On the Report of Performance Analysis of Electrospun Carbon Nanofibers based Strain Sensor for Applications in Human Motion Monitoring

Ahsan Aqueeb [1], Sayan Roy [1*], Yichun Ding [2], Obiora Onyilagha [2], and Zhengtao Zhu [2]
Department of Electrical Engineering [1], *Department of Chemistry Biology and Health Sciences* [2]
South Dakota School of Mines & Technology
Rapid City, SD-57701, USA
sayan.roy@sdsmt.edu, sayan.roy.us@ieee.org*

***Abstract*—Flexible and wearable sensors are currently being extensively used in versatile applications including wireless body area network. Specifically, such sensors are mostly incorporated to yield a linear response within their range of operations. A recently developed flexible and wearable resistive strain sensor made of electrospun carbon nanofibers has been reported with a gauge factor up to 72. In this paper, the performance of the strain sensor embedded in a polyurethane matrix was studied at first. A linear region of operation of such sensor was defined from direct measurements for wireless body area network applications. The equivalent analytical expressions were established and reported.**

***Index Terms*—resistivity, strain sensor, wireless body area network.**

I. INTRODUCTION

Strain sensors have been a very popular choice by scientists and engineers due to its low-cost, simplicity, and versatility. Currently they are being used for applications, like human monitoring where various motion (bending finger, arms or legs) require high stretch ability and sensitivity. Recently, various methods of fabrication such as electrospun carbon nanofibers [1], graphite-based strain sensors by pencil-trace drawn on flexible printing paper [2] and commercial plain weave carbonized cotton fabric [3] were reported. As reported in [4], prior studies of such sensors did not explore the change of resistance based on the amount of angle created by applied stress.

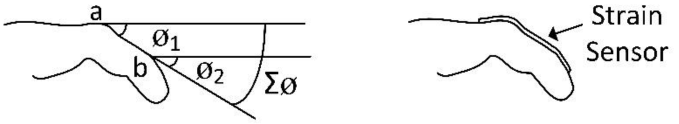
The objective of this paper was to study the change of resistance followed by the applied stress due to wireless body area network applications in determining a region of linear operation of such a sensor. As shown in Fig. 1 (a), a highly stretchable and sensitive strain sensor composed of free-standing electrospun carbon nanofibers (CNGs) embedded in a polyurethane (PU) elastomer with gauge factor up to 72 [1] was incorporated here to perform a study on finger movements for wireless body area network applications. In particular, the linear region of the strain limit was identified of the CNG based sensor where a change of angle within the specific linear region would produce a linear change of resistance.

II. METHODOLOGY

Initially, a single CNG based strain sensor was placed on the index finger to analyze the strain performance. Using a glove, the sensor was electrically separated and evenly distributed over the finger, as illustrated in Fig. 1 (b).

(a) (b)

Fig. 1. (a) Highly stretchable strain sensor based on electrospun carbon nanofibers and distribution of the Strain Sensor (Dimensions (in mm): A = 1.31, B = 27.6, C = 0.99, W = 2.86 and L = 29.9). (b) Distribution of the strain sensor over the finger using a glove.



(a) (b)

Fig. 2. (a) Point a and b on a finger where the bend angles are $ø_1$, $ø_2$ and the summation of both the angle is defined as Σø. (b) Sideview: CNG based strain sensor is placed on a finger.

Typically, a finger bends at two interphalangeal joints as shown in Fig. 2 (a). These two points of bending can be identified as points a and b, where the respective bend angles have been defined as $ø_1$ and $ø_2$. It can be observed that even though such joints bend at two different locations with different angles, in terms of the equivalent total applied stress on a strain sensor placed on the finger, they can be analytically represented using a single angle, Σø where,

$$\Sigma ø = ø_1 + ø_2. \tag{1}$$

III. RESULT AND DISCUSSION

A. *Measurement of Bending Angles and Resistances*

An extensive study on most possible combinations of bending angles was taken into consideration here. In a few cases, measurements of the resistances (R) using various possible combinations of $ø_1$ and $ø_2$ yielded identical values of $\Sigma ø$ and R where an average resistance value was considered. Next, a voltage divider circuit was used to generate an equivalent change in voltage for change in resistance for variable applied stress. Changes of per unit resistance ($\Delta R/R$) and per unit voltage ($\Delta V/V$) were then measured for a possible range of Σø, as shown

Submitted On: September 9, 2020
Accepted On: September 9, 2020

https://doi.org/10.47037/2020.ACES.J.351131

in Figs. 3 and 4. Based on the measured data, a linear relation between $\Delta R/R$ and $\Sigma ø$ was analytically approximated,

$$y_1 = 0.0019x_1 - 0.0733 \,, \tag{2}$$

where y_1 and x_1 represents $\Delta R/R$ and $\Sigma ø$, respectively. Similarly, a linear relation was analytically approximated between $\Delta V/V$ and $\Sigma ø$,

$$y_2 = 0.00018767x_1 - 0.0072 \,, \tag{3}$$

where, y_2 represents ΔV/V. Next, the accuracy of equations (2) and (3) was analyzed by calculating equivalent total bend angle ($\Sigma ø_{calc}$) directly from measured per unit resistances and voltages using the above two equations. The error (in percentage) were then measured using equation 4 and reported in Table I.

