarter-bridge with active R1 (QB-B) has the lowest sensitivity, 0.019 mV/V/mmHg, which is 17% of full-bridge sensitivity. Even though the percentage is lower than the theory, but the trend is consistent, i.e. the sensitivity is greatly improved with more resistors acting as the sensing elements, i.e. the active piezoresistors. This is because the passive piezoresistor does not change its electrical properties when the pressure changes as depicted in Fig. 4. The lower results are due to the piezoresistors are subjected to the combined effect of longitudinal and transverse effect rather than on the uniaxial stress only [10],[13].

Despite that, the sensitivity of quarter-bridge with active R2 (QB-A) is 37% of FB, higher than that of half-bridge with active parallel piezoresistors (HB-B). This clearly indicates the change in resistance of active perpendicular piezoresistor is larger than that of parallel piezoresistor as illustrated in Fig. 4. This is because the change depends on the piezoresistive coefficients. The longitudinal coefficient is larger than that of transverse one [13]. Hence, the active perpendicular piezoresistor is more prominent in producing higher sensitivity compared to the parallel one.

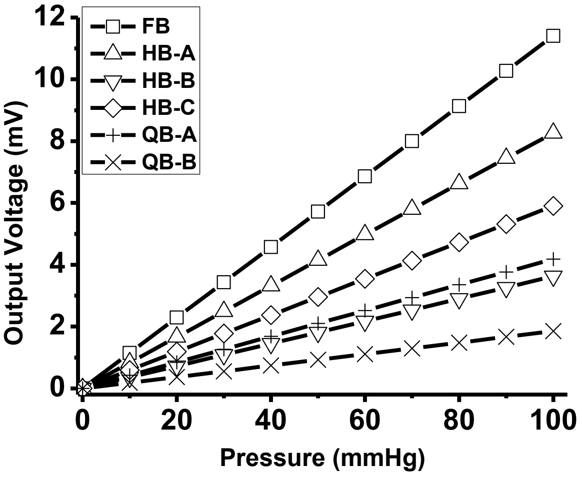


Fig. 3 - Output voltage of the sensors

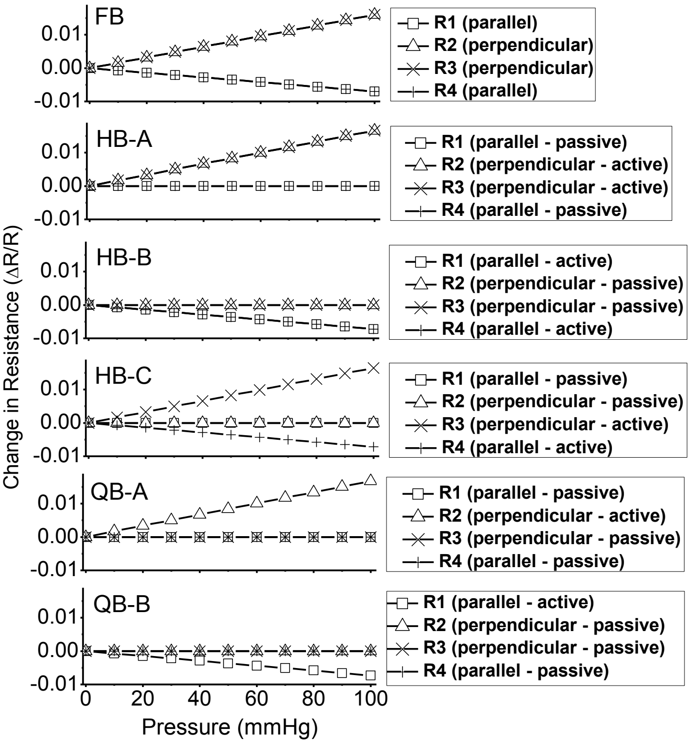


Fig. 4 - Change in resistance of the sensors

4.2 Analysis of Nonlinearity of Different Wheatstone Bridge Configurations

Overall, the nonlinearity errors of all the circuit configurations are very small. From the percentage of nonlinearity indicated in Table 3, the relatively high nonlinearity error is obtained when the perpendicular piezoresistor(s) is active (QB-A and HB-A). Meanwhile, the ones with active parallel piezoresistor(s), i.e. HB-B and QB-B, have the least linearity errors. Accordingly, the sensors which have both active perpendicular and parallel piezoresistors fall in between. This is probably due to the shape of piezoresistor used in the designs. The difference in stress experienced by the piezoresistive bars is significant with the increasing number of piezoresistive bars, and this contributes to the linearity error [14]. Since the longitudinal piezoresistive coefficient of <110> p-type is larger than the transverse coefficient, therefore the effect is more pronounced on active perpendicular piezoresistor.

The Wheatstone bridge circuit is inherently nonlinear, and its value depends the number of mechanically loading resistors [4]. However, in this study, the Wheatstone bridge configurations did not seem to affect the linearity of the sensor. This is due to its linearity error depends on the absolute value of change in resistance [15]. However, when both perpendicular and parallel piezoresistors are mechanically loaded, i.e. for FB and HB-C, the Wheatstone bridge configurations do influence the linearity error. The relative changes of these resistors compensate each other making the sensors' nonlinearity lower than the ones with only active perpendicular piezoresistors [15].

Table 3 - Designs of Piezoresistive Intracranial Pressure Sensors

Model Name	Nonlinearity (%)
FB	0.00112
HB-A	0.00208
HB-B	9.25669E-4
HB-C	0.00114
QB-A	0.00208
QB-B	9.40212E-4

5. Conclusion

The sensitivity of piezoresistive intracranial pressure sensor is very much affected by the Wheatstone bridge circuit configurations. The configuration with the greatest number of active piezoresistors gives the highest sensitivity. Relative comparison shows that the sensors of half-bridge and quarter-bridge with active perpendicular piezoresistor(s) produce higher sensitivity than those of active parallel piezoresistor(s). However, it is at the expense on the linearity. Apparently, the linearity is very much affected by the type of active piezoresistors rather than on the Wheatstone bridge configurations.

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