An Electronic Skin Readout System for Liquid Metal based Flexible Resistive Sensor Array

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Abstract - Liquid metal alloy, incorporated with microfluidic manipulation, has become a promising candidate for flexible resistive sensor array (RSA) that can imitate the functions of human skin. One advantage of RSA with shared rows and shared columns is to reduce the number of wires from M × N to M + N (rows: M and columns: N) and hence to greatly lessen the complexity and burden on the electrical system. The associated drawback is the crosstalk effect between adjacent elements during measurement. Although many literatures have reported several methods to resolve this limitation, almost all of them focus only on the high resistance value (≥100 Ω) RSA. There is a lack of detailed experimental data that addresses low resistance RSA with sensing elements below 100 Ω. Here, we aim to fill the gap of this field. We established two common RSA readout systems, i.e. zero potential methods (ZPM) (setting non-scanned-sampling-electrode zero potential (S-NSSE-ZP) and setting non-scanned-sampling-electrode zero potential with amplifier (S-NSSE-ZP-A)) and to compare their performances in low resistance value (≤100 Ω) RSA. For ideal resistor RSA, the measurement results show that S-NSSE-ZP has at least one time higher error than S-NSSE-ZP-A.

Keywords – Resistive sensor array, measurement error, zero potential methods, liquid metal, flexible electrical skin.

1. Introduction

Electronic skin (e-Skin) is a synthetic human skin, capable of detecting mechanical pressures of various intensities and frequencies. This emerging technology are now widely applied in medical and healthcare products, such as prosthesis, robotics, patient monitoring systems etc. [1]. On top of the demanding technical specification such as high sensitivity and quick responsiveness, e-Skin necessitates three key features that distinguishes it from other physical sensors, namely stretchability, flexibility and conformability. Soft elastomers come forth as an appealing substrate choice, based on the above-mentioned criteria.

Eutectic gallium indium (EGaIn), an alloy consisting of 75% gallium and 25% indium, is a low viscosity liquid metal at room temperature and has good electrical conductivity [2]. These unique characteristics of EGaIn accomplish the making of active components in soft sensors, which to measure strain and pressure [3-5] with varying capacitance and resistance values of EGaIn upon deformation.

Capacitive sensors have advantages of high spatial resolution and good frequency response. But they suffer from stray capacitance and field interaction when they are connected in a mesh network. Resistive sensors, on the other hand, are less susceptible to stray parameters and field interaction and hence they are favored in mesh network. One drawback of resistive sensors is lower frequency response as compared to capacitive sensors; nonetheless this limitation has negligible effect on e-Skin application as only low frequency forces come into play [6]. By encapsulating liquid metal with soft elastomers, our group has previously designed and fabricated single EGaIn based pressure sensors [7-9] with relatively low resistance range of 10 Ω baseline (no load), up to 20 Ω with car rolling and 200 Ω with foot stomping on...
it. The promising research outcome has successfully spin off two startup companies (i.e. FlexoSense Pte Ltd. and Microtube Technologies Pte Ltd.) specializing in sensing for healthcare and wearable electronics. Many of the key researches focus on alleviating the patient and healthcare system burden by realizing self-monitoring of health data, such as keeping track of foot plantar pressure in potential diabetic foot patients with the aid of flexible pressure sensing insole.

These sensors are soft, stretchable, conformable and sensitive to mechanical loading and have great potentials to be used as the building block of e-Skin. Without question, single sensor is not sufficient to duplicate the function of human skin which has densely packed mechanoreceptors with very small receptive fields. To achieve high spatial resolution, a large number of individual sensors have to be merged to form a resistive sensor array (RSA). RSA enables the increment of sensing element with minimal wire linkage and least possible burden to the electrical system. The only major concern is the crosstalk effects resulted from adjacent idle sensors that gives rise to additional measurement error.

A number of RSA readout systems have been proposed to eliminate the crosstalk effect. These approaches include inserting diode method (IDM)[10, 11], inserting transistor method (ITM) [12] [13-15], passive integrator method (PIM) [16-18], resistance matrix approach (RMA) [19], improved RMA [37] and incidence matrix approach (IMA) [20], voltage feedback method (VFM) [21-30] and zero potential method (ZPM) [29, 31-37]. Aforementioned systems only address high resistance designs; electronic networks with low resistance below 100 Ω are often left unattended. To date only one research [24] reported a mathematical simulation from 10 Ω to 100 kΩ; nonetheless, no detailed experimental data was presented in the range of 1 Ω to 100 Ω.

