Electromagnetically Enhanced Soft and Flexible Bend Sensor: A Quantitative Analysis With Different Cores

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Abstract—Advantages of soft, flexible materials with developments in refined magnetic actuation can be intertwined for a promising platform to work on a resilient, adaptable manipulator aimed to meet ever-increasing demands in safe regulated medical environments. Taking advantages of these soft magnetic polymers, we propose a novel, soft-squishy and flexible bend sensor by determining the relationship between inductance changes with bending angle. This bend sensor employs flexible wire embedded in a silicone elastomer with the different permeable core. The principle notion is to have a comprehensive analysis of the change in morphology of the sensor with bending angle which can be translated to inductance generated therein. The performance of the sensor is evaluated with various experimental trials while analytical modeling elucidates that the bend angle is linearly proportional to the sensor signal citing R-square value up to 0.9204. The proposed sensor produces the desired output in the EM frequency range of 8–10 MHz with a tunable sensitivity of 0.418 mV/rad. The sensor is robust enough to stretch up to twice of its original length. The main advantage of this bend sensor is its simple fabrication technique, flexibility, robustness, and economical. Conclusively, this paper on induction based tactile bending sensor is proved to produce robust output and can be extrapolated to sense bending angle using induction principle for the rehabilitative device, wearable robots, and related biomedical applications requiring low cost, soft and flexible operations.

Index Terms—Electromagnetic induction, flexible bend/force sensor, tactile sensor, soft embodiment, medical rehabilitation.

I. INTRODUCTION

TO EQUIP robotic manipulators with intelligence, tactile sensors are extensively used for detecting various external stimuli like slippage, grasping force and imitate the tactile perceptions [1]–[6]. Since past few decades, there have been various researches in realising sensing element on a soft surface to obtain stretchable, foldable and flexible sensors. Apart from these external stimuli measurements, various bend sensors were developed to determine the curvature of bending and utilized in different applications like measurements of flexion and extension of body joints [7]–[9]. These bend sensors were realised on different hardware and software technology namely optical fibre bend sensor [10]–[15], resistive [16]–[19] and capacitive-based sensor [20]–[28]. For small size, increased MEMS sensors were developed [28]–[31]. Resistive based sensors consist of pressure sensitive element which changes its resistance based on force or induced deformation. The sensitive element is usually comprised of conductive ink, rubber or elastomer. These sensors are affordable and commercially available in the market with a higher spatial resolution that employs fewer electronics which makes signal processing easier to work in mesh configurations. However, some of the typical disadvantages of resistive tactile sensors are its lower frequency response and non-linearity in operation. Some of the commercially available sensors still suffer from hysteresis [20], [32], temperature response, humidity and hence user will require to optimally configure the sensor before use [33].

On the other hand, capacitive-based sensors consist of electrodes separated by a dielectric medium. These sensors do exhibit higher frequency response, good spatial resolution, and wider range but a major limitation is that they are highly susceptible to noise. This phenomenon is more prominently observed in mesh configuration due to crosstalk, fringing capacitance and field interactions [34]. Due to this, they require complex electronic circuits to filter noise. MEMS and Micromachining technologies are powerful techniques used in the miniaturization of sensors. These technologies are employed in design and development of sensor in smaller sizes in the range of Nanoscale and used in a variety of applications. The major disadvantages of this technology are complex fabrication technique that incurs increasingly high initial capital [33].

Optical fiber based sensors, on the other hand, employs a light source, a transduction medium and photodetector. These optical fiber sensors are classified into two types depending on the type of measurements i.e. the spectrum measurement or the entire light intensity [10]. The grating-based sensors like the Low Period Fiber Grating (LPFG) and Fiber Bragg Grating (FBG) are commonly used to measure the intensity variation. The transduction occurs when there is a modulation of transmission and reflection of the intensity of light by the tactile medium. They have a high spatial resolution compared to the resistive and tactile sensor and are immune to interferences. In spite of many advantages, they still require complex signal processing technique and thus difficult
to minimize the effect of temperature and nonlinearities with
simple fabrication with size restrictions [14].

