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Modelling of an Efficient Conversion Mechanism for Tunnel Magnetoresistive Sensor

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ABSTRACT:

In this paper, modelling a conversion mechanism for Tunnel Magneto-resistance (TMR) based angle sensor with $0-360°$ range and monitoring its angle is proposed. In general, the output and sensing angle most of the existing magneto-resistive angle sensors have a sine/cosine relationship. But a linear characteristic is highly desired. This model uses technique to process the inherent non-linear outputs from MR angle sensor. The final output of the sensor varies linearly with-respect-to input angle over 360° range. The Logic Unit employed in the conversion mechanism gives digital output and can be monitored. The functionality and performance of proposed circuit is validated using simulation.

Keywords:-MR sensor, Giant Magneto-resistive sensor, Tunnel Magneto-resistive sensor, Logic unit.

I. INTRODUCTION

Sensors for automotive applications operate in harsh environments. They must be sensitive and accurate, but must be immune to vibration and contamination, and must operate under a wide range of temperatures. MR sensors meet these environmental criteria. Their non-contact principle of operation makes them superior to contact devices in terms of accuracy and durability.

The rate of change in the resistance of an element under external magnetic field called the MR ratio. For Elements like AMR and GMR elements the conventional MR ratios are about 3% and 12% respectively. Whereas, the MR ratio of a TMR element is 100%.The magnetic structure of a TMR element is same as that of a GMR element. However, in a TMR element, the current flows perpendicular to the film surface, while it flows horizontally to the film surface in a GMR element. A TMR element is a thin-film element with a structure in which a barrier layer made of a thin insulator of 1 to 2 nm is sandwiched between two ferromagnetic layers (free layer/pinlayer), made using advanced thin-film processing technology. This solution utilizes an array of Magneto-resistive (MR) sensors, a magnet and signal conditioning electronics. The sensors are used to determine the position of a magnet that is attached to a moving object or shaft of a machine. In addition to mechanical benefits, this solution offers a high accuracy, low power solution.

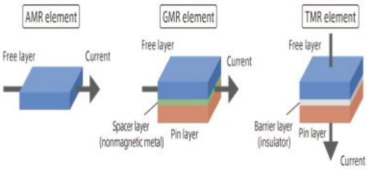

Fig.1. layouts of different types of magnetoresistive sensors.

A simple analog circuit for GMR sensors which works well for 160° range has been explained in [1]. An efficient analog transducer with full circle range has been presented in [2]. A novel approach resist to parasitic capacitances of TMR elements has been illustrated in [3]. Nevertheless, this approach needs a

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complex circuit, comprising many matched resistors, precision-opamps and high performance electronic switches to ensure good performance. In addition, the scheme requires a mechanical angular offset (of -45°) to be incorporated between the magnet and MR sensor. It also needs an analog to-digital converter to obtain a digital angle indication. This approach will be beneficial in applications for linear position or displacement, valve positioning, automotive steering, proximity detection, shaft travel, brake and throttle position systems. This will be used in industries including Automotive, Aviation and Industrial Process Control.

II. DESIGNING OF MAGNETO RESISTIVE SENSOR IN SIMULATION

The sensor element free layers will align with the external magnetic field. As the applied field changes direction, the angle between the free layer and the pinned layer changes, changing the resistance of TMR elements, which changes the device output voltages. Variations in the air gap between the magnet and the sensor element will cause slight changes in the output depending on the size and strength of the external magnet. Many magneto resistive sensors are available for sensing position and angle. AAT001-10E is one of the TMR IC available [4]. From this the output of TMR is considered and simulation is processsed in simulation.

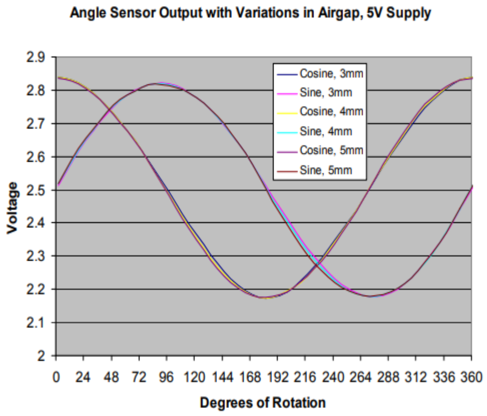

Fig.2. Sine/Cosine Output of AAT001-10E (TMR sensor)

These outputs were created with same magnitude, same offset and with 90° phase difference in simulink.