The low popularity and slow research progress on low resistance network is partially attributed to the technical challenges, such as larger crosstalk effect and associated greater PCB parasite effect that are adversely affecting the system performance. In addition, majority of the mechanical sensors and actuators in the market are high resistance transducers, due to the construction materials, fabrication techniques and sensing mechanisms involved.

Unquestionably, more effort is directed to study the more ubiquitous sensor array (>100 Ω) to improve usability. More recently, however, there has been a growing interest in the development of liquid metal based RSA along with e-Skin, which registers low resistance value and inevitably triggers large PCB parasitic effect.

Here, we compared two commonly practiced readout system (setting non-scanned-sampling-electrode zero potential (S-NSSZP) and setting non-scanned-sampling-electrode zero potential with amplifier (S-NSSZP-A)) in order to decrease the crosstalk of the RSA system in PCB test. We first examined the effects in low value RSA and analyzed the electrical theory of these methods. We also demonstrated the best case analysis experiments with optimum circumstances.

2. Effects in low value RSA

One of the most notable effects in low value RSA is the crosstalk from adjacent unmeasured resistors.

As shown in Figure 1, the RSA is organized in the form 3*3 array. To calculate the resistance of the target resistor 'Rzz', we require the current flowing through it and the voltage difference across the element which are denoted as 'Izz' and 'Uzz' accordingly. 'Uzz' equals the voltage difference between the row and column wire 'Vrow2 - Vcol2'. However, current 'Izz' cannot be measured directly, as 'Izz' on the column wire is not equivalent to 'Izz'. The crosstalk currents from unmeasured resistors will be measured as well. The dashed arrow line in Figure 1 illustrates one example of the crosstalk currents. Consequently, the actual value of 'Rzz' cannot be calculated easily from 'Icol2' and 'Uzz'.
Another drawback in low value RSA is the parasitic resistance originating from the conducting strands in the printed circuit board (PCB). A copper line with 0.254 mm width, 10 mm length and 1 oz thickness will have a resistance of 19 mΩ. It appears to be a fairly insignificant value, but it will actually contribute 1% error for a 2 Ω sensor. What should be noted is that each sensor has two end lines and crosstalk effect will magnify this parasitic effect. Totally error is further boosted by increasing the array size. Fortunately, this effect can be eliminated by using wider and thicker wires.

3. Readout circuit methods for RSA

Several methods, ZPM, VFM and IDM, have been developed to omit crosstalk effect. Based on a detailed comparative analysis [24], Liu concluded that ZPM has the best performance, as compared to VFM and IDM.

In this study, two types of ZPM are discussed, namely S-NSSE-ZP and S-NSSE-ZP-A, as shown in Figure 2. The difference between these two ZPM designs is that S-NSSE-ZP uses only one driving amplifier to run all the all rows and columns, while S-NSSE-ZP-A has one driving amplifier in each row and column. The tradeoff between circuit complexity and system performance is assessed carefully.

For S-NSSE-ZP method, resistor $R_x$ is linked with two switches on each of its node. Two amplifiers drive resistor $R_x$ through two switches. One amplifier provides driving voltage $V_{in}$ on one node while the second amplifier clamps the second node to ground potential. $V_{out}$ is generated by the second amplifier. The other unmeasured resistors $R_{um}$
are grounded through corresponding switches. The ideal measurement value can be calculated from Equation 1:

\[ R_x = \frac{V_{in}}{I_f} = -\frac{V_{in}}{V_{out}} R_f \]  

(1)

For S-NSSE-ZP-A method, resistor \( R_{xi} \) is linked with two amplifiers on each of its node. Resistor \( R_{xi} \) is driven by \( V_{in} \) and grounded by two amplifiers. \( V_{outi} \) is generated by the amplifier which forces one node of \( R_{xi} \) to ground. The other unmeasured resistors \( R_{um} \) are grounded through connected amplifiers. The ideal measurement value can be calculated from Equation 1 as well.

