Polarimetric Microwave Sensor for Angular Speed Measurement

Ademola Mustapha 1, Mohammed Saif ur Rahman 1, and Mohamed A. Abou-Khousa 1

1Affiliation not available

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Polarimetric Microwave Sensor for Angular Speed Measurement

Ademola A. Mustapha, Member, IEEE, Mohammed Saif ur Rahman, and Mohamed A. Abou-Khousa, Senior Member, IEEE

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Index Terms—Angular displacement, angular speed, circular aperture, dual-polarization, microwave sensing, polarimetric, pulse, rotation, sensor, waveguide

I. Introduction

Monitoring the angular speed of a rotating object is critical in many industries. Typical application areas include ignition timing of spark-ignition (SI) engines [1], roller bearing fault detection [2], diesel engine fault detection [3], high-speed spindle error measurement in CNC machines [4], and shaft crack detection in electrical machines [5]. Various methods have been adopted for achieving this purpose. These include the use of optical encoders [6], laser encoders [7], capacitive sensors [8], and microwave-based sensors [9]-[12]. Among these commonly used methods, microwave-based sensing techniques are preferred due to their compact size, non-contact feature, and high sensitivity sensing approach. The microwave sensors for angular displacement and velocity measurement typically consist of a stator and a rotor. While the rotor is attached to the rotating object, the stator is fixed and positioned in a place such that there exists electromagnetic interaction between itself and the rotor. As the rotor rotates, the change in the electromagnetic interaction is used in quantifying the angular displacement and velocity of the rotating object. The measured parameters could include resonant frequency, reflection coefficient, or transmission coefficient.

Several microwave sensing techniques for angular displacement [14]-[19] and speed measurement [10]-[12] have been proposed in the literature. The transversal signal interference technique was employed in [14], [15] for the detection of angular displacement. The technique consists of a fixed-length transmission line on one path and a variable-length on the other. In [14], the variable-length transmission line was achieved by implementing an open-ended stub on a circular disc such that by rotating the rotor, the contact point of the stub on the stator changes, thereby changing the effective length of the variable-length transmission line, and hence the inter-transmission zeros of the dual-path transversal interference circuit. An angular displacement detection range of 180° was achieved with a dynamic range of 90°. This technique has however not been extended for speed detection due to the difficulty of having a smooth rotation of the circular disc.

An angular speed measurement technique involving the use of two circularly polarized antennas, one acting as stator and the other as rotor was also demonstrated in [10]. The link transfer function between the two antennas changes as the rotor rotates. The demodulated phase response shows a linear relationship as a function of the rotation angle and hence can be used in quantifying angular displacement and speed.

Resonator-loaded coplanar waveguides (CPW) have also been demonstrated for the measurement of angular displacement and velocity in [11]-[12]. In [11], the CPW was loaded with an S-shaped split ring resonator (S-SRR) and the magnetic coupling between the CPW and the S-SRR was

The authors are with the Electrical Engineering and Computer Science Department, Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates, (e-mail:ademola.mustapha, mohammed.urrahman mohammed.aboukhousa@ku.ac.ae).

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measured in the form of the transmission coefficient of the CPW. The transmission coefficient changes as S-SRR is rotated, and this gives an indication of the angular displacement and speed. This method relies on measuring the transmission coefficient at the resonant frequency. The major feature of this approach is that the measured transmission coefficient results in two dips at 90° and 270° within a complete 360° rotation. This implies that for speed estimation, several rotations will be needed to accurately estimate the speed. For angular displacement, however, it can only detect a maximum angular displacement of 90°.

A maximum angular displacement detection range greater than 90° was achieved in [18]-[19] by using modified SRRs such that the resonators are asymmetric. With only one line of symmetry on the complimentary SRR (CSRR) in [18], the angular displacement detection range was extended to 180°. The dynamic range, in this case, was however +5° to +60° and -5° to -60°. In [19], a 360° angular displacement measurement was achieved by modifying the SRR such that the C-shaped slot inside the resonator is positioned in a manner that there is no line of symmetry on the whole SRR. However, only [18] could be used for angular speed measurement due to the generation of 4 pulses in the reflection coefficient response in a complete rotation.

