An Eddy-Current-Based Angle Sensor With a Minimally Modified Shaft as a Sensing Element

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ABSTRACT Eddy current sensors are an attractive choice due to their high resolution, reliability, and durability in harsh environments while being able to measure in a noncontact manner. This article presents a novel design to realize a thin eddy-current-based angle sensor. It is realized by converting the shaft, whose rotation angle is to be measured, into the sensing element. The modification to the shaft is minimal; a small surface groove is introduced without affecting the mechanical strength. The stationary part of the sensor consists of two layers of flexible square-planar coils. Depending on the angular position of the shaft, the inductances of the planar coils get modified. These are measured using a specially designed circuitry, optimized for this sensor. The output for the entire circle range (360°) is derived from the inductance values of each coil using a successive approximation algorithm developed for this purpose. Finite-element analysis was employed to design the sensor and analyze the axial/radial misalignment of the rotor. A sensor prototype was built and tested. The output showed a resolution of 0.1° and the worst case linearity error of 0.9%. The prototype sensor dimensions are designed to fit in a standard steering column. The proposed sensor is thin, easy to manufacture at low cost, tolerant to axial vibration by design, and has a 360° sensing range.

INDEX TERMS Eddy current sensor, planar coils, steering angle sensor, surface groove, variable inductance.

I. INTRODUCTION

Thin noncontact angle sensors that provide reliable high-resolution output, even in a dusty and humid environment, are preferred in automotive and industrial applications [1], [2]. If we take a steering wheel angle sensor, real-time data from it is needed for electronic power steering, electronic stability programs, and anti-lock braking systems [2], [3], [4]. While the above-mentioned features are important, the other key factors are: 1) insensitivity to the vibration, and mechanical misalignments between the shaft and the sensor; 2) no wear and tear; 3) compactness; and 4) easy to manufacture and hence low-cost [2].

Sensors based on various noncontact sensing techniques, such as magnetic [2], [3], [4], [5], MEMS (capacitive) [6], optical [7], and capacitive [8], [9], have been reported for steering angle sensing. In addition, other general-purpose rotary sensors reported in the literature can be incorporated to measure the steering position [10], [11], [12]. Nearly all of the reported sensors [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12] require an attachment (to make changes in the output with respect to the position) to be fitted to the shaft whose position is to be measured. Moreover, the axial/radial misalignment of the rotating part generates erroneous responses from the sensor. Of all these, magnetic sensors have certain benefits, considering their ruggedness [4]. Designs employing highly sensitive magnetoresistive (MR) sensors have been reported [4], [13], [14], but need a permanent magnet (PM) attached to the shaft. MR element senses the magnetic field of the PM with a sensing angle. The aging of the PM, sensitivity to external magnetic interferences, and temperature are the important limitations of these sensors [14], [15]. Some of these need gear wheels [2], [4] leading to additional errors due to backlash. It will be advantageous if a thin angle sensor that does not require any attachment to the shaft can...
be developed, but, at the same time, possesses the benefits of magnetic sensors and does not have the limitations introduced by the PM.

One of the best sensing techniques to realize a sensor, meeting the above requirements, is based on eddy current [16]. To achieve high compactness, the eddy-current-based sensor design would require the shaft to serve as one of the sensing elements. Attaching any new part to the shaft is not preferred as it will increase the thickness [16], [17] of the sensor and any slip between the shaft and attachment will introduce an error. Another approach is to introduce a surface groove with a minimal depth [18] on the moving part and sense its position based on the change in the inductance of thin planar coils. But the output should not be sensitive to misalignment between the moving part and the sensing coil, which is a limitation in the eddy current linear position sensor given in [18]. A similar approach is explored in [17] but the shaft needs a through-hole groove.

This article presents a thin, noncontact eddy-current-based angle sensor that gives a linear output for the full circle range. It makes use of a metallic shaft with a small surface groove. The output is not sensitive to dust, moisture, axial vibration, or associated misalignment. As a proof of concept, a sensor design was made for the steering wheel position sensing application. The details of the sensing technique, design, algorithm to compute the output, experimental results, and performance comparison with existing schemes are presented in the sequel.

