A Linear Variable Differential Capacitive Transducer for Sensing Planar Angles
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Abstract—A linear variable differential capacitive transducer for the measurement of planar angles (from 0° to 360°) is presented in this paper. The sensor part of the transducer is made of parallel plates of standard and easy-to-fabricate shapes, and the signal-conditioning electronics are realized, employing a couple of simple relaxation oscillators. The output of the transducer is only dictated by a pair of dc reference voltages, and hence, high accuracy and linearity over the entire range (from 0° to 360°) are easily obtained by the use of precision dc reference voltages. Detailed analysis indicates that the sensitivity of the transducer is minimal for variations in different parameters. Experimental results obtained on a prototype transducer that has been built and tested establish the efficacy of the proposed transducer. The worst-case error of the prototype transducer is found to be less than 0.1%.

Index Terms—Angle transducer, angular-position measurement, differential capacitive sensor, ratiometric measurement principle, relaxation oscillator.

I. INTRODUCTION

SENSING OF planar angles plays an essential role in numerous key applications in automation, automobile, ship, and aerospace industries. Commercially available angle sensors either have limited range of operation (±100° maximum) [1], [2] or possess low resolution and accuracy [3], [4]. Compared with other types of angle transducers, the capacitance-type angle transducers provide low-power and maintenance-free operation. Various forms of capacitance-type angle sensors have already been proposed [5]–[18]. Of these, some have limited resolution [5], [6], some possess limited range of operation [5], and some have nonlinear characteristics [6], [17]. It has been established that the nonlinearity can be minimized by the use of optimal geometry [7]. Some of the limitations can be overcome by employing charge amplifiers and a special excitation pattern [8]. The angle transducer that uses ratiometric computation requires extensive compensation [9]. The transducer based on an integrated sensor approach provides fast response at the cost of resolution [10]. The transducer based on the phase-discrimination principle requires involved computations [11]. The combination of capacitance and magnetic principles for sensing a planar angle results in a very complex transducer [12]. An optimization of the capacitance type angular sensors has been proposed [13], and the effects of asymmetry have also been studied [14]. The angle transducer that employs a synchro resolver needs the use of a complex signal-conditioning circuit based on analog multipliers [15]. Brasseur [16] has described a capacitance-type angle transducer that requires special pulsed voltage sources for proper operation. Mathamad et al. have demonstrated that an output proportional to the tangent of the angle being sensed can be obtained by exciting the sensor part of the transducer proposed by Brasseur with four sinusoidal voltages having equal magnitudes but possessing the phase angles of 0°, 90°, 180°, and 270°. However, the output of this transducer is nonlinear and sensitive to the magnitudes and phases of the four sinusoidal voltages employed for excitation. In order to reduce the nonlinearity introduced by the tan function, they proposed the use of complicated nonstandard-shaped plates that are difficult to fabricate with precision and accuracy [17].

We now describe a novel linear variable differential capacitive transducer (LVDCT) for angular-position sensing [18]. The sensor part of the transducer is made of simple standard-geometry-shaped plates, and the signal-conditioning circuitry uses a set of relaxation oscillators. The output of the proposed transducer is linearly proportional to θ (the angle being measured) for the entire range (from 0° to 360°). The output of the proposed transducer is only dependent on a couple of dc reference voltages. Hence, high accuracy can easily be obtained by employing precision dc reference voltages.