Apart from these above-mentioned technologies, inductive
based tactile sensors are based on the principle of magnetic
coupling. Modulating the inductance of the coil by varying the
length and the permeable core, in turn, modulates the sensing
voltage. The sensors based on this technology are still under
development and not widely explored like others. Although
they do not fix all the disadvantages of the above-mentioned
technologies, they have a high dynamic range, linear output
and can be employed at a higher frequency. On the same hand,
you do not require complex fabrication process or excessive
cost as well. Most of the sensor based on this technology is on
the mutual induction principle where a primary coil induces
a magnetic field in the secondary coil (sensing coil) which is
sensed. This makes the construction bulky and incurs higher
losses. Therefore, we aimed to develop a sensor with only one
coil that acts as both primary and secondary/sensing coil.

Specifically, in this paper, we propose a novel soft inductive
Solenoidal Bend Sensor (SBS) completely different from the
existing technology. This sensor comprises of a flexible coil
with a protective covering made of elastic material as shown
in Fig. 1. This silicone elastomer provides mechanical com-
pliance and robustness to the sensor. Due to SBS flexible yet
resilient properties, this has promising applications in the field
of wearable electronics, soft robotics, drug delivery, medical
implants, human-machine interaction [35]–[40]. In this paper,
the geometry of the sensor is considered like a single cantilever
beam hung through certain height and bent with tangential
and normal force. Thus, the characterization and mathematical
modelling of the sensor is simpler due to the simpler geo-
metrical structure. This developed sensor uses a passive L–R
circuitry that consists of a fixed resistor and a variable inductor.
The variable inductor is coupled with elastomer element that
makes dimensional changes in response to the target parameter
to modify the inductance.

The material and the design of the sensor is economical,
readily available and does not require complex fabrication pro-
procedure. SBS can be modified by varying the wire gauge length.
This novel SBS is sensitive to bidirectional force and can be
calibrated in near terms for the measurement of the angle or the
force in the finger joints for rehabilitation.

II. ANALYTICAL MODELLING

This proposed bend sensor consists of an electromagnetic
coil coupled with a passive resistor and excited by AC voltage
source. The electromagnetic coil acts as a variable inductor and
the entire circuitry is a combination of LR circuit. With the
application of external force, the sensor is deformed through a
certain angle and the bending moment causes transformation
of mechanical energy to electrical energy as shown in Fig. 2.
Due to the deformation of the sensor with a change in angle,
there is a change in magnetic field, induced EMF and
inductance of the sensor.

To determine and verify the transformation parameters and
validate the experiments conducted using prototype model of the
bend sensor, this section numerically investigates the relation-
ship between the various magnetic properties of the sensor
with the deformation induced due to bending. The deformation
of the sensor induces a change in the pitch angle of the coil
which varies the change in magnetic field detected by the
magnetometer. For this modelling, we assume the following
conditions:

1) The sensor is a soft flexible solenoid as the elastomeric
coating is of negligible thickness and does not affect the
magnetic flux linkage.
2) The force exerts only a bending deformation in the
sensor without stretching or compressing the coil.
3) Exponential decay in initial to a final value of inductance
caused due to change in deformation of the sensor.

The cross-sectional image of the sensor is shown in Fig. 3(a).
The radius of the sensing coil ($R_{oi}$)differs from the average

![Fig. 1. (a) Initial prototype of Soft Solenoidal Bend Sensor (SBS) with flexible coil embedded in polymer. (b) Testing SBS on patient’s Distal Interphalangeal joint (DIP) to cite an example for rehabilitative care to quantify bend angle.](image1)

![Fig. 2. Working principle of the sensor.](image2)

![Fig. 3. (a) Flexible coil when laid flat. (b) Cross-sectional view coil with the inner and outer radius.](image3)
radius \( R_a \) of the sensor since the coil is a cylindrical wire. \( R_a \) of the sensor is measured from the axis of the solenoid to a point inside the body of wire. Thus, the conduction zone is between the ranges \( R_a - R_w \) and \( R_a + R_w \). Hence the effective radius will be less than the average radius as shown in Fig. 3(b) (measured from the axis of solenoid axis of wire).

At low frequencies, \( R_a \) and effective radius \( R_{eff} \) of the solenoid are assumed to be equal. But, this assumption leads to erroneous results in comparison to the practical solenoids as the current density in the coil is biased at the centre since current conduction at the outer surface of the coil is larger than inner surface [39].