In the case of actual hardware system, two parasitic effects need to be included into the ideal equation, the switch ON resistor \( R_{ON} \) and amplifier offset voltage \( V_{OS} \), as shown in Figure 2.

\[ R_x = \left( -\frac{V_{in} - V_{OS1} - V_{OS2}}{V_{out}} \right) R_f + \left( V_{in} - V_{OS1} - V_{OS2} \right) \]  

(2-1)

\[ R_x = \left( -\frac{V_{in} - V_{OS1} - V_{OS2}}{V_{out}} \right) \]  

(2-2)

The major difference between the above mentioned two methods is that S-NSSE-ZP-A method is capable of eliminating the parasitic effect of \( R_{ON} \) with the use of amplifiers in each row and column, whereas S-NSSE-ZP does not. However, Figure 2 is just a simplified model without crosstalk effect, which is different from the more practical applications and scenarios such as sensors array in e-Skin, whereby crosstalk is not negligible (Figure 3).

Figure 3 shows an example of 2*2 RSA with the crosstalk effect. In order to include parasitic effect of \( R_{ON} \) in this model, we use S-NSSE-ZP method for analyzing.
Figure 3. 2\times2 array circuit model including parasitic effects and crosstalk effect for S-NSSE-ZP method

In order to calculate the existing crosstalk effect, we extract the array network and apply Kirchhoff Laws to analyze the network, as shown in Figure 4 and Equation 3.

\[
\begin{align*}
V_a &= V_{os} + I_f \cdot R_{ON} = V_{os} + (I_{21} + I_{11}) \cdot R_{ON} \quad (3-1) \\
V_b &= V_{os} + V_{in} - I_b \cdot R_{ON} = V_{os} + V_{in} - (I_{12} + I_{11}) \cdot R_{ON} \quad (3-2) \\
V_c &= -I_c \cdot R_{ON} = -(I_{21} + I_{22}) \cdot R_{ON} \quad (3-3) \\
V_d &= -I_d \cdot R_{ON} = (I_{12} + I_{22}) \cdot R_{ON} \quad (3-4) \\
V_b - V_a &= I_{11} \cdot R_{11} \quad (3-5) \\
V_c - V_a &= I_{21} \cdot R_{21} \quad (3-6) \\
V_b - V_d &= I_{12} \cdot R_{12} \quad (3-7) \\
V_c - V_d &= I_{22} \cdot R_{22} \quad (3-8)
\end{align*}
\]

We hypothesize that \(R_{11} = R_x\) and \(R_{12} = R_{21} = R_{22} = R\) and \(10 \cdot R_{ON} < R \approx R_x\). After substituting (3-1, 3-2, 3-3, 3-4) to (3-5, 3-6, 3-7, 3-8), we obtain Equation 4.

\[
\begin{align*}
I_{11}(R_x + 2R_{ON}) + I_{12}R_{ON} + I_{21}R_{ON} + I_{22} \cdot 0 &= V_{in} \quad (4-1) \\
I_{11}R_{ON} + I_{12} \cdot 0 + I_{21}(R + 2R_{ON}) + I_{22}R_{ON} &= -V_{os} \quad (4-2) \\
I_{11}R_{ON} + I_{12}(R + 2R_{ON}) + I_{21} \cdot 0 + I_{22}R_{ON} &= V_{os} + V_{in} \quad (4-3) \\
I_{11} \cdot 0 + I_{12}R_{ON} + I_{21}R_{ON} + I_{22}(R + 2R_{ON}) &= 0 \quad (4-4)
\end{align*}
\]
Equation 4 is a nonhomogeneous linear equation \( R \cdot 1 = V \) and it can be written as Equation 5.

\[
\begin{pmatrix}
R_x + 2R_{ON} & R_{ON} & R_{ON} & 0 \\
R_{ON} & 0 & R + 2R_{ON} & R_{ON} \\
R_{ON} & R + 2R_{ON} & 0 & R_{ON} \\
0 & R_{ON} & R_{ON} & R + 2R_{ON}
\end{pmatrix}
\begin{pmatrix}
V_{in} \\
-V_{os} \\
V_{os} + V_{in}
\end{pmatrix}
\]