II. SENSOR PART OF THE PROPOSED LVDCT

The sensor part of the proposed LVDCT for sensing planar angles is made of three circular-shaped conducting plates that are concentrically mounted, as shown in Fig. 1. The top plate and the bottom plate are firmly fixed, whereas the middle plate is mounted on a spindle, freely rotates between the top and bottom plates. Insulation is provided between the top and the middle as well as between the middle and the bottom plates. The top circular plate is split into four quarters (marked as TP1, TP2, TP3, and TP4), as shown in Fig. 1. The bottom plate is identical to the top one and is also made of four-quarter circular plates (marked as BP1, BP2, BP3, and BP4). Each of the quarter circular plates is insulated and, hence, does not have a galvanic connection with the other parts of the sensor. The top four-quarter circle plates are positioned such that each top quarter circle plate is perfectly aligned with the corresponding quarter circle plate at the bottom. The middle plate is composed of two parts, namely, a half circular plate MP...
mounted on a spindle that can freely be rotated and an annular ring AP. The spindle is mechanically linked to the element whose angular position $\theta$ is to be measured. The radius of the middle half circular plate $r_{mp}$ is chosen to be less than that of the top and bottom plates, and the annular guard ring AP has an inner radius $> r_{mp}$ and an outer radius that is the same as the top or bottom plate and, hence, encircles the half circular plate. The annular ring AP (firmly fixed and insulated from the other parts of the sensor), the middle plate MP, and the four bottom quarter circle plates are all kept at the same potential. Although the potential at which these plates are to be kept can be any arbitrary value, it is advantageous to keep the potential of these plates equal to the ground potential of the circuit to which the sensor needs to be connected. Keeping these (four bottom plus one middle) plates at the ground potential eliminates the effects due to stray capacitances and fringing on the performance of the transducer.

This structure then results in four variable capacitances $C_1$, $C_2$, $C_3$, and $C_4$ between lead pairs TP1–BP1, TP2–BP2, TP3–BP3, and TP4–BP4, respectively. The maximum value $C_M$ that any of these capacitances can attain occurs when the middle plate MP is in a position such that it is completely outside the corresponding pair of plates of that capacitance. Here, $C_M \approx [\varepsilon_0 \pi r_{mp}^2 / 4(\Gamma_{MP} + (2\Gamma_1/\varepsilon_1))]$, where $\varepsilon_0$ is the permittivity of free space, $\varepsilon_1$ is the dielectric constant of the insulator employed, and $\Gamma_{MP}$ and $\Gamma_1$ are the thicknesses of the middle plate and the insulator, respectively. Likewise, the minimum value $C_{\text{min}}(\approx 0)$ for any of the capacitances $C_1$, $C_2$, $C_3$, and $C_4$ occurs when the middle plate MP covers the complete area between the pair of plates of a particular capacitance. For example, Fig. 2(a) shows the middle plate MP at the initial ($0^\circ$) position. For this condition, $C_3 = C_4 = C_M$, and $C_1 = C_2 = C_{\text{min}}$. Fig. 2(b) shows the middle plate moved by an angle $\theta$, ($\theta < 90^\circ$). In this case, the value of $C_1$ will increase, whereas that of $C_3$ will decrease in equal proportions ($= C_M(\theta/90)$), and the values of $C_2$ and $C_4$ remain unaltered. As the middle plate goes through a rotation of $360^\circ$, the values of capacitances $C_1$, $C_2$, $C_3$, and $C_4$ vary, as shown in Fig. 3. It is easily seen that the values of the capacitance pair $C_1$ and $C_3$ vary in a push–pull (differential) manner for $0^\circ \leq \theta \leq 90^\circ$ and $180^\circ \leq \theta \leq 270^\circ$ and remain constant during $90^\circ < \theta < 180^\circ$ and $270^\circ < \theta < 360^\circ$. $C_2$ and $C_4$ also vary in a push–pull manner but in the ranges $90^\circ < \theta < 180^\circ$ and $270^\circ < \theta < 360^\circ$ and remain constant in the ranges $0^\circ \leq \theta \leq 90^\circ$ and $180^\circ \leq \theta \leq 270^\circ$, as shown in Fig. 3.