II. EDDY-CURRENT-BASED ANGLE SENSOR

A. SENSOR STRUCTURE

The structure of the proposed angle sensor is illustrated in Fig. 1. The sensor comprises a stationary part with two identical flexible printed circuit boards (PCBs), one top PCB and a bottom PCB. Each PCB consists of six identical square-shaped planar coils. The PCBs are wrapped around the shaft in such a way that coils in the top PCB have an offset of 30° with the corresponding coils in the bottom PCB, as shown in Fig. 1(c) and (d). The coils are energized using sinusoidal voltage sources, either $V_{S} \angle 0^\circ$ or $V_{S} \angle 180^\circ$, using suitable multiplexers. In this sensor design, the shaft whose angle of rotation is to be measured itself serves as the sensing element. A small surface groove is introduced on the shaft. The length of the surface groove should be greater than or equal to the width of the planar coil.

B. SENSING PRINCIPLE

When the coil is excited, the magnetic field produced by the eddy current opposes that of the coil, changing the flux linkage of the coil and its effective inductance. When a groove is present in the shaft, the eddy current path will be altered in that area. Thus, the inductance of the planar coil will change depending on the position of the groove in relation to the position of the coil. As a result, the impedance of the stationary coil varies as a function of the rotation angle ($\theta$) of the shaft.

Compared to a through-hole type groove, the change in inductance produced by the surface groove is low, which will affect the resolution and sensitivity of the sensor. Hence, a suitable differential measurement scheme is required to enhance the resolution and sensitivity of the sensor. In addition, the shape of the inductance versus $\theta$ characteristics is strongly dependent on the coil width to groove width ratio. It is, therefore, useful to conduct a finite-element analysis (FEA) study to optimize the scheme in terms of the number of coils required, the linearity of the output characteristic, and the complexity of the measurement circuit.

III. FINITE-ELEMENT ANALYSIS

The FEA of the proposed system was carried out using the AC/DC module of the COMSOL Multiphysics software. A 3-D model of the sensor was developed. A solid cylindrical shaft with a surface groove of the depth of 1.5 mm was modeled in the COMSOL. The coils, A–F, were made by the square-shaped homogenous multiturn coils, with 50 number of turns. Then, these coils were introduced around the shaft, with an air gap of 0.5 mm, as shown in Fig. 2(a) and (b). A constant current of 100 mA, 250 kHz, was injected into the coils.
Depending on the groove’s position with respect to coils, the magnetic field strength around the coils changes. Fig. 2(a) and (b) shows the 3-D simulation model of the sensor, when the angular position of the shaft, \( \theta = 95^\circ \). Fig. 2(c) shows the magnetic field distribution of coils A and B at the same angle. At this position, as the groove does not see coil A, the magnetic flux density around coil A is symmetric around its center. But, as in Fig. 2(c), in coil B, the flux linkage due to the groove produces a change in magnetic flux density over the groove surface.

To obtain the inductance versus \( \theta \) characteristic of the coils, in the FEA, the shaft was rotated from \( 0^\circ \) to \( 120^\circ \), in steps of \( 5^\circ \) and the self-inductance values were recorded. The self-inductances of the coils A and B with respect to \( \theta \), for the range \( 0^\circ \leq \theta < 120^\circ \), are presented in Fig. 2(d). As seen in Fig. 2(d), for \( 0^\circ \leq \theta \leq 60^\circ \), the inductance \( L_A \) of the coil A alone changes with respect to \( \theta \). As the surface groove is not under coil B, its self-inductance \( L_B \) remains unchanged. Similarly, for \( 60^\circ < \theta \leq 120^\circ \), the value of \( L_B \) alone changes while \( L_A \) stays constant. At \( 60^\circ \), the individual inductance values are slightly higher than the other flat region. Also, when the groove is very close to coil B but under coil A, there is a minor effect in \( L_B \). The reverse is also true.