We define \( R + 2R_{ON} = R_+ \) and \( R_x + 2R_{ON} = R_{x+} \), then we have:

\[
\begin{pmatrix}
R_+ & R_{ON} & R_{ON} & 0 \\
R_{ON} & 0 & R_+ & R_{ON} \\
R_{ON} & R_+ & 0 & R_{ON} \\
0 & R_{ON} & R_{ON} & R_+
\end{pmatrix}
\begin{pmatrix}
V_{in} \\
-V_{os} \\
V_{os} + V_{in}
\end{pmatrix}
\]

After rearranging, we have:

\[
\begin{pmatrix}
1 & 0 & 0 & -R_x/R_{x+} \\
0 & 1 & 0 & -R_x/R_{x+} \\
1 & 0 & -1 & 0 \\
0 & 1 & 1 & R_+/R_{ON}
\end{pmatrix}
\begin{pmatrix}
V_{in}/R_{x+} \\
V_{in}/R_{x+} \\
V_{os}/R_{ON} - V_{in}/R_{x+} \\
(2V_{os} + V_{in})/R_+
\end{pmatrix}
\]

Rearranging row 2 and 3, we have:

\[
\begin{pmatrix}
1 & 0 & 0 & -R_x/R_{x+} \\
0 & 1 & 0 & -1 + R_x/R_{x+} \\
0 & 0 & -2 & -R_x/R_{ON} \\
0 & 1 & 1 & R_+/R_{ON}
\end{pmatrix}
\begin{pmatrix}
V_{in}/R_{x+} \\
V_{os}/R_{ON} - V_{in}/R_{x+} \\
(2V_{os} + V_{in})/R_+ \\
0
\end{pmatrix}
\]

Rearranging row 3, we have:

\[
\begin{pmatrix}
1 & 0 & 0 & -R_x/R_{x+} \\
0 & 0 & 1 & 1 + R_x/R_{x+} \\
0 & 0 & 0 & 1 \\
0 & 1 & 1 & R_+/R_{ON}
\end{pmatrix}
\begin{pmatrix}
V_{in}/R_{x+} \\
-V_{os}/R_{ON} - V_{in}/R_{x+} \\
-V_{in}R_{x+x}/2R_{x+}^2R_{x+} \\
0
\end{pmatrix}
\]

Rearranging row 1, we have:

\[
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 + R_x/R_{x+} \\
0 & 0 & 0 & 1 \\
0 & 1 & 1 & R_+/R_{ON}
\end{pmatrix}
\begin{pmatrix}
V_{in}(2R_{x+x}R_+ - R_{ON}R_x)/2R_{x+}^2R_+ \\
-V_{os}/R_{ON} - V_{in}/R_{x+} \\
-V_{in}R_{x+x}/2R_{x+}^2R_{x+} \\
0
\end{pmatrix}
\]

Rearranging row 2, we have:

\[
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
0 & 1 & 1 & 0
\end{pmatrix}
\begin{pmatrix}
V_{in}(2R_{x+x}R_+ - R_{ON}R_x)/2R_{x+}^2R_+ \\
-V_{os}/R_{x+x} - V_{in}R_{ON}(2R_{x+x}R_+^2 - R_xR_{ON}R_{x+x} + R_xR_{x+x})/2R_{x+}^2R_{x+}^3 \\
-V_{in}R_{x+x}/2R_{x+}R_{x+x} \\
-V_{in}R_{x+x}/2R_{x+}R_{x+x}
\end{pmatrix}
\]

Rearranging row 2, row 3 and row 4 again, we have:

\[
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
V_{in}(2R_{x+x}R_+ - R_{ON}R_x)/2R_{x+}^2R_+ \\
-V_{os}/R_{x+x} + V_{in}R_{x+x}(2R_{x+x}R_+^2 - R_xR_{ON}R_{x+x} - R_xR_{x+x})/2R_{x+}^2R_{x+}^3 \\
-V_{os}/R_{x+x} - V_{in}R_{ON}(2R_{x+x}R_+^2 - R_xR_{ON}R_{x+x} - R_xR_{x+x})/2R_{x+}^2R_{x+}^3 \\
-V_{in}R_{ON}R_{x+x}/2R_{x+}^2R_{x+x}
\end{pmatrix}
\]