These can mathematically be expressed as $C_1 = C_M(\theta/90)$, $C_2 = 0$, $C_3 = C_M(1 - \theta/90)$, and $C_4 = C_M$ for $0^\circ \leq \theta \leq 90^\circ$; $C_1 = C_M$, $C_2 = C_M[(\theta - 90)/90]$, $C_3 = 0$, and $C_4 = C_M[1 - (\theta - 90)/90]$ for $90^\circ \leq \theta \leq 180^\circ$; $C_1 = C_M[1 - (\theta - 180)/90]$, $C_2 = C_M$, $C_3 = C_M[(\theta - 180)/90]$, and $C_4 = 0$ for $180^\circ \leq \theta \leq 270^\circ$; and $C_1 = 0$, $C_2 = C_M[1 - (\theta - 270)/90]$, $C_3 = C_M$, and $C_4 = [(\theta - 270)/90]$ for $270^\circ \leq \theta \leq 360^\circ$.

Now, we define a function $f(C_1, C_2, C_3, C_4)$ as

$$f(C_1, C_2, C_3, C_4) = \frac{(C_1 - C_3 + C_2 - C_4)}{(C_1 + C_3 + C_2 + C_4 - 2)} \times \text{sgn} \left(\frac{C_1 - C_3 - C_2 - C_4}{C_1 + C_3 - C_2 - C_4}\right).$$

Here, $\text{sgn}(x)$ is $-1$ for $x < 0$ and equal to $+1$ otherwise. It nicely turns out that

$$f(C_1, C_2, C_3, C_4) = \frac{\theta(8/360) - 4}{\text{if } \theta \text{ is measured in degrees or}}$$

$$= \frac{\theta(4/\pi) - 4}{\text{if } \theta \text{ is expressed in radians}}.$$

It is easily seen that, if we design a signal-conditioning circuitry that evaluates (1), the output of such a circuitry will be a linear function of $\theta$, where the angle is measured by the sensor, as shown by the bottommost graph in Fig. 3.

### III. SIGNAL-CONDITIONING CIRCUITRY

The schematic diagram of a novel signal-conditioning circuitry that evaluates (1) is shown in Fig. 4. The differential capacitances $C_1$ and $C_3$, op-amp OA1, comparator OC1, four single-pole double-throw (SPDT) switches S1, S2, S3, and S4, and resistor $R_1$ constitute the relaxation oscillator (OSC-$\alpha$) [19]. Similarly, $C_2$ and $C_4$, op-amp OA2, comparator OC2, SPDT switches S5, S6, S7, and S8, and resistor $R_2$ form the second relaxation oscillator (OSC-$\beta$). In both oscillators, $+V_T$ and $-V_N$ are the dc reference voltages. First, the operation of OSC-$\alpha$ is explained here. Switches S1, S2, S3, and S4 are all controlled by the output of the comparator OC1 and, hence, simultaneously change state. Initially, let all the switches (S1, S2, S3, and S4) be at position 1. Then, capacitor $C_1$ is included in the feedback path of op-amp OA1, and $C_3$ simply becomes a load on the output of OA1. Hence, at any given instant, the voltage across $C_1$ would be equal to that of $C_5$. Op-amp OA1

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Fig. 1. Sensor part of the proposed LVDCT.
with capacitor $C_1$ in the feedback path and resistor $R_1$ at its input becomes an integrator. Since $S_1$ is in position 1, the voltage connected to this integrator is $-V_N$, and hence, its output voltage $\nu_{\text{out}}$, shown in Fig. 5, increases in the positive direction with a slope of $(V_S/R_1C_1)$. This situation continues until $\nu_{\text{out}}$ reaches $+V_P$. As soon as $\nu_{\text{out}}$ reaches $+V_P$, say after $T_H$, comparator OC1 changes state, forcing switches $S_1, S_2, S_3$, and $S_4$ to position 2. In this condition, capacitance $C_3$ comes into the feedback path of OA1, and $C_1$ is connected to the ground. Since $S_1$ is now in position 2, $+V_P$ is connected to the input of the integrator, and its output voltage $\nu_{\text{out}}$ gradually decreases with a slope of $(-V_P/R_1C_3)$ until it reaches $-V_N$. As soon as $\nu_{\text{out}}$ reaches $-V_N$, say, after a time period $T_L$, comparator OC1 reverts to its earlier state and sets all switches ($S_1, S_2, S_3$, and $S_4$) to position 1. Now, the circuit goes to the initial stage, leading to sustained oscillations at a frequency $f_{\text{osc}}[f_{\text{osc}} = 1/T, T = T_H + T_L]$. Fig. 5 shows the output of switch $S_4$ along with $\nu_{\text{out}}$. It is easily seen that