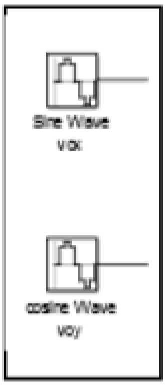

Fig.3. Modelled TMR sensor in simulation

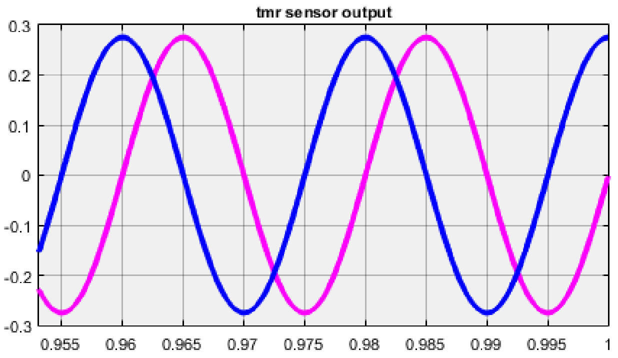

Fig.4.Sine and cosine outputs from simulation fabricated TMR sensor with offset clearance (a). V_{ox} and V_{oy}

III. SINE/COSINE CONVERSION TECHNIQUES

Magnetic sensors for position and angle sensing in dynamic control systems generally provide sine and cosine output signals for conversion. The 90° phase shift between sine and cosine allows determination of the position or angle within the 360° input cycle, as well as the direction of rotation or movement. For resolutions in the micrometer, precise interpolation of the sine and cosine signals is necessary. This sine/cosine-to-digital conversion (SDC) can be performed in several ways, either in practical or simulation. For high-precision results, the quality of the signal conditioning and of the S/D conversion is of major importance. Several SDC (interpolation) methods are analyzed in the following. The non-linear function usually used for Sine/Cosine-to-Digital conversion (SDC) is the arc tangent, which calculates the output angle directly from the conditioned sine and cosine output signals of a sensor. Many different A/D conversion methods can be used to implement the arc tangent function, depending on the application requirements:

- Flash conversion, which uses many individual comparators to perform the conversion almost instantly.
- Vector-tracking conversion, which uses a single comparator to increment or decrement a digital counter to track the input angle.
- SAR (Successive Approximation Register) conversion, which is similar to vector-tracking conversion, but which samples and holds the input signal until the counter has settled.
- DSP (Digital Signal Processing) conversion, which digitizes the sine and cosine signals individually and calculates the arc tangent function in a Digital Signal Processor using a CORDIC or other numerical algorithm.

Modern interpolators typically employ either the vector-tracking or DSP conversion approaches.

IV. METHODOLOGY

The circuit operates on the outputs of MR sensor (say,V_{ox} and V_{oy}) of an MR sensor unit and gives a linear digital output (D_{OUT}) of the angle being measured. They follow (1), where θ is the input-angle and v_{so} stands for the maximum value of the sensor signals.

$$V_{ox} = V_{s0} sin\theta \text{ and } V_{oy} = V_{s0} cos\theta \qquad (1)$$

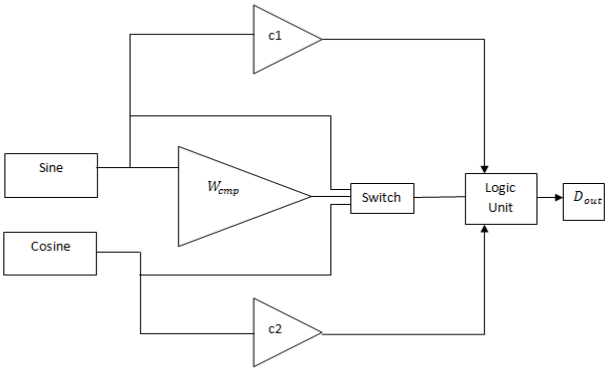

Fig.5. Block Diagram of proposed model for MR sensor.