FIGURE 2. FEA of the proposed sensor. (a) 3-D model developed for the FEA study. (b) Cross-sectional view of the model. (c) Magnetic flux density around coils A and B. (d) Inductance change obtained for coils A and B for \( 0^\circ \leq \theta < 120^\circ \). (e) Difference in inductance \( (L_{AB} = L_A - L_B) \) noted for the coil pair A-B for \( 0^\circ \leq \theta < 120^\circ \).

A. MULTIPLE COIL PAIRS
The system mentioned above with two coils enables to measure \( \theta \) in the range of \( 0^\circ \)–\( 120^\circ \). Multiple coil sets with identical shapes and sizes can be used to extend the measuring range. For the measurement of \( 0^\circ \)–\( 360^\circ \), three sets of such coil pairs can be used. The coil pair C-D is introduced to measure from \( 120^\circ \) to \( 240^\circ \). Similarly, the coil pair E-F gives an inductance change for the range \( 240^\circ \) to \( 360^\circ \). The resulting inductance curves, against \( \theta \), for \( 360^\circ \) are shown in Fig. 3(a). Here, each coil set will have an inductance change for \( 120^\circ \), as explained above.

B. TOP AND BOTTOM PCBs
As explained above, \( \theta \) can be obtained from the sinusoidal differential inductance curve. As in Fig. 3(a), within \( 60^\circ \), the inductance curve is symmetrical with respect to the center of the coil. Therefore, two \( \theta \) positions can give the same inductance value. For example, for \( 0^\circ < \theta < 60^\circ \), the inductance curve is symmetrical with respect to \( 30^\circ \). Here, a mechanism is required to detect whether \( 0^\circ \leq \theta < 30^\circ \) or \( 30^\circ \leq \theta < 60^\circ \). Similarly, for \( 60^\circ < \theta < 120^\circ \), we need to find out whether \( \theta < 90^\circ \) or \( \theta > 90^\circ \). Moreover, as shown in Fig. 3, at every \( 60^\circ \) starting from \( 0^\circ \), the differential inductance provides zero output value.

To solve these problems, as shown in Fig. 1(d), another identical PCB layer, is introduced on top of the bottom PCB. The top PCB is arranged in such a way that its coils, \( L_1-L_6 \), are aligned at an offset angle of \( 30^\circ \) with the coils in the bottom PCB. The resulting difference in inductance characteristics of the top PCB is shown in Fig. 3(b).
the differential inductance for bottom coils is zero, the position information can be obtained from the coils in the top PCB. Moreover, the limitations due to the symmetry of the inductance curve can be overcome by comparing the information from both the PCBs. In a nutshell, the position information can be calculated using the sinusoidal curve fit of the inductance data obtained from the bottom PCB while the ambiguity that arises due to the symmetry of the curve can be solved by using the polarity of the inductance characteristics of the top PCB.

It is very clear from Figs. 1(d) and 2(b) that, at a time, the groove will see only one coil from the top and bottom PCBs. Once those coils are identified, the corresponding angular position information can be obtained from the differential inductance values of the corresponding coil pairs. A successive approximation (SA) approach is proposed to determine the coils where the surface groove is present.

IV. SUCCESSIVE APPROXIMATION ALGORITHM AND THE MEASUREMENT APPROACH

A. SUCCESSIVE APPROXIMATION ALGORITHM

The proposed SA-based angle measurement method is divided into a quadrant selection phase and an angle measurement phase, as shown in Fig. 4. The quadrant selection phase is a coarse-level measurement where the quadrant in which the surface groove is present is identified. Once the quadrant is identified, the absolute angle is calculated using the coils from top and bottom PCBs, which belong to that particular quadrant. This is a fine measurement resulting in accurate angle information. As shown in Fig. 4, the final angle is computed in five steps. In the quadrant identification phase, the algorithm will find whether the angle \( \theta > 180^\circ \) or \( \theta < 180^\circ \). After the first step, if \( \theta > 180^\circ \), next it will find whether \( \theta > 270^\circ \) or \( \theta < 270^\circ \), otherwise, \( \theta > 90^\circ \) or \( \theta < 90^\circ \) to be identified. As shown in Fig. 4, the absolute angle measurement phase is performed in three steps. In the third measurement step, the position is known over a range of \( 60^\circ \). In the fourth step, the algorithm determines the position over a range of \( 30^\circ \), and the exact position of the surface groove can be obtained in the final step. The SA algorithm can be operated, and the final position can be obtained using a suitable microcontroller/processor.