$$\text{Error (in \%)} = \frac{\Sigma ø - \Sigma ø_{\text{calc}}}{\Sigma ø_{\text{calc}}} \times 100\ \%. \tag{4}$$

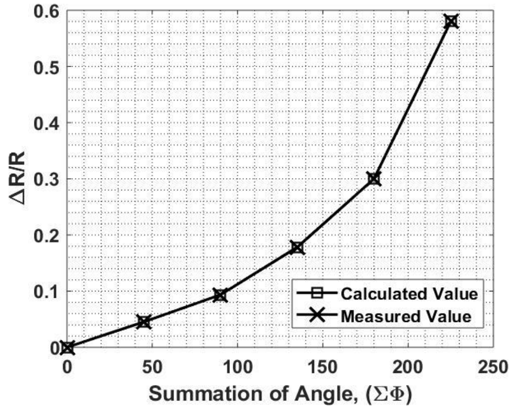


Fig. 3. Comparison between measured and calculated per unit resistance $\Delta R/R$ with change of angle $\Sigma ø$.

TABLE I
MEASUREMENT OF PERCENTAGE ERROR

$\Sigma ø$ (degrees)	$\Delta R/R$	$\Delta V/V$	$\Sigma ø_{calc}$ (degrees)	Error (%)
45	0.0452	0.0045	62.3435	38.54
90	0.0935	0.0093	87.9203	-2.31
135	0.1784	0.0178	133.2126	-1.32
180	0.3	0.0298	197.1546	9.53

Now, the relations between per unit components ($\Delta R/R$ and $\Delta V/V$) with the total bend angle $\sum ø$, as can be seen in Figs. 3 and 4, are non-linear and equations (2) and (3) are only linear approximations with the reported error in Table I. For further accuracy, an exponential equation is analyzed if the CNG based sensor is needed to be operated beyond its linear region. The following parameters a and z are then defined analytically and Table II summarizes their values using curve fitting techniques:

$$a = ln(x+1). \quad . \tag{5}$$

$$z = e^a - 1. \tag{6}$$

B. Result

The CNG based sensor yields an approximately linear response between 90° to 180° region of operation with percentage error of less than 10%. The sensor can also be used from 0° to 225° with non-linear approximations, as reported.

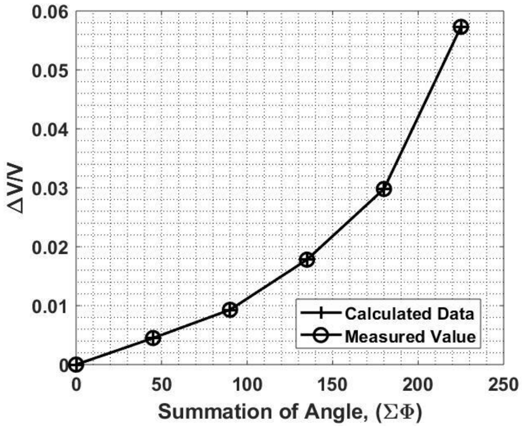


Fig. 4. Comparison between measured and calculated per unit voltage $\Delta V/V$ with change of angle $\Sigma ø$.

TABLE II
CALCULATION OF EXPONENTIAL OUTPUT

$\Sigma ø$°	$\Delta R/R$	a	z	$\Delta V/V$	a	z
45	0.0452	0.0442	0.0452	0.0045	0.0045	0.0045
90	0.0935	0.0894	0.0935	0.0093	0.0093	0.0093
135	0.1784	0.1638	0.1780	0.0178	0.0176	0.0178
180	0.3	0.2624	0.3	0.0298	0.0294	0.0298

IV. CONCLUSION

A study on the performance of CNG based strain sensor was reported. Specifically, relations between the bend angles caused by the movement of fingers and its equivalent changes in resistance and voltage were established. Finally, it was concluded that CNG based strain sensor reported in [1] could be used between 90° to 180° which is the sum of bend angles at two interphalangeal joints of a finger for linear operations.

ACKNOWLEDGMENT

This research is supported by the National Aeronautics and Space Administration (NASA) of the United States. (Grant Number – 80NSSC18M0022). The authors declare no competing financial interest.

REFERENCES

[1] Y. Ding, J. Yang, C. R. Tollebc, and Z. Zhu, “A highly stretchable strain sensor based on electrospun carbon nanofibers for human motion monitoring,” RSC Adv., vol. 8, no. 26, Aug. 2016.

[2] X. Liao, Z. Zhang, Q. Liao, Q. Liang, Y. Ou, M. Xu, M. Li, G. Zhanga, and Y. Zhang, “Flexible and printable paper-based strain sensors for wearable and large-area green electronics,” Nanoscale, vol. 8, no. 26, June 2016.

[3] M. Zhang, C. Wang, H. Wang, M. Jian, X. Hao, and Y. Zhang, “Carbonized cotton fabric for high-performance wearable strain sensors,” Advanced Functional Materials, vol. 27, no. 2, Nov. 2016.

[4] M. Sanati, A. Sandwell, H. Mostaghimi, and S. S. Park, “Development of nanocomposite-based strain sensor with piezoelectric and piezoresistive properties,” Sensors (Basel), vol. 18, no. 11, Nov. 2018.