$$T_H = 2R_1C_1, \quad T_L = 2R_1C_3.$$ (2)

The output of $S_4$ is fed as input to a low-pass filter $\text{LPF}_\alpha$. Now, if we choose $V_P = V_N = V_R$ and the cutoff frequency $f_{\text{LPF}}$ of the low-pass filter $\text{LPF}_\alpha$ to be very low compared with the frequency of oscillation $f_{\text{osc}}$, then the output of the filter $\nu_{\text{osc}}$ is

$$\nu_{\text{osc}} = \frac{1}{T} \left[ \int_{0}^{T_H} V_H dt - \int_{T_H}^{T} V_H dt \right] = V_R \left( \frac{T_H - T_L}{T_H + T_L} \right).$$ (3)

Substituting for $T_H$ and $T_L$ in terms of $C_1$ and $C_3$ in (3) gives

$$\nu_{\text{osc}} = V_R \left( \frac{C_1 - C_3}{C_1 + C_3} \right).$$ (4)

Similarly, switches $S_5, S_6, S_7$, and $S_8$, along with op-amp OA2, comparator OC2, and resistance $R_2$, combined with sensor capacitances $C_2$ and $C_4$, form the second relaxation oscillator OSC-$\beta$ (with a frequency of oscillation $f_{\text{osc}}$), whose operation is identical to that of OSC-$\alpha$. Therefore, the expression for output voltage $\nu_{\text{osc}}$ from the low-pass filter $\text{LPF}_\beta$ (with a cutoff frequency $f_{\text{LPF}} = f_{\text{osc}} = f_{\text{oc}}$) is

$$\nu_{\text{osc}} = V_R \left( \frac{C_2 - C_4}{C_2 + C_4} \right).$$ (5)

The voltage signals $\nu_{\text{osc}}, \nu_{\text{osc}}$, and $-V_N$ are fed to a three-input inverting summer realized with four resistors and op-amp OA3. The gains for $\nu_{\text{osc}}$ and $\nu_{\text{osc}}$ are kept at $-1$ each, and the gain for $-V_N$ is chosen as $-2$. The output of OA3 is again inverted with op-amp OA4 that is configured as an inverting unity-gain amplifier. The output voltage $\nu_{\text{out}}$ from this inverter is

$$\nu_{\text{out}} = \nu_{\text{osc}} + \nu_{\text{osc}} - 2V_N = V_R \left( \frac{C_1 - C_3}{C_1 + C_3} + \frac{C_2 - C_4}{C_2 + C_4} - 2 \right).$$

The voltage signals $\nu_{\text{osc}}$ and $\nu_{\text{osc}}$ are also given to a unity-gain differential amplifier, formed by four equal resistors of value $R_3$ and op-amp OA5, whose output $\nu_{\text{osc}} = (\nu_{\text{osc}} - \nu_{\text{osc}})$. Hence, $\nu_{\text{osc}} = \nu_{\text{osc}} - \nu_{\text{osc}} = V_R((C_1 - C_3)/(C_1 + C_3) - (C_2 - C_4)/(C_2 + C_4))$. $\nu_{\text{osc}}$ is positive during $0^\circ \leq \theta \leq 180^\circ$ and negative in the range $180^\circ < \theta < 360^\circ$. Therefore, the state of comparator OC3 is high for the period $0^\circ \leq \theta \leq 180^\circ$, whereas it is low during $180^\circ \leq \theta \leq 360^\circ$. If $\theta$ lies in the range $0^\circ \leq \theta \leq 180^\circ$, then the output of OC3 is high, and switch $S_9$ gets set to position 1. Hence, the final output voltage $\nu_{\text{out}}$ of the signal-conditioning circuit becomes $\nu_{\text{out}}$. On the other hand, if $\theta$
Hence, \( \nu_s \) setting switch 180 (Fig. 4. Relaxation-oscillator-based signal-conditioning circuit for the LVDCT.