B. ANGLE CALCULATION FOR MULTIPLE REVOLUTIONS

If the shaft undergoes multiple revolutions, the number of revolutions completed is needed to estimate the actual angle \( \theta \). In addition, it is necessary to detect the direction of rotation in some applications. The estimation process is illustrated in Fig. 5. Three variables, \( \theta_t \), \( \theta_n \), and \( \theta_{n-1} \) are introduced to enable the process. The current angle is \( \theta_n \). It is obtained using the SA algorithm as in Fig. 4. \( \theta_n \) can be in the range of \( 0^\circ-360^\circ \). It is considered that the output update rate of the sensor is such that at least two \( \theta_n \) values are obtained within a rotation. \( \theta_{n-1} \) is the previous angle. \( \theta_t \) is a temporary register where the final output is available when the system is turned off, \( \theta_{n-1} \) is retained safely as it is always stored in the nonvolatile memory (NVM). When the system is turned on or when a new measurement is available, \( \theta_{n-1} \) is read and, initially, set it as \( \theta_t \). Then, the difference \( \Delta \theta = \theta_n - \theta_{n-1} \) is computed. This will directly give the direction of rotation of the shaft and the change in the angle. As in Fig. 5, once the magnitude and sign of \( \Delta \theta \) are obtained, the actual angle \( \theta_t \) is computed and updated. Once the angle \( \theta_t \) is calculated, \( \theta_n \) is stored as \( \theta_{n-1} \) for future use or next measurement cycle.

It is possible that the shaft may rotate when the sensor is turned off (e.g., dead battery). In such a case, \( \theta_{n-1} \) stored in NVM becomes not useful. An equivalent problem has been tackled earlier by researchers, for similar applications. One option is to use a pulse wire sensor presented in [19] to count the revolutions even when the sensor is not powered. This mechanism generates electricity from the shaft rotation and increases or decreases the NVM automatically, for every full circle rotation [19].
C. MEASUREMENT SCHEME

A circuit that measures the differential inductance of two coils is shown in Fig. 6(a). Consider two coils, A and B, with inductances $L_A$ and $L_B$, respectively. These coil’s nominal inductance values $L_0$ (without the presence of the surface groove) will be equal where $L_A = L_B = L_0$. The groove will introduce a change, as a function of $\theta$, in $L_A$ or $L_B$ depending on the position of the groove. As the groove sees only one coil at a time, the inductance of the other coil remains $L_0$. As shown in Fig. 6(a), coils A and B are excited using two sinusoidal sources, $V_S \angle 0^\circ$ and $V_S \angle 180^\circ$, respectively. The sum of currents that flows through coils A and B flows through the feedback resistor $R_F$ of the op-amp $OA$. This current $I_F$ gives a voltage $V_O$ at the output of $OA$.

When $L_A = L_B$, the currents $I_A$ and $I_B$ are equal in magnitude and opposite in direction, and the output voltage $V_O = 0$. Now, for $0^\circ < \theta \leq 60^\circ$, the surface groove is under coil A (refer to Fig. 2(a) and (b)), the inductance of coil A is greater than that of coil B, i.e., $L_A > L_B$. In this condition, the output $V_O$ can be expressed as

$$V_O = \frac{\sqrt{2}V_S R_F}{\omega} \left( \frac{L_A - L_B}{L_AL_B} \right) \sin(\omega t + 90^\circ). \quad (1)$$

In (1), $\sqrt{2}V_S$ and $\omega$ represent the peak value of the signal and the frequency of the signal, respectively. For a range of $60^\circ$ to $120^\circ$, $L_A < L_B$ (the groove is under coil B), the magnitude of the output in (1) remains the same, however, the phase of the signal will change to ($-90^\circ$). In a nutshell, the value of $\theta$ can be obtained using the magnitude of $V_O$, and the in which the groove is present can be identified using the phase value of $V_O$. This idea is used to implement the SA algorithm shown in Fig. 4.