At higher frequencies, the effective diameter of the electromagnetic coil is affected by proximity and skin effect i.e. the adjacent coils experience a repulsion force and an increased interaction with the overall magnetic field. Hence, it requires an appropriate correction factor to determine the diameter at higher frequencies. The effective radius is calculated as per (1).

\[
R_{eff} = R_a \left[ 1 - \left( \frac{R_w}{R_a} \right)^2 \right] \quad (1)
\]

Due to the difference between effective radius and average radius of the coil, there is a variation in the conduction length and wire length of the solenoid. The effective conduction length varies with frequency and is always less than the physical wire length. The length of the coil \( L_c \) is usually pitch \((P)\) times the number of turns \( (N) \). As the variation in the pitch angle is considerably smaller the coil length can be approximated by the formula given below.

\[
L_c = PN
\]

\[
L_{eff} = \pi D_a N \quad (2)
\]

The initial sensor dimensions are \( 40 \times 10 \text{ mm} \) (length and outer diameter respectively) with an effective radius of \( 3.871 \text{ mm} \) as calculated from equation (1). The sensor samples are operated at a cut-off frequency of \( 8 \text{ MHz} \) and the angular frequency is \( 50 \text{ MHz} \). The main active element of the sensor is a fine copper wire of resistivity \( 1.68 \times 10^{-8} \Omega \text{m} \). A total of 9 sensor samples were tested with different core and a varying number of turns \( 50, 100 \) and \( 150 \) while maintaining a constant ratio between the length and the number of turns. By Faraday’s law, the rate of change of magnetic flux linked with the coil is dependent on the rotation or bending of the coil in a magnetic field. This results in induced voltage (EMF) in the coil, \( E \).

\[
E \propto \omega NA B_0 \sin \omega t
\]

\[
E_{max} = \omega NA B_0 \sin \omega t \quad (3)
\]

where, \( \omega \) is the angular frequency, \( B_0 \) is the initial magnetic field (field induced when sensor at \( 0^\circ \) or initial position), \( A \) is the cross-sectional area of the sensor, \( E_{max} \) is the maximum induced voltage when \( \cos \omega t \) is one. The above expression can be expressed in terms of the volume \( (V) \) which is cross-sectional area times the length of the solenoid as it remains constant during the deformation. Replacing area with volume

\[
E_{max} \propto \frac{NV}{l} B, \text{ where } V = A l \quad (4)
\]

Fig. 4. Variation of deflection with \( d \) due to applied external force.

Thus, the induced voltage (EMF) produced is proportional to the \( N, l \) and \( B \) in the solenoid at a constant frequency. A magnetometer is employed to determine the magnetic field change in the sensor sample by placing the tip of the magnetometer into the sensor winding. The rate of change of magnetic field can be expressed in terms of current \((I)\), \( N \) and the permeability of free space \((\mu_0)\) and the medium \((\mu_r)\) as shown in (5).

\[
B_0 = \mu_r \mu_0 N I \quad (5)
\]

Substituting (5) in (3) we get,

\[
E_{max} = \omega NA \mu_r \mu_0 N I \quad (6)
\]

The maximum induced EMF can also be expressed in terms of root mean square value is:

\[
E_{rms} = \omega NA \mu_r \mu_0 N Irms \nabla
K \frac{A}{l} \quad (7)
\]

where, \( K = 2\pi f \mu_r \mu_0 Irms \) and \( n = \frac{N}{l} \). For samples fabricated with iron core or magnetic strip, the permeability of the material is included i.e. \( K = 2\pi f \mu_r \mu_0 Irms \). With this formulation of the induced EMF, the experimental values can be determined.

In order to determine the inductance \((H)\) change in the sample caused due to the change in deformation is given by (8) and the change in deflection is shown in Fig. 4.

\[
H = \mu_0 \mu_r N^2 \delta \quad (8)
\]

where \( \delta \) is the deflection from the initial to final state of the sensor given by \( l \sin \theta \). The variation of inductance from the initial \((H)\) to the final value \((H_f)\) is assumed to vary exponentially. The system is excited by AC voltage and due to constant period change in the input signal, there exists a local maximum/minimum. Hence, the variation in inductance is assumed to change exponentially and not linearly [41].