A. Effects Due to Tolerances in Dimensions and Alignments

Finite deviations would be introduced in the dimensions of the parts of the sensor during fabrication and in alignment during assembly. It is easily seen that any irregularity or deviation from the expected circular shape of the outer edges of the bottom, the annular ring, and the top plates does not affect the performance of the transducer. On the other hand, any deviation or irregularity in the outer edge of the middle plate directly affects the transducer output. If the radius of the middle plate varies by \( \pm \Delta r_{mp} \) with \( \theta \), then the variations in \( C_1, C_2, C_3, \) and \( C_4 \) will become a function of \( \Delta r_{mp} \). For a change in angle \( \Delta \theta \) radian, it can be deduced that the relative dimensional tolerance \( \pm (\Delta r_{mp}/r_{mp}) \) in \( r_{mp} \) will introduce a relative error of \( 2(\Delta r_{mp}/r_{mp}) \) in the corresponding change in area and, hence, a relative full-scale error of \( \pm (\Delta \theta/\pi)(\Delta r_{mp}/r_{mp}) \) in the output. Due to misalignment, both \( \nu_{\alpha} \) and \( \nu_{\beta} \) change by an amount \( V_R(2\Delta \theta_{b}/\pi) \), leading to a full-scale relative error of \( (\Delta \theta_{b}/\pi) \) in the output. If any one of the top plates is misaligned by an amount \( \Delta \theta_{b} \) rad with its pair at the bottom, the value of capacitance \( C_M \) will reduce by \( \Delta C_M = C_M(2\Delta \theta_{b}/\pi) \), resulting in a relative full-scale error of \( (\Delta \theta_{b}/\pi) \) in the output. A small deviation \( \Delta d \) in the distance between the top and bottom plates affects the final output. If the middle plate MP rotates by an angle \( \Delta \theta \) rad, and if the distance between the top and bottom plates in this area deviates by \( \pm \Delta d \), a worst-case error of \( (\Delta \theta/\pi)(\Delta d/d) \) is introduced in the output. If the top and bottom plates are not parallel, it is seen that the output becomes a nonlinear function of \( \theta \). Due to the inclination, the distance between the plates is \( d \) when \( \theta = 0 \), whereas it is \( (d + D)/2 \) when \( \theta = 90 \), where \( D \) is the total deviation of the plates from the expected parallel position, as shown in Fig. 6.

\[
\nu_0 = \begin{align*}
&V_R \left(\frac{C_1 - C_3}{C_1 + C_3} + \frac{C_2 - C_4}{C_2 + C_4} - 2\right) \\
&\times \text{sgn}\left\{V_R \left(\frac{C_1 - C_3}{C_1 + C_3} - \frac{C_2 - C_4}{C_2 + C_4}\right)\right\} \\
&= V_R[\theta(8/360) - 4], \quad \text{if } \theta \text{ is measured in degrees or} \\
&= V_R[\theta(4/\pi) - 4], \quad \text{if } \theta \text{ is expressed in radians.}
\end{align*}
\]

Hence, \( \nu_0 \) is linearly related to \( \theta \). In the foregone description, ideal parts and circuit components were assumed. However, in a practical transducer, the characteristics of parts and circuit components will deviate from the expected ideal ones. The effect of such nonidealities on the performance of the transducer is analyzed next.
output then has an additional component \( (2D/d) [(\theta/90) - 2(\theta/90)^2 - (3D/2d)(\theta/90)^2] V_R \). In fact, this is the major source of error in the prototype, and eight spacer screws (one every 45°) are employed to position the plates to be parallel to each other.