During the first step of the algorithm, six coils in the bottom PCB are divided into two groups with three coils each. As shown in Fig. 6(b), the first group of coils, $L_A$, $L_B$, and $L_C$, are connected to $V_S \angle 0^\circ$ and, the second group, $L_D$, $L_E$, and $L_F$ are connected to the signal $V_S \angle 180^\circ$. If the groove is present under the first group of coils, i.e., $0^\circ < \theta \leq 180^\circ$, the phase of $V_O$ will be ($-90^\circ$). For $180^\circ < \theta \leq 360^\circ$, the groove position is under the second group of coils, and the phase value of the output $V_O$ will be ($+90^\circ$). During the second step, the coils from the top PCB are connected to the circuit in a similar fashion where $L_1$, $L_2$, and $L_3$ are connected to $V_S \angle 0^\circ$ and, the second group, $L_3$, $L_4$, and $L_5$, are connected to the signal $V_S \angle 180^\circ$. As a result, after the completion of two steps, the groove position can be determined with a quadrant level resolution. During the third step, coils 1, 2, and 3 are connected to the signal $V_S \angle 0^\circ$ while coils 4, 5, and 6 are connected to $V_S \angle 180^\circ$, such that the groove position can be identified more precisely, as shown in Fig. 4. In the fourth step, the angle information can be obtained over a range of $30^\circ$ using two coils from the bottom PCB from the corresponding quadrant. Finally, in the last step, the exact angle can be calculated with the help of two coils from the bottom PCB. As the coils from the top and bottom PCBs are not used simultaneously, and when one is used, the other one is in open circuit, any error that arises due to the interaction between these coils in the PCBs is avoided. It is clear from Figs. 1(d) and 6(b) that after the first measurement step, the output voltage $V_O$ is zero if $\theta = 0^\circ$ or $\theta = 180^\circ$. However, this can be identified and solved in the second measurement step. As shown in Fig. 4, the total measurement process consists of five steps. The total time taken to get the output mainly depends on the conversion time of the analog to digital converter used to acquire $V_O$. It should be noted here that the magnitude of $V_O$ is not required for one to four steps of the algorithm, which helps to reduce the complexity. Once we identify $\theta$ over a range of $30^\circ$, the final angle can be calculated using the magnitude of differential inductance values of the corresponding two coils from the bottom PCB in the last step.

D. EFFECT DUE TO CHANGE IN MATERIAL PROPERTIES OF THE SHAFT

Any change in the electrical conductivity ($\sigma$) and magnetic properties, e.g., relative permeability ($\mu_r$), of the shaft material will affect the eddy current. To evaluate the effect, an FEA was conducted using the AC/DC module of the COMSOL Multiphysics software. The performance of the sensor was evaluated for two materials; steel with $\sigma = 4.03 \times 10^6$ S/m and $\mu_r = 1$, and iron with $\sigma = 1.12 \times 10^7$ S/m and $\mu_r = 4000$. The change in output was recorded for different values of $\theta$, for both the cases. It is noted that the use of these materials does not alter the shape of the output versus angle characteristics. However, the results show an increase in peak-to-peak amplitude of the output versus angle curve, with respect to that of Aluminium. The maximum relative amplitude change in the output is found to be 16.1% for steel and 10.8% for iron. This is expected as the properties are different. In the actual application, once the material of the shaft, whose angular position is to be measured is known, the sensor output can be calibrated once as done in the current prototype developed.

V. EXPERIMENTAL SETUP AND MEASUREMENT RESULTS

A. PROTOTYPE SENSOR

To verify the design and demonstrate the feasibility, a prototype of the proposed sensor was fabricated using flexible PCB technology. Fig. 7(a) shows the photograph of the fabricated prototype and measurement circuit. Two identical
ANIL KUMAR et al.: EDDY-CURRENT-BASED ANGLE SENSOR WITH A MINIMALLY MODIFIED SHAFT

**FIGURE 7.** Experimental setup and measurement results. (a) Photograph of the prototype sensor and measurement circuit. In (a), 1. Display of reference angle sensor. 2. LabVIEW-based graphical user interface. The inset picture shows the top view of the PCB used in the prototype. (b) Schematic of the measurement circuit.