Another factor for this consideration is that if the inductance change is linear the force for different deformation must be constant which is not optimally correct in reality. Hence the variation of inductance is defined as

\[
H_f = H e^{-\frac{\delta}{\delta_x}} \quad (9)
\]
where $\beta = \ln(\mu_r)$. The value of $\beta$ is lower than this but greater than unity. From this, the inductance is directly proportional to the induced EMF due to variation in structure caused by bending, the relative permeability of the core and the number of turns. The experimental setup similar to an LR circuit and the power loss $(P)$ can be determined by the product of the voltage and current in the circuit which is given by

$$P = \frac{E_{rms}}{Z_f} e^{-\tau t} (1 - e^{-\tau t}), \quad (10)$$

where, $Z_f$ is the total impedance of the circuit defined as

$$Z_f = \sqrt{R_{int}^2 + (\omega L_f)^2}$$

and $R_{int}, \omega$ are internal resistance and supply angular frequency respectively.

### III. Device Principle and Design

The sensor consists of electromagnetic coil excited by AC voltage source. There is an inductive change in the sensor due to the change in length ($\Delta l$) which is directly proportional to the angle of deformation induced. This sensor can also be calibrated to measure the amount of force exerted for the bending. To implement proposed SBS as a force sensor, a relationship between the rates of change of energy transformation with the externally applied force required to induce the bending must be established. The fitting function of this relationship can then be integrated to determine the force generated by SBS.

#### A. Elastomer Design

Unlike the other soft induction based force sensors, SBS is fabricated by embedding polyurethane enameled copper wire wound spirally around a magnetically permeable material in an elastomer. The sensitivity of the sensor depends on the material of fabrication. For the sensor to be flexible and better responsive to a slight change in force, the sensor should be comprised of soft material. For this reason, the sensor is fabricated with eco-flex. Eco-flex has added advantage of ensuring the helical coil configuration remains intact when subjected to external force and does not affect the magnetic flux induced in the coil. Fabrication of this sensor is economical, pliable, reliable and highly robust in nature.

The detailed configuration of the sensor and the process of fabrication is depicted in Fig. 5 (a) & (b) respectively. This involves helically winding 0.25 mm copper wire over a magnetically permeable core to varying number of turns either manually or through the coil winding machine. The pitch angle of the coil is 1 mm, the total diameter is 10 mm and the total conduction length of the solenoid depends on the number of turns. The sensor is tested with three different cores to relatively comparing the variation of the inductance change with a change in the permeability of the medium. We tested with a simple air core and then increased the permeability of the sensor by using ultrafine carbonyl iron powder for inductive electronics with >99% iron (SQ BASF) with molecular formula Fe. The average particle size is around 4.5 $\mu$m with relative permeability approximately around 38 at a frequency of 200–2000 MHz. Then the sensor was tested with flexible Magnetic Strip (MS) (3M EM80KM) with dimension 120 × 420 × 0.02 mm. The magnetic permeability of the tape is around 80,000 at 0.1 MHz.

A cylindrical mold of dimensions slightly greater than 10 mm is 3D printed using XYZ noble 1.0 printer. A mixture of Eco-flex (A&B) 00–30 (Smooth-on) is poured into the mould which is degassed by placing in a vacuum chamber for 5–10 min. The wounded helix copper coil is slowly immersed into the cylindrical mould which is then cured by placing in an oven for about 30 min at 90°C for curing. Multiple layers of Eco-flex coating are provided for a thickness of about 2 mm by the same method of fabrication as described above for making the device robust under different working conditions.

#### B. Experimental Setup

The simplified circuit diagram and the experimental setup is shown in the Fig. 6 (a) & (b) below the cylindrical SBS is fixed to a support and a 33$\Omega$ series resistor are excited by a 10 MHz, 50$\Omega$ signal generator (SFG-2010 GW INSTEK).
Fig. 6. (a) Circuit diagram of experimental setup excited by AC source with $33\Omega$ series resistor. (b) Experimental setup of SBS with Fe core.