Several pulses per revolution (PPR) have also been reported in another design involving SRR loaded transmission line [12] for measuring angular speed. The stator is a CPW loaded with two SRRs on the bottom side while the rotor is a circular disk consisting of an array of identical SRRs arranged on the edge of the circular disk. The rotation of the disk is detected through the interaction between the CPW and the SRRs on the rotor. A change in the transmission coefficient of the CPW indicates the relative position of the closest SRR on the disk to the center of the CPW. The number of peaks per unit time in the transmission coefficient also gives an indication of the angular speed of the rotor. Several pulses per revolution (PPR) were generated due to the large number of SRRs on the rotor. While the several PPRs in the design allow for instantaneous speed measurement, the estimation method inherently limits the detection range and increases the error in the estimated angular speed value.

In this paper, a simple low-cost angular speed measurement technique is being proposed. The technique offers a wider detection range with the least estimation error possible. It involves the use of a two-port dual-polarized circular aperture waveguide as the stator and an FR-4 printed circuit board consisting of a circular array of traces of wire as the rotor. The transmission coefficient of the waveguide changes as the rotor rotates. The angular speed measurement is facilitated by the number of pulses per unit time in the measured transmission coefficient.

The remainder of the paper is organized thus: the sensing concept is described in section II. In section III, the design and optimization of the sensor are presented. The rotor prototype characterization is discussed in section IV, while the speed measurement setup is presented in section V. Measurement results are discussed in section VI and the paper is concluded in section VII.

II. SENSING CONCEPT

The proposed polarimetric sensing concept is illustrated in Fig. 1(a). A thin dielectric disk rotating around its center at an angular speed $\omega = \frac{d\phi}{dt}$ is irradiated by a dual-polarized antenna at a distance $d$. A waveguide-fed circular aperture of diameter $D$ is used here as a dual-polarized antenna (c.f., Fig. 1 (b)). The antenna has two orthogonal ports, Port 1 (P1) and Port 2 (P2) which allow for the transmission of a vertically polarized microwave field, $E_{uv}$, through P2 and the detection of a horizontally polarized field, $E_{uh}$, through P1. To this end, P2 is connected to a microwave source, and P1 is connected to a detector. The disk has a thin conducting trace of length $L$ and width $w$ at $\phi = \phi_0$. The trace is centered along the radial line at a distance $r = \frac{D}{r}$ away from the center of the disk. The trace is oriented at an angle $\phi_0$ from the horizontal reference direction (established by port 2 of the antenna). The antenna is fixed at a distance $r$ from the center of the disk. Effectively, when the disc rotates, the trace traverses the irradiated area under the antenna (i.e., footprint) once every rotation.

The conducting trace is a polarizing target. It reflects maximally when the incident electric field is aligned parallel to it. By decomposing the incident field vector over the trace, the cross-polarization transmission coefficient (vertical-to-horizontal) when the trace is positioned under the antenna can be found as [20], [21],

$$S_{uv} = \frac{E_{rh}}{E_{uv}} = (\Gamma_1 - \Gamma_2) \frac{\sin 2\phi'_0}{2}$$

where $\Gamma_1$ and $\Gamma_2$ are the reflections from the disc portion within the footprint of the antenna when the incident field is parallel and orthogonal to the trace, respectively. For thin wire scatterers like the trace, $\Gamma_1 \gg \Gamma_2$ in general.

The result in (1) was verified by 3D electromagnetic simulations performed using Computer Simulation Technology (CST) software. The simulation setup consists of a copper trace of length $L = 15$ mm and width $w = 0.5$ mm printed on a 1.5mm-thick FR4 substrate. The waveguide-fed circular aperture was centered above the copper trace at a distance of $d = 1$ mm. The trace was rotated over a 180° range and the
cross-polarization transmission coefficient, $S_{hv}$, as a function of its orientation angle, $\phi_0$, was recorded. The results at 25.4 GHz plotted in Fig. 2 shows that the magnitude of $S_{hv}$ follows the dependency predicted in (1). It is remarked here that the model in (1) predicts the coefficient at the plane of the disk. As shown in Fig. 2(b), $|S_{hv}|$ is maximum at two angular displacements within a 180° interval. These correspond to the points when the trace is oriented at $45^\circ$ and $135^\circ$ relative to the direction of the incident electric field.

As the disk in Fig. 1(a) rotates, the trace is brought within the footprint of the antenna. Therefore, the cross-polarization transmission coefficient $S_{hv} \neq 0 \forall \phi_0$ since $\Gamma_t \gg \Gamma_0$. However, when the traces leave the footprint, the only possible reflection will be due to the un-polarized background whereby $\Gamma_t = \Gamma_\perp$. Therefore, $S_{hv}$ will be zero $\forall \phi_0$ when the trace moves outside the antenna’s footprint.

Fig. 2. 3D simulation model (left) and cross-polarization response to a rotating trace (right).