The signals V_{ox} and V_{oy} are fed to the switch SW and is controlled by a control signal DC (output from comparator).

With a reference sine wave $v_r = V_m \sin \omega t$, the duty ratio of switch (SW) operation is obtained. The parameters V_m and ω represent, respectively, the amplitude and angular frequency of sine wave v_r .In this work, V_m is selected asV_{s0}.

The output of comparator (say, D_θ) is in pulse form and it can be mathematically expressed as-

$$D_\theta = \begin{cases} 1\, when (v_r - v_s) > 0 \\ 0\, when\, (v_r - v_s) < 0 \end{cases} \qquad (2)$$

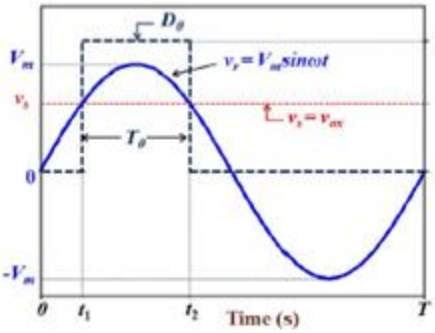

Fig.6. Voltage waveforms when $V_s = V_{ox}$ is fed to the comparator. The pulse width of output D_θ of comparator is proportional to the angle.

The waveform of the signals v_r, v_{ox} and D_θ for a typical angle $\theta \epsilon (0°, 180°)$ is shown in Fig.5. The signal turns logic HIGH at a time instant t_1 when v_r becomes greater than *vs*. The expression for *t*1 can be obtained as in (3).

$$t_1 = \frac{1}{\omega} \sin^{-1}\left(\frac{V_s}{V_m}\right) = \frac{T}{4} - \frac{\theta}{\omega} \qquad (3)$$

$$t_2 = \frac{T}{2} - \frac{1}{\omega} \sin^{-1}\left(\frac{V_s}{V_m}\right) = \frac{\theta}{\omega} - \frac{T}{4} \qquad (4)$$

$$T_\theta = t_2 - t_1 = T\left(\frac{\theta}{180}\right)$$

$$D_{AVG} = \frac{\theta}{180}\, for\, \theta \epsilon (0°, 180°) \qquad (5)$$

The equation (5) shows that $D_{AVG}(v_s = v_{ox})$ □is proportional to θ for $\theta \in (0°, 180°)$.The characteristic of $D_{AVG}(v_s = v_{ox})$□□is shown in Fig. . In a similar fashion, it can be shown that $D_{AVG}(v_s = v_{ox})$ □ decreases from 1 to 0 as θ increases from 180º to 360º.

These high sensitivity regions are selected using the signal $D_c$and the switch SW. The expression for D_c is given in (6).

$$D_c = \begin{cases} 0 \; when \; (-0.707 \times v_{so}) < v_{ox} < (0.707 \times v_{so}) \\ 1 \; elsewhere \end{cases} \quad (6)$$

When $D_c = 0$, V_{ox} will have higher sensitivity when compared to V_{oy}. Hence, V_{ox} is fed to the circuit by setting SW to position-0. Likewise, the switch SW is put in position-1 when $D_c = 1$. This ensures that high-sensitivity regions of V_{ox} and V_{oy} will be processed by the front-end. This procedure of selection of MR sensor signals is summarized in the below equation.

$$v_s = \begin{cases} v_{ox} \; for \;\; D_c = 0 \\ v_{oy} \;\; for \; D_c = 0 \end{cases} \qquad (7)$$

To achieve full-circle linearity, the piecewise linear signal D_{AVG} is further processed using a new function D_{OUT} given in (7).