From (3-1), we have \( I_f = I_{11} + I_{11} \). From (12) row 1 (1_{11}) and 3 (1_{21}), we have:

\[
I_f = -V_{os}/R_+ - V_{in}R_{ON}(2R_{x+x}R_+^2 - R_xR_{ON}R_{x+x} - R_xR_{x+x})/2R_{x+}^2R_{x+}^3 + V_{in}(2R_{x+x}R_+ - R_{ON}R_x)/2R_{x+}^2R_+
\]

After simplifying, we have:

\[
I_f = \frac{-3R_{ON}R_+ + 2R_xR_+ + 4(R + R_+)R_{ON}V_{in} - V_{os}}{2R_{x+}^2R + 4R_{ON}(R_{x+}^2 + 2RR_{x+})}
\]

We can evaluate \( I_f \) from Equation (14) by assuming \( R_{ON} \) and \( V_{os} \) equal to zero (ideal case), then \( I_f = \frac{V_{in}}{R_x} \) and it
matches equation (1).

Even though Equation (14) is derived from S-NSSE-ZP method, it can also be applied in the case of S-NSSE-ZP-A given that $R_{ON} = 0$, as shown in Equation (15):

$$I_f = \frac{V_{in} - V_{ao}}{R}$$

(15)

and it matches Equation (2-2).

From Equation (1), we know for S-NSSE-ZP method:

$$V_{out} = -I_f \times R_f = -\frac{-3R_{ON}R_x + 2R_xR + 4(R + R_x)R_{ON}}{2R_x^2R + 4R_{ON}(R_x^2 + 2RR_x)}V_{in}R_f + \frac{V_{ao}R_f}{R}$$

(16)

And we know for S-NSSE-ZP-A method:

$$V_{out} = -I_f \times R_f = -\frac{-3R_{ON}R_x + 2R_xR + 4(R + R_x)R_{ON}}{2R_x^2R + 4R_{ON}(R_x^2 + 2RR_x)}V_{in}R_f + \frac{V_{ao}R_f}{R}$$

(17)

4. Best-case Circuit Analysis

In this section, best-case circuits are examined. Various experiments have been designed to evaluate the performances of the S-NSSE-ZP method and the S-NSSE-ZP-A method under optimum circumstances, with varying parameters such as switch resistor value ($R_{ON}$), array size ($S_{AR}$), unmeasured array resistors value ($R_{um}$) and measured resistor value ($R_x$).

The output amplifier’s voltage of an ideal single resistor is represented as $V_{id}$. Meanwhile, the output amplifier’s voltage of array resistors is measured as $V_{arr}$. The measurement error between them are evaluated as follows:

$$e\% = \frac{V_{id} - V_{arr}}{V_{id}} \times 100$$

(18)

The number of possible outcomes, from the combination of the selected 4 varying parameters, is too large to be studied. Many of these combinations are less useful and lack practical application. To optimize the experiment effort and outcome, only sets of experiments (EXP) with carefully chosen combinations are analyzed (Table 1). The switches resistances ($R_{ON}$) of S-NSSE-ZP have several value such as: 0.5Ω, 1Ω, 1.5Ω, 2Ω, 2.5Ω, 3Ω, 3.5Ω, 50Ω and 53.5Ω. The array size ($S_{AR}$) is in the range of 2×2, 3×3, 4×4, 5×5, 6×6, 7×7 and 8×8. The unmeasured array resistors values ($R_{um}$) are 1Ω, 2Ω, 3Ω, 4Ω, 5Ω, 10Ω, 20Ω, 50Ω and 100Ω. The measured resistor values ($R_x$) are: 1Ω to 10Ω with 1Ω each step, 19Ω to 20Ω with 1Ω each step, 20Ω to 100Ω with 10Ω each step, 100Ω to 200Ω with 10Ω each step.