### B. Effects Due to Nonidealities Within the Signal-Conditioning Circuit

1) **Relaxation Oscillators:** Stray capacitances between each plate and ground and between plates introduce errors in the output. A part of OSC-\( \beta \), showing the sensor capacitances \( C_2 \) and \( C_4 \) along with all possible stray capacitances, is shown in Fig. 7. Here, \( C_{G21}, C_{G22}, C_{G41}, \) and \( C_{G42} \) are the stray capacitances between the plates and ground of \( C_2 \) and \( C_4 \), respectively. \( C_{P2} \) and \( C_{P4} \) are the stray and cable capacitances, respectively, that come in parallel with the sensor capacitances. \( C_{G22} \) and \( C_{G42} \) are driven by the op-amp and, hence, do not affect the operation of the circuit. The terminals of \( C_{G21} \) and \( C_{G41} \) are either at the ground or at virtual ground, depending on the position of the switches \( S_6 \) and \( S_7 \). Thus, \( C_{G21} \) and \( C_{G41} \) are always under short-circuit conditions and, hence, do not hinder the operation of the circuit. Since the design and construction of the sensor ensure symmetry, \( C_{P2} = C_{P4} = C_P \). \( C_P \) alters the voltage \( \nu_{o\beta} \) as \( \nu_{o\beta}' = \nu_{o\beta} [1 - (C_P/C_M)] \), thus introducing a gain error.

The errors introduced by mismatch in dc reference voltages, finite and unequal on-resistances of the SPDT switches, and delay in switching are comparatively very small and negligible [19]. All terminals of switches \( S_2, S_3, S_6, \) and \( S_7 \) are either at the virtual ground or ground; thus, the leakage currents of these switches are zero. Since \( S_1 \) and \( S_4 \) operate on voltage sources on one side and that their outputs are connected to the noninverting input terminals of op-amps, the leakage currents in them also do not adversely affect the operation of the circuit. However, the leakage currents of \( S_1 \) and \( S_4 \) alter \( \nu_{o\alpha} \) and \( \nu_{o\beta} \), respectively, and, hence, introduce an error in the output. By choosing the charging currents \( V_R/R_1 \) and \( V_R/R_2 \) to be several orders higher than the leakage currents, the error due to the leakage currents of \( S_1 \) and \( S_4 \) can be made negligible.

2) **Errors Introduced by Various Functional Blocks:** The mismatch in resistances and offset voltages of OA3 and OA4 will introduce an error in the final output. Similarly, if we look at the unity-gain differential amplifier, the mismatch in the resistances associated with OA5, as well as the offset voltage of OA5, will introduce an error in its output. All these errors will be in the form of an offset voltage or gain error or both and can easily be compensated. The worst case error in the differential amplifier and the offset of OC3 in conjunction with the hysteresis of comparator OC3 select the output as either \( +\nu_{o1} \) or \( -\nu_{o1} \) or vice versa slightly above or below the actual zero output of the difference amplifier by an amount \( \nu_{o\text{sign}} \), as shown in Fig. 8. Instead of the polarity of the output voltage getting changed at exactly 180°, the polarity of the output gets altered at \((180 \pm \Delta \theta)^\circ \), depending on the polarity of \( \nu_{o\text{sign}} \). Like the error due to misalignment in the parallelism of the top and bottom plates, this error is also significant but is only present in a small range around 180°.