$$D_{OUT} = \begin{cases} \left[1 + (D_{AVG} - 1) \times sgn(v_{oy})\right] \times 180 \\ for \; D_c = 0 \\ \left[0.5 - D_{AVG} \times sgn(v_{oy}) + \left(1 - sgn(v_{oy})\right) \times u(v_{ox})\right] \times 180 \\ for \; D_c = 1 \end{cases} \qquad (8)$$

$$sgn(v_{oy}) = 2 \times u(v_{oy}) - 1 \; and$$

$$sgn(v_{ox}) = 2 \times u(v_{ox}) - 1 \qquad (9)$$

Here, '*u*' stands for unit-step function. A linear MR angle transducer with full-circle range is expected. To achieve full-circle linearity, the piecewise linear signal D_{AVG} is further processed using a new function D_{OUT} given in (8).Thus, we can conclude that the D_{OUT} in (8) assists to realize a linear MR angle transducer over 360º range. The (linearizing) function D_{OUT} is implemented using the Logic Unit and realised by programming code.

This model is suitable for only the sensor with single Wheatstone bridge TMR sensor but not with double Wheatstone bridge TMR sensor.

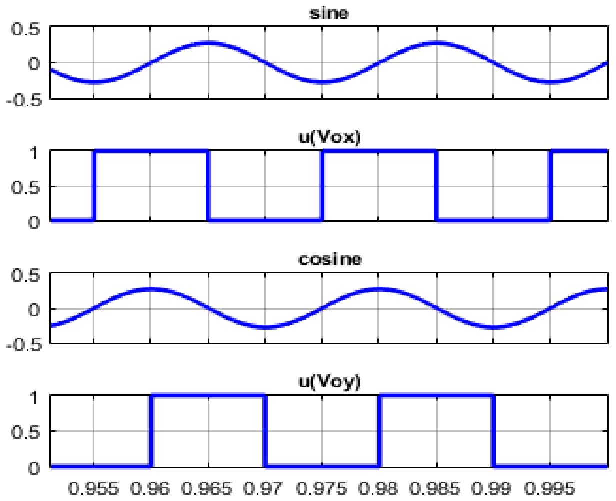

Fig.7. outputs of comparators as u(V_{ox}) and u(V_{oy})of sine and cosine inputs.

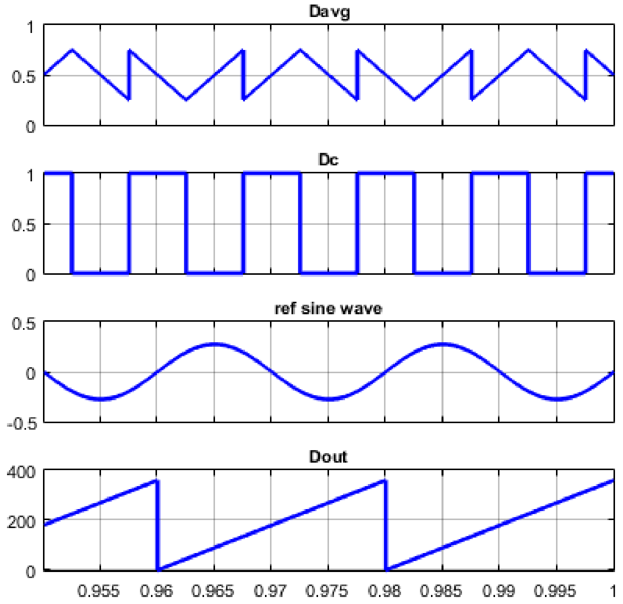

Fig.8.Various signals as a function of reference angle.

The average value of D_θ varies in a piecewise linear fashion in D_{AVG} plot. The final output D_{OUT}, however, varies linearly with-respect-to θ in radians as shown in waveform.

V. CONCLUIONS

A circuit for rotational angle measurement and position measurement based on MR angle sensors has been presented. The proposed circuit provides linear digital output for 360º range. The proposed methodology has been validated using simulation. The interfacing of proposed circuit to the angle sensing unit yielded a linear digital output over 360º range. The overall scheme is useful for many applications, including steering wheel positioning, throttle-valve positioning, robotics, etc.

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