Flexible PCBs were fabricated; one bottom PCB and a top PCB. Each PCB contains six identical planar square coils. To increase the number of turns and sensitivity, the coils in the PCBs were manufactured in two layers connected through a via at the center of the coils. For the prototype sensor, each layer contains 35 turns. The dimensions of the individual square coils are 16 mm × 16 mm and, hence, the total length of the PCB is 96 mm. The stationary part (top and bottom PCBs) was wrapped around the rotating shaft using a Teflon bobbin, with an air gap of 0.5 mm, as shown in Fig. 1(d). The dimensional details of the sensor parts are listed in Table 1.

The total weight of the material which was removed to form the groove is very small (≈0.25 g) compared to the total weight of the shaft corresponding to the groove length. The depth of the surface groove is 1.5 mm which is very small compared to the shaft radius of 15 mm. Therefore, the presence of the surface groove will have a negligible effect on the strength of the shaft. When such a sensor is designed, the designer should ensure that the strength of the shaft is not compromised.

During the design process, the parameters of the square planar coils were selected considering the application and performance specifications. The parameters of the coils such as: 1) size (length and width); 2) number of turns; and 3) operating frequency were optimally chosen considering the installation space limitations, cost, performance, and the availability of the PCB manufacturing facilities.

### TABLE 1. Parameters of the prototype sensor.

| Parameter      | Value |
|----------------|-------|
| Number of layers | 2     |
| Total no. of turns | 70    |
| PCB            |       |
| Track width    | 0.12 mm |
| Coil inductance| 40.8 μH |
| Coil resistance | 12.5 Ω |
| Shaft          |       |
| Outer diameter | 29.24 mm |
| Length         | 30 mm |
| Groove dimensions | Length = 20 mm, width = 2 mm, depth = 1.5 mm |

**B. MEASUREMENT CIRCUIT AND TEST SETUP**

A circuit shown in Fig. 7(b), has been developed to perform the differential inductance measurement and help to realize the SA algorithm. As explained in Section IV-B, to perform the algorithm, the coils from the top and bottom PCBs need to be connected to a current-to-voltage (i-to-v) converter. This was implemented with the help of twelve 4 × 1 multiplexers. IC ADG 609 [20] is used to realize the multiplexer. The sinusoidal excitation signals $V_S \angle 0^\circ$, and $V_S \angle 180^\circ$ were generated using a signal generator, Tektronix AFG 3022B. The frequency of the signals was 200 kHz, which is much below the self-resonant frequency of the coils.

During the experiment, $\theta$ was changed from 0° to 360°, with a step of 5°. A digital optical angle sensor (HENGSTLER 0521088) [21], with a resolution of 0.1°, was used as a reference. As shown in Fig. 7(a), the steering column was mechanically coupled to the shaft of this reference sensor. During the operation, the coils were selected using multiplexers which were controlled using a virtual instrument developed in a LabVIEW environment. The switching signals $S_{1}$ to $S_{12}$ and the enable signal (EN) were realized using a LabVIEW program and NI-ELVIS II+ data acquisition system (DAS). The output $V_O$ of the i-to-v converter was acquired using the DAS and processed as per the SA algorithm to obtain the value of $\theta$. As explained in Section IV, the phase value of the output $V_O$ has to be obtained to perform the SA algorithm. A multiplier type phase-sensitive detector (PSD) [22] is used to extract the phase information of $V_O$, as shown in Fig. 7(b). The phase can be calculated...
from the in-phase ($V_{OP}$) and quadrature-phase ($V_{OQ}$) components of the PSD output [17], [22]. In the prototype, the PSD is implemented in a computer using LabVIEW.

### C. TEST RESULTS

The rms value of $V_{O}$, for the coils from top and bottom PCBs, with respect to $\theta$ has been recorded. As expected, the curves follow the same trend obtained in the FEA shown in Fig. 3. The vertical gap between the shaft and each PCB is different due to the thickness of the PCB which is around 0.3 mm. This introduces different gains for the coil pairs, and hence, the sensitivity of coils in the top PCB is less than that of the bottom PCB. However, the final output will not be affected as the amplitude of signals from the top PCB is not used in computation, instead, its polarity alone is used. Moreover, this gain error can be corrected using a one-time calibration process if required.