3) **Errors Due to Tolerances of Circuit Components:** Tolerances in \( R_1 \) and \( R_2 \) simply alter the frequencies of oscillation \( f_{o\alpha} \) and \( f_{o\beta} \). As long as \( f_{o\alpha} \) and \( f_{o\beta} \) are high compared with the cutoff frequencies of the low-pass filters LPF_\( \alpha \) and LPF_\( \beta \), the effect due to the tolerances in \( R_1 \) and \( R_2 \) will be negligible. The tolerances in the capacitances would only arise due to the tolerances in their dimensions and hence are already dealt with. The tolerances of resistances with value \( R_3 \) will affect the three gains obtainable with the inverting summer. The output of OA3, including the tolerances of the gain-determining resistances, is

\[
-\nu_{o1} = -\frac{R_3(1 \pm \sigma)}{R_3(1 \pm \sigma)} \nu_{o\alpha} - \frac{R_3(1 \pm \sigma)}{R_3(1 \pm \sigma)} \nu_{o\beta} + \frac{R_3(1 \pm \sigma)}{0.5R_3(1 \pm \sigma)} V_R
\]

where \( \sigma \) is the tolerance of the resistors of value \( R_3 \). The output of the summer is then inverted using a unity-gain inverter.
realized with op-amp OA4 and two resistances of equal value $R_3$. Thus, the output voltage of the inverter, with the effects owing to the tolerances in circuit components, can be expressed as

$$
\nu_{01} = \left( \frac{R_3(1 + \sigma)}{R_3(1 + \sigma)} \nu_{0a} + \frac{R_3(1 + \sigma)}{R_3(1 + \sigma)} \nu_{0b} - \frac{R_3(1 + \sigma)}{0.5R_3(1 + \sigma) V_R} \right) \frac{R_3(1 + \sigma)}{R_3(1 + \sigma)}.
$$

If $\sigma$ is small, then the worst-case scenario can be obtained as

$$
\nu_0 = V_R \left( \frac{C_1 - C_3}{C_1 + C_3}(1 + 2\sigma) + \frac{C_2 - C_4}{C_2 + C_4} \times (1 + 2\sigma) - 2(1 + 3\sigma) \right)(1 + 2\sigma).
$$

It is easily seen that the tolerances of resistors generate an offset and introduce gain errors. Hence, the resistors of value $R_3$ must be the precision resistors of tolerance 0.1% or better. For the prototype, the metal-film-type resistors that matched to have equal values within 0.05% were used. The tolerances of gain-determining resistors, if any, used in the low-pass filters contribute additional errors. To avoid the error due to the LPF gains in the prototype, the LPFs are chosen to be Sallen–Key unity-feedback type.

4) Dynamic Response of the Transducer: The cutoff frequency $f_c$ chosen for the LPFs introduces a dominant pole in the transfer function of the overall transducer. Hence, the dynamic response of the transducer is primarily dictated by $f_c$. $f_c$ in turn depends on the oscillator frequencies. Hence, to have a large bandwidth and a good dynamic range, each of the relaxation oscillators must be designed to have as high a frequency of oscillation as practically feasible.

5) Effect Due to Temperature, Moisture, and Dust: The sensor part of the transducer is made of metallic plates. Any change in the operating temperature equally affects all the plates as the thermal conductivity of the plates is quite high. Thus, any variations in the operating temperature change the value of $C_M$ of the sensor to $C_M'$. Since the output, as given by (1), is independent of $C_M$, the transducer performance is not affected due to a change in the operating temperature. Similarly, the variations in moisture and dust levels will not affect the operation of the transducer if these variations are uniformly spread throughout the sensor.

6) Effect Due Electromagnetic Interference: Since the top plates of the sensor capacitances are tied to the output of an op-amp (OA1 or OA2 as the case may be) possessing very low output impedance, the effect of electromagnetic interference on these plates will be negligible. However, the bottom plates are either connected to the ground or virtual ground. Hence, whenever a particular bottom plate is connected to the virtual ground, the effect due to electromagnetic interference will be appreciable. This effect can be made negligible if all the wires (nine in total) connecting the sensor to the signal-conditioning circuitry are provided with appropriate shielding, with the shield being connected to the ground potential.