**Table 1. Experiments with selected combinations**

<table>
<thead>
<tr>
<th>EXP 1</th>
<th>EXP 2</th>
<th>EXP 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_x$(Ω)</td>
<td>$R_{um}$(Ω)</td>
<td>$S_{AR}$</td>
</tr>
<tr>
<td>All</td>
<td>1</td>
<td>2×2</td>
</tr>
<tr>
<td>values</td>
<td>200</td>
<td>3×3</td>
</tr>
<tr>
<td></td>
<td>4×4</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>5×5</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>6×6</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>7×7</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>8×8</td>
<td></td>
</tr>
</tbody>
</table>

EXP 1 analyzed the effect of array size $S_{AR}$ on $e\%$ with the best state of switch resistor $R_{ON}$ and the worst/best states of unmeasured array resistors $R_{um}$.

EXP 2 analyzed the effect of unmeasured array resistors $R_{um}$ on $e\%$ with the best state of switch resistor $R_{ON}$ and the best state of array size $S_{AR}$.

EXP 3 analyzed the effect of different switch resistor value $R_{ON}$ on $e\%$ with the best state of array size $S_{AR}$ and the
worst/best state of unmeasured array resistors $R_{um}$ and measured resistor $R_x$.

The best and the worst states refer to the minimum and the maximum $e\%$ in (16) and (17).

The two parallel connected amplifiers used in S-NSSE-ZP method are OPA197, because of its low $V_{os}$ (100uV) and relatively high output current (65mA). High output current is important for S-NSSE-ZP circuit design, as the whole array is driven by only one amplifier. It is difficult to find one single suitable amplifier that owns these two characteristics, as high drive ability and low $V_{os}$ are opposite in nature and cannot be satisfied simultaneously. In order to increase the driving ability without raising $V_{os}$, we used two parallel connected amplifiers. The switches used in S-NSSE-ZP method are TS3A24159, because of its low ON state resistance ($0.3 \, \Omega$).

Meanwhile in S-NSSE-ZP-A design, the amplifiers used are OPA4388, because of their low $V_{os}$ ($2.25 \, \mu V$). The switches are ADG804, due to the low ON state resistor ($0.5 \, \Omega$). However, it is not a critical parameter for this method.

Because of the power supply requirement of OPA197 and OPA4388, S-NSSE-ZP and S-NSSE-ZP-A are supplied with 3.3V and 2.5V power sources respectively.

The experimental setup is shown in Figure 5. We can change $R_{sw}$ of S-NSSE-ZP by plugging in/out the wiring cap of the experimental resistors. Different $S_{AR}$ and $R_{um}$ are realized by using PCB arrays with varying $S_{AR}$ and $R_{um}$ value. The value of $R_x$ is adjusted by the resistor box. Figure 5 is the hardware experimental system.

![Figure 5. Experimental setup for S-NSSE-ZP and S-NSSE-ZP-A design (only S-NSSE-ZP is shown)](image)

5. Results and Discussion

S-NSSE-ZP method is labeled as 8sw in the result graphs, as 1 amplifier and 8 switches are used to drive the array resistors arranged in rows or columns. S-NSSE-ZP-A method is named as 8op, as 8 amplifiers are adopted.

Figure 6 shows the error in S-NSSE-ZP and S-NSSE-ZP-A method when $R_{um}$ is 200 $\Omega$ and $S_{AR}$ changes from 1*1 to 8*8.
Figure 6. The effect of $R_x$ on measurement error of different $S_{AR}$ when $R_{um} = 200\Omega$ in S-NSSE-ZP and S-NSSE-ZP-A method.

Figure 7 shows the error in S-NSSE-ZP and S-NSSE-ZP-A method when $R_{um}$ is 1Ω and $S_{AR}$ changes from 1×1 to 8×8.

Figure 7. The effect of $R_x$ on measurement error of different $S_{AR}$ when $R_{um} = 1\Omega$ in S-NSSE-ZP and S-NSSE-ZP-A method.

Figure 8 shows the error in S-NSSE-ZP and S-NSSE-ZP-A method when $S_{AR} = 2 \times 2$ and $R_{um}$ changes from 1Ω to 200Ω.