The magnitude of $V_{O}$ from the bottom coils is used to compute the value of $\theta$. The voltage curve for the bottom PCB has a sinusoidal shape for every $60^\circ$, and it can be represented as $V_{O} = V_x + V_y \sin(\alpha \theta - \beta)$. The parameters, $V_x$, $V_y$, $\alpha$, and $\beta$, of the sinusoidal curve fit for each $60^\circ$, obtained from the prototype output data are shown in Table 2. Fig. 8 shows the final output from the prototype computed using the SA algorithm and the error characteristics of the prototype. The output has a worst case linearity error of 0.9%. The standard deviation ($\sigma$) of the sensor output is found to be 0.0058 mV. The resolution of the sensor was obtained as 0.1 mV. The main performance parameters of the prototype sensor are shown in Table 3. The proposed sensor has been compared with the existing ones and presented in Table 4. It is inferred from Table 4 that the proposed sensor has advantages such as: 1) high resolution; 2) good linearity; 3) low power consumption; 4) requires very less radial space for installation; 5) no electrical contacts to the rotor; 6) less sensitive to axial/radial misalignments of the rotor; and 7) uses the existing shaft itself as the sensing element without attaching any additional element to it.

### D. EFFECT OF AXIAL AND RADIAL MOVEMENT OF THE SHAFT

In practice, the shaft of the sensor will have an up/down vibration depending on the application. If the shaft undergoes an axial movement, the groove moves out of the coils, and a large error will be introduced. To avoid this problem, the length of the groove should be increased so that, any expected axial movement of the shaft will not change the inductance of the coil. The prototype sensor has a groove length of 30 mm and a coil width of 16 mm. Here, any axial misalignment of the shaft up to $\pm 7$ mm will not affect the output of the sensor.

If there is any mismatch between the center of the shaft and that of the PCB, the differential inductance curve will deviate from the expected characteristics with this misalignment. To evaluate the error in the output, an FEA was conducted using a 3-D model, as shown in Fig. 2. In the study, the center of the shaft was moved, in the $y$-axis direction, from $-0.3$ to $+0.3$ mm, in steps of 0.1 mm. Each 0.1-mm misalignment, the angular position of the shaft was varied from $60^\circ$ to $90^\circ$ to evaluate the error value for different positions of the groove with respect to the coil. The results show a maximum error of $6^\circ/0.1$ mm. Thus, to keep the associated error low, the mechanical tolerance will have to be kept accordingly.

A compensation method for the radial misalignment is proposed without any modifications to the sensor structure and measurement circuit. In the proposed misalignment correction, we first need to know if there is any misalignment or not. Once the groove position is identified using the SA algorithm, the corresponding coil pair and the pair opposite to that coil pair are considered. In the FEA study, $\theta = 95^\circ$, the coil pairs A-B and D-E were used to sense and correct the misalignment. As shown in Fig. 2, for a correctly aligned system, the inductance $L_{T} (= L_{E} + L_{D})$ will be a constant value for the range $60^\circ < \theta \leq 120$. However, this value will be changed if there are any changes in $d_{G}$. This was verified by varying the value of $d_{G}$ from $-0.3$ to $+0.3$ mm, in steps of 0.1 mm, and $L_{T}$ was noted in each case. $L_{T}$ varies as a linear function of misalignment and, thus, values of

### TABLE 2. Sinusoidal curve fitting parameters for the top PCB.

| Angle ($\theta$) | $V_x$ | $V_y$ | $\alpha$ | $\beta$ |
|-----------------|-------|-------|----------|---------|
| $0 < \theta \leq 60$ | -0.150 | 1.7937 | 0.048 | -0.061 |
| $60 < \theta \leq 120$ | 0.1009 | 1.518 | 0.0535 | -0.981 |
| $120 < \theta \leq 180$ | -0.453 | 2.0861 | 0.0442 | -2.380 |
| $180 < \theta \leq 240$ | -0.791 | 2.428 | 0.0403 | -3.794 |
| $240 < \theta \leq 300$ | -0.617 | 2.236 | 0.0427 | -4.814 |
| $300 < \theta \leq 360$ | -0.410 | 2.4186 | 0.0459 | -5.691 |