The overall system operates at the cut off frequency (8MHz) determined by comparing voltage drop across the series resistor and sensor using an oscilloscope (Rigol DS1102E Digital Oscilloscope) and Digital Multimeter (73203/R, Yokogawa) respectively. With external force applied to the free end, the SBS is deformed to a certain angle (0-180) which induces a fluctuation in the induced EMF of the sensor. The bending angle is controlled manually through steps of 30°. This deformation which is analogous to the bending of the sensor, causes the outer curvature of the solenoidal coil to be displaced more than the inner curvature as shown in Fig. 2. A magnetometer (HT20, Hangzhou BST Magnet Co. Ltd) employed determines the changes in flux linkage induced in the coil due to the source and the deformation of the solenoid. The displaced pitch angle of the solenoid coil depends on the angle of bending on the sensor which is proportional to the induced EMF, which can be calibrated to equivalent force generated. The sensor was subjected to tensile stress using INSTRON UTM and observed that SBS is highly flexible and expand up to twice its original length.

**IV. RESULTS AND DISCUSSION**

This proposed sensor (SBS) is based on the principle of electromagnetic induction, where there is a change in induction with respect to external stimuli like force, pressure etc. The rate of change of induction can directly be calibrated to determine the amount of bending. The sensor magnetic field range lies between the low to medium range i.e. mT to T. Thus, the sensitivity of the sensor can be modified in different range by varying cut off frequency of the sensor. There different parameters like a magnetic field, induced EMF and Inductance were measured and compared with different sensor sample. These were mainly tested to determine the optimal parameters that can be used for measuring the inductance with respect to the analytical modelling. This was done to evaluate the sensor performance with a change in different parameters. The best results were obtained for MS core with 150 turns and this section provides a detailed comparison of different parameters between various cores and turns employed. This is due to the change in the relative permeability of core and the sensitivity of the sensor can be enhanced by modifying the core materials of the sensor.

**A. Magnetic Field Change of Different Sensor Sample**

The initial dimensions of the sensor like the cross-sectional area are varied due to the deformation while bending, this in-turn produces a variation in magnetic field. The variation in a magnetic field was determined for every 30 degrees change in deformation of the sensor. Although the other core followed a similar trend, MS core provided the best results. This is due to the difference in permeability which is evident from (3). The defining feature of our sensor is the fabrication process where the thin flexible copper wire is wrapped tightly around the core and sealed with a polymer. We had maintained a constant length in fabricating a different number of turns. Due to this, the sensor with 150 turns has a greater resistance and current in each loop experiences a proximity effect and the effective magnetic field is reduced for the higher turns. The Fig. 7 shows the average variation of magnetic field and deformation for every 30-degree change in angle for MS core operated at cut off frequency. The variation in the magnetic field is found out to be almost linear. During the experimental process,
the sensor is clamped at one end and the free end is subjected to bending. During the forward bend, the outer curvature of the sensor is widened and increases the spacing between the numbers of turns which in-turn reduces the magnetic field generated. The field is almost linear until 90-degree as the spacing between the number of turns doesn’t change significantly but when further bent the number of turns in the sensor tend to remain close to each other which concentrates the magnetic field. When the turns are brought closer the field strength induces a proximity effect which causes an increase in the field. Due to this, there is a sharp increase in the field strength for higher bending angle.

B. Induced EMF Measurement

The induced EMF in the sensor varies with the deformation induced due to the change in the dimension of the sensor, magnetic field and the pitch angle of the coils. By keeping the core constant and measuring the EMF induced for different turns, MS core with 150 turns shown to be a reasonably better response.

A comparison of EMF induced between 100 and 150 turns normalised by the EMF of 50 turns for sensor sample with MS core is shown in Fig. 8. These measurements were taken at the cut-off frequency for three different trials at 10 min interval by maintaining the external conditions, frequency and current constant. This induced EMF is dependent on the current flowing through the sensor and the series resistor and hence the value of current is kept between the ranges is 0.8 mA ± 0.1. The average standard error for different trials was found to be around 0.3%. The induced EMF is proportional to the number of turns as seen from (4) and hence the average of the EMF induced across the sensor sample with 150 turns is 1.78 times greater than the average of 100 turns. The sensitivity of the sensor with MS core and 150 turns was found to be 0.418 mV/rad.