Figure 8. The effect of $R_x$ on measurement error of different $R_{um}$ when $S_{AR} = 2 \times 2$ in S-NSSE-ZP and S-NSSE-ZP-A method.
As shown in Fig. 6, the error of 8sw is twice higher than 8op. That is because 8sw is restricted by \( R_{sw} \) and amplifier driving ability.

In Fig. 6, when the \( R_x \) is increasing from 1Ω to 100Ω, both errors of 8sw and 8op will decrease quickly. This is because the effect of connect wire parasitic resistor and PCB trace resistor will decrease with increasing \( R_x \).

Also, when \( R_x \) is larger than 100 Ω, the error will increase again. We think it is the result of the real hardware limitation. As shown in Fig. 2, the output amplifier has a feedback resistor which is 100 Ω in our design. If the \( R_x \) is more than 100 Ω, the gain of amplifier will be less than 1. As the \( V_{in} = 10 \ mV \), so the \( V_{out} \) will be less than 10mV. We can rewrite equation (2-1) as equation (18). When \( V_{out} \) is decreasing, the middle term in the right side of equation (18) will increase and the error effect of \( V_{OS1} \) and \( V_{OS2} \) will also increase. So the totally error will increase.

\[
R_x = \left( \frac{V_{in}}{V_{out}} \times R_f - \frac{V_{OS1} + V_{OS2}}{V_{out}} \times R_f + R_{ON} \right) \quad (18)
\]

A more common way to explain this phenomenon is that \( V_{out} \) is limited in a small range when gain is less than 1. The effect of \( V_{OS} \) will increase with decreasing \( V_{out} \).

In Fig. 6, the array size change leads to a monotonic change in error.

As shown in Fig. 7, the error of 8sw and 8op is much higher than in Fig. 6. This is because \( R_{um} \) changed from 200 Ω in Fig. 6 to 1 Ω in Fig. 7. The smaller \( R_{um} \) needs the larger driving ability, which is limited by the amplifier feature. In Fig. 7, we can see the errors converge to a negative value instead of zero. That is because the simple equation (2) cannot match the real system when \( R_{um} \) decreases to 1 Ω. The crosstalk effect is the dominant error now. We should use equations (16) and (17) which are derived from crosstalk effect to analyze this phenomenon. The last term in the right side of equation (16) and (17) is a constant, so that it will form an offset after the first item converge to its minimum.

In Fig. 7, the array size change leads to a monotonic change in error.

In Fig. 8, we can see the error of 8sw is higher than 8op. This is because 8op has 8 separated amplifiers and each one of them has enough driving ability to force one column or row resistors, but 8sw has only one amplifier and its driving ability is not enough for the whole array of resistors.

We can see the error converge to an offset value when \( R_x \) increases as well. With increasing \( R_{um} \), the offset value will decrease. This can be proven by the last term in the right side of equation (17) and (18) as well.

In Fig. 9, we can see the error of 8sw increases with \( R_{sw} \). There is a negative convergent offset when \( R_{um} = 1 \) and zero convergent offset when \( R_{um} = 200 \). Both can be proven by equations (16) and (17). As the last term in equation (16) and (17) is divided by \( R \) which is rewritten as \( R_{um} \) here, thus the larger \( R_{um} \) leads to the smaller offset.

From the above analysis, we can make some suggestions in the design of an actual hardware system to measure low value RSA.

- Decreasing the connection wire, PCB trace and switch resistor.
- Increasing the amplifiers current driving ability.
• Decreasing the offset voltage of all amplifiers and making sure their offset voltage is equalized to zero.
• Decreasing the array size and separating large array to several independent small arrays.
• As the power cost increases greatly with array size, it is not recommended to use this circuit design in battery driven wearable system, especially without any low power design.
• S-NSSE-ZP-A method has lower error than S-NSSE-ZP method, because this method bypasses the switch resistor and has enough amplifier current driving ability.

6. Conclusions

We discussed the designs of S-NSSE-ZP and S-NSSE-ZP-A methods and established their simplified models and derived their output voltage equations. We also analyzed their measurement error with different array size, unmeasured resistor value, switch resistor value and measured resistor value. Several design suggestions are made for low value RSA measurement system. The results revealed S-NSSE-ZP-A has smaller resistor measurement error than S-NSSE-ZP.
Preprints

References

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