### TABLE 3. Key performance parameters.

| Parameter      | Value       | Parameter      | Value       |
|----------------|-------------|----------------|-------------|
| Range          | $0^\circ-360^\circ$ | Repeatability | 0.0058 mV |
| Linearity      | 0.85%       | Power consumption | $\approx 750$ mW |
| Resolution     | $0.1^\circ$ | Sensitivity    | 0.053 V/m |

FIGURE 8. Measured output and error characteristics of the prototype sensor. The worst case error noted was 0.9%.
$L_T$ can be used to determine the misalignment. In practice, $L_T$ can be obtained by connecting $L_D$ and $L_E$ to the signal $V_S\angle0^\circ$ [refer to Fig. 6(b)].

Once we quantify the misalignment from the output voltage, the error correction can be done using the inductance values $L_A$, $L_B$, $L_D$, and $L_E$ as follows:

$$L'_{AB} = \frac{(L_B - L_A)(L_T)}{1 - k(L_T)}G$$

(2)

Here, $L'_{AB}$ represents the differential inductance of coils A and B after the misalignment correction. The constants $k$ and $G$ are used to compensate for the gain and offset errors. For the prototype sensor, the constants $k$ and $G$ are $53350$ and $7.6 \times 10^5$, respectively. Now, the angular position $\theta$ can be obtained. The results showed that, after the error compensation, the maximum error due to radial misalignment is reduced from $6^\circ$/$0.1$ mm to $0.65^\circ$/$0.1$ mm, which is an improvement of about ten times.

**E. EFFECT OF ANGULAR VELOCITY OF THE SHAFT**

Rotation of the shaft results in a change in the eddy current distribution in the shaft [29]. As a result, the inductance of the sensing coil will change with the rotational velocity. However, if the frequency of excitation used to measure the inductance is sufficiently high, then, due to the low penetration depth on the shaft, the change in inductance due to the speed of the shaft can be a negligible value [29], [30]. In [29] and [30], the material used for the shaft/moving part is Aluminium. The same material is used in the prototype of the proposed sensor.

To estimate the effect, an analysis was conducted using FEA using COMSOL Multiphysics software. In this study, the sensor was validated for a range of excitation frequencies, from $100$ Hz, $200$ Hz, $1$ kHz, $10$ kHz, $100$ kHz, to $200$ kHz. The rotational speed of the shaft was varied from 0 to $35,000$ rpm, in each case. The maximum errors in the angle, obtained from the inductance output are $8.82^\circ$, $4.41^\circ$, $2.29^\circ$, $0.01^\circ$, $0.005^\circ$, and $0.003^\circ$ for excitation at $100$ Hz, $200$ Hz, $1000$ Hz, $10$ kHz, $100$ kHz, and $200$ kHz, respectively. At the operating frequency ($200$ kHz) of excitation, the associated % worst case error in the prototype sensor is estimated as $0.0008\%$, which is negligible. This was experimentally verified by a test performed at a rotational speed of $750$ rpm. The worst case error noted was $0.004\%$.

**VI. CONCLUSION**

An eddy-current-based angle sensor that uses the shaft whose angle is to be measured as the sensing element has been designed and presented in this article. A small surface groove was introduced onto the shaft. The stationary part is composed of two flexible PCBs, each containing six planar square coils, whose inductances are varied as a function of angle. A prototype of the proposed sensor has been designed, optimized using FEA, and fabricated. An efficient measurement circuit and scheme have been proposed to read from this sensor. The same has been realized and interfaced with the sensor. The output from the circuit has been processed using the proposed SA algorithm and the final output proportional to the angle has been obtained. The developed prototype unit has been tested in detail. The test results from the developed prototype showed a worst case linearity error of $0.9\%$ and a resolution of $0.1^\circ$.

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