C. Inductance of Various Sensor Sample

Inductance is a variable quantity which varies with induced EMF, current and magnetic permeable core. The rate of change of current is 0.8 mA and input sine wave of 8 MHz is utilized to excite the sensor. Due to the periodic change in input, inductance variation depicts a local maxima/minima. For various samples with different core and number of turns, the inductance change demonstrated a similar trend. The bending of the sensor is shown in Fig. 9 (a) for different angle range. From initial to mid position, the inductance tends to increase exponentially describing inductance and EMF are directly proportional. Increasing the core also has a significant increase in inductance. Inductance comparison was determined by having the core constant and varying the number of turns.

During the forward bending of the sensor, the relative electrical resistance increases as the conduction path through the wire increases this decreases the magnetic field change, but the induced EMF increases across the sensor. This induces an exponential increase in induction. During the backward bending, the resistance decreases as the pitch angle of the coil winding decreases which reduces the conduction path and there is an increase in magnetic field. Due to this, there is an exponential decrease in induction. The difference between the forward and backward bend can be identified by measuring the change in the magnetic field and the induced EMF. The inductance change for sensor sample with 50 turns wasn’t significant in comparison with 100 and 150 turns as elucidated with results. It was observed that the variation of inductance between MS core of 100 and 150 turns was 1.5 times higher and for 150 turns between MS core and Fe core was about 20 times higher for different deformation induced in the sensor. Fig. 9 (b) shows the difference in inductance between sensor samples with different turns.

D. Mechanical Properties of the Sensor

To determine the flexibility, strength and to the effects of an in-plane strain of silicon elastomer embedded with flexible copper wire tensile testing was conducted through INSTRON-UTM. It was observed that the sensor could bear a strain of about 100% (2 times stretch) for the test piece dimensions used. The experiment was conducted on different samples for varying trial and provided almost the similar amount of stress the sensor can handle. From this, it can infer that the sensor sample is highly durable and flexible. Due to the high flexibility, there is an easy bending of sensor sample.

The performance of the sensor isn’t affected due to the loading the sensor. The Fig. 10 shows the tensile expansion of sensor sample of air and Fe core. MS core sample wasn’t tested for tensile measurement as the strip is flexible but not stretchable. It was observed that iron core had less modulus of elasticity then air core. This is due to the concentration of iron particles in the sample. The mixture of the iron and the silicon material is a composite material and this reinforced matrix contributes significantly to the change in physical properties. During the expansion, there is a huge interaction of the iron particle with the interface of the silicon matrix and hence this material possesses mixed elastic material as it is
Fig. 9. (a) Overall bending of sensor sample excited by AC source of 8 MHz. (b) Inductance measurement of different sensor sample with different core and varying number of turns during the forward and reverse bending. (i) Inductance of MS core for different turns, the inductance between 100 and 150 turns is 1.5 times higher. (ii) Inductance of Fe core with varying turns, inductance of Fe and MS core for 150 turns is twenty times higher. There is a slight variation between the values of the left half and right half graphs with an average difference in the reading to be around 0.004 mH and the average value of the inductance with error bar also show the difference.

Fig. 10. Mechanical testing of MS core sample of 150 turns, tensile strain of twice stretch.

The percentage of the iron filler in the polymer matrix is around 85%, increasing the concentration of the particle beyond this can affect the mechanical properties of the composite material [43], [44]. Also, this mechanical testing combination of a stiffer material with an elastic phase. Due to this, the elongation is higher than the pure silicon matrix [42]. The mechanical properties of these composite materials also depend on the relative amounts of the individual components.
TABLE I