IV. EXPERIMENTAL RESULTS

In order to demonstrate the practicality of the proposed LVDCT, a prototype transducer based on the proposed technique was built and tested. The top, middle, and bottom plates of the sensor were fabricated with a flat aluminum sheet of 700 $\mu$m thick. The outer and inner radii of the top and bottom layers are 125 and 10 mm, respectively. The middle half circular plate of 114-mm radius is fastened to a 3-mm-radius spindle. The annular ring is 10 mm wide with an outer radius of 125 mm. The top and bottom plates are then fastened to thick insulating sheets. A circular sheet of 125-mm radius, which is made of a Mylar material of 100-$\mu$m thickness, having a $\varepsilon_r$ of 3.6, is placed between the top and middle plates. Another identical sheet is inserted between the middle and bottom plates. For ease of fabrication and testing, the prototype is intentionally made to have large dimensions. However, the transducer can be made to suit a given dimensional requirement. For smaller size transducers, multiple units can be ganged, as in a variable capacitor used in radio receivers.

The signal-conditioning circuit is implemented using commercially available ICs and is tested. Precision reference voltages $+V_P$ and $-V_N$ are derived from an LM 385-2.5 reference diode and an inverter made up of op-amp OP07. Three CD4053 ICs are used to realize switches $S_1$–$S_5$. All the op-amps (OA1–OA5) are type OP07. Comparators are realized with LF357. Two metal-film resistors, each having a value of 4.7 M$\Omega$, serve as $R_1$ and $R_2$, whereas for resistors of $R_3$ value, 100-k$\Omega$ resistors are used. To bring down the frequency of oscillation to be compatible with the gain-bandwidth and slew-rate properties of the op-amps, each of the sensor capacitors $C_1$, $C_2$, $C_3$, and $C_4$ is shunted with capacitors of 180-pF value. Two second-order Sallen–Key active low-pass filters with a cutoff frequency of 1 Hz serve as low-pass filters $LPF_\alpha$ and $LPF_\beta$. The prototype was tested for the entire range (0°–360°), and the output from the signal-conditioning circuit was measured using an HP34401A 6-1/2-digit digital multimeter. The angle is measured using a precision protractor having an attached Vernier giving a resolution of 0.05°. The waveforms at cardinal points of the circuit were observed on an Agilent 54624A oscilloscope. The output voltage $\nu_\alpha$, which is recorded for every 0.5°, and the resulting errors computed therefrom are shown in Fig. 9. The dynamic range, as shown in Fig. 9, extends from 0° to 360°. The worst-case error is found to be $< 0.1\%$ for the full 360° range and is $< 0.02\%$ for the restricted range of 90°. The hysteresis effect near the 180° mark was observed to be 0.07%. It should be noted here that, except at the 180° mark, the hysteresis effect was not measurable in the entire range of operation of the transducer.

V. CONCLUSION

A novel LVDCT for the measurement of planar angles from 0° to 360° has been developed. The sensor part of the transducer is made of easy-to-fabricate shapes. Signal-conditioning electronics, although designed to evaluate a complex equation, are based on simple oscillator circuits. The output sensitivity of the proposed transducer is only dictated by a couple of dc reference
voltage, and hence, high accuracy is easily obtained by the use of precision dc reference voltages. Since the intermediate signals in the proposed transducer (\(V_{\text{in}}\) and \(V_{\text{out}}\)) are two-level discrete ones, they can easily be interfaced to a digital system. The effects of important mechanical and electrical parameters on the performance of the transducer are analyzed and found to be minimal. The developed and tested prototype establishes that the transducer provides a linear output for the entire 360° range of an input angle. The worst-case error spotted during a test on the prototype was less than 0.1%. Since the spindle is not constrained and is free to rotate over several turns, the transducer can be extended to measure angles of more than 360° (several turns) by simply counting the number of complete rotations made by the spindle.

**Fig. 9.** Actual output and error obtained from the prototype LVDCT.

**REFERENCES**


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