<table>
<thead>
<tr>
<th>Type</th>
<th>Polynomial Function</th>
<th>Coefficient of Determination, $R^2$</th>
<th>Sensitivity(mV/rad)</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flex sensor</td>
<td>$y = 0.015x^2 + 0.076x + 0.1531$</td>
<td>0.9901</td>
<td>0.777</td>
<td>0.003445</td>
</tr>
<tr>
<td>SBS MS core</td>
<td>$y = -0.0007x^2 + 0.0004x + 0.0577$</td>
<td>0.9815</td>
<td>0.418</td>
<td>0.000691</td>
</tr>
<tr>
<td>SBS Fe core</td>
<td>$y = -0.0017x^2 + 0.0056x + 0.0538$</td>
<td>0.9369</td>
<td>0.085</td>
<td>0.000409</td>
</tr>
<tr>
<td>SBS air core</td>
<td>$y = -0.0006x^2 + 0.001x + 0.0587$</td>
<td>0.9429</td>
<td>0.024</td>
<td>0.00057</td>
</tr>
</tbody>
</table>

was performed by clamping the samples directly to the INSTRON-UTM machine. Due to this, the critical internal pressure of the air core SBS sensor has increased during the tensile strain measurement which has a lower elongation when compared to the other sensor with a magnetic core.

E. Comparative Result

A comparative analysis of the induced EMF with the deformation induced was conducted to evaluate the performance of SBS sensor fabricated with 150 turns and commercially available flex sensor 2.2" (Spark fun). Three different trials were performed, and the flex sensor had to be calibrated for every set of experiments. This was due to the resistance change at the initial stage (0°) after a set of experiments which is not the case with SBS sensor. There is a minimal or negligible change in the inductance of the sensor after it is calibrated. Another main advantage of our sensor is that it is bidirectional, unlike the flex sensor. There is a uniform change in inductance of the sensor when bent through different directions as a change in inductance depends on the change in the magnetic flux which is independent of the direction of bend and only depends on the configuration of the sensor.

The EMF-deformation curve is obtained by extracting the output voltage ($V$) and the deviation angle and a linear trend line are obtained based on the three different cyclic trials. The calibration equation that best fits is the second-order quadratic function, $y = ax^2 + bx + c$ where $y$ is the induced EMF($V$) and $x$ corresponds to the deformation of the sensor. The sensitivity of the sensor was determined by the formula ($\Delta E$) $\Delta D$ where $\Delta E$ is the change in induced EMF in mV, $E$ is the initial EMF at zero degree and $\Delta D$ is the change in angle in radians. Thus, from this, the sensitivity of the SBS is nearly close to the commercial flex sensor. Along with sensitivity comparison, we also have calculated power consumption during varying bending angle in different SBS core (MS and Fe) as per (9).

The value of power consumption in MS core in 150 turns changes from 0.5 W to 0.6 W while Fe core in 150 turns changes from 0.3 W to 0.5 W during entire deformation.

V. Conclusion

In this present paper, a flexible bend sensor which is electromagnetically enhanced is proposed. This sensor has a unique design of helically wound flexible coil in an elastomer. By formulation of numerical analysis and experimental procedure, the inductance is determined based on the bending moment. Here we have experimentally observed that there is an increase in inductance when deformed in forward direction and vice versa. The other parameters of the sensor like the induced EMF and the magnetic field do have a monotonous variation throughout the deformation of the sensor but the inductance change is significant over the other parameters. This proposed sensor is highly flexible with a tensile strain of twice its original dimensions due to the soft embodiment. Due to the flexible coil in a helical structure, the magnetic field in the sensor is concentrated at the centre and linearly decrease during the forward bending.

The sensor doesn’t require high input supplies and operates at 8 MHz and 0.8 mA. The sensor can also bear a tensile stress of twice the length, making the sensor highly flexible and durable to the exerted load. In comparison with the commercially available sensor, the sensitivity of the sensor is almost comparable and have a lower root mean square error. Increasing the magnetically permeable core of the sensor would improve the sensitivity. This novel flexible sensor is customized to be bidirectional and lower cost. The proposed sensor’s main advantage lies in its easier fabrication and simpler mode of operation. The calibration of the sensor can be performed once for a separate set of experiments, unlike the commercial resistive based sensor which requires multiple calibrations as the resistances changes for the initial condition once strained. The concept we imbibed here in this manuscript can be further extrapolated into different regimes of biomedical applications e.g. wearable exoskeleton, stretchable electronics and can also in future be applied as secondary skin.

REFERENCES

PRITUJA et al.: ELECTROMAGNETICALLY ENHANCED SOFT AND FLEXIBLE BEND SENSOR


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