For a very thin trace, the response of the sensor as the trace traverses the footprint, depends on the size of the footprint on the disc. This in turn depends on the sensing distance $d$ and the aperture’s dimension. With short sensing distances, the diameter of the footprint is approximately equal to the aperture’s diameter, $D$. Therefore, the response will resemble the function $g(\phi)$ illustrated in Fig. 1(c) where the maximum occurs at $\phi = \phi_0$ and tapers off to zero once the trace clears the footprint area. In this case, the angular width of the response will be approximately $D/r$.

To increase the angular resolution of the sensor, multiple traces evenly spaced over $360^\circ$ should be utilized. The angular spacing between the traces is limited by half the angular width of the response function $g(\phi)$, i.e., $D/2r$. All the traces should be oriented at the same angle $\phi_0$ to maximize $S_{hv}$ (i.e., $\phi_0 = 45^\circ$). The detector response to $N$ traces in one rotation could be written as:

$$v_m(\phi) = k|S_{hv}|^2 \sum_{i=0}^{N-1} g(\phi - \phi_i)$$

where $\phi_i$ is the angular position of the $i^{th}$ trace on the disc, and $k$ is the system sensitivity constant. The model in (2) assumes that the detector is biased in the square-law region where its output voltage is proportional to the input power.

The angular speed at which the disc rotates can be determined from the observed voltage $v_m(\phi)$ over a certain period of time using two methods. Using a time-domain approach, the temporal spacing, $\Delta t$, between observed peaks corresponding to $n$ traces spaced by $\Delta \phi$ on the disc can be used to estimate the angular speed as:

$$\dot{\omega} = \frac{\Delta \phi_n/360^\circ}{\Delta t}$$

The angular speed can also be determined using the frequency domain approach. In this approach, the spectrum of the observed voltage over a certain record length, $\Delta t$, is estimated using Fast Fourier Transform (FFT). The angular speed can then be estimated from the locations of the peaks in the spectrum.

### III. SENSOR DESIGN AND OPTIMIZATION

The sensor introduced in this paper consists of a stator (fixed antenna), rotor (rotating disk), and the detection subsystem.

**A. Stator**

The stator is a two-port circular aperture fed by a circular waveguide made from aluminum and internally loaded with Teflon dielectric [20]. The Teflon loading reduces the cut-off frequency while providing a small footprint. Fig. 1(b) shows the waveguide which has an inner diameter of $D = 6.15$ mm and an outer diameter of $9.45$ mm. The resulting cutoff frequency of the waveguide based on its dimension is 19.73 GHz which effectively defines the waveguide to be operational from 22 GHz to 26 GHz.

The two ports of the waveguide as shown in Fig. 1(b) are positioned orthogonal to the longitudinal axis of the waveguide and orthogonal to each other. Depending on the port of excitation, the waveguide can support electric fields in two orthogonal directions.

**B. Rotor Design**

Equation (1) stipulates that the cross-polarization coefficient depends on the scattering characteristics of the trace. This dependency is embedded in the reflections $\Gamma_t$ and $\Gamma_\perp$. Therefore, one can maximize the sensitivity of the sensor by maximizing $\Gamma_t$ and minimizing $\Gamma_\perp$. This will lead to maximizing the dynamic range and it could be accomplished by judicious choice of the trace geometrical parameters, $L$ and $w$.

Extensive numerical EM simulations were performed to investigate the cross-polarization response of the waveguide-fed circular aperture to printed traces of various widths and lengths. In all simulations, the aperture was positioned 1 mm above the PCB and the trace was oriented at $45^\circ$ with reference to the direction of the incident electric field by exciting Port 2. The trace width and length were varied and $S_{hv}$ was computed for each combination. Fig. 3(a) shows $|S_{hv}|$ as a function of the trace length and width. A PCB prototype with traces of different lengths and widths was fabricated to validate the simulations using measurements. Fig. 3(b) shows the simulated and measured cross-polarization response of the sensor as a function of the trace length when $w = 0.25$ mm. The simulation and measurement results show that the maximum response occurs at 3 mm which corresponds to the resonant length of the printed trace on the FR4 PCB substrate ($\lambda/2$). While there is good agreement between the simulations and measurements, discrepancies between them are mainly due to the fact that the measurements were not calibrated owing to the lack of a circular waveguide calibration kit.
circumference was further investigated in simulation by varying the angular separation $\Delta \phi$ while keeping the trace width at $w = 0.25$ mm. Fig. 4(c) shows the obtained response for various angular separations between the traces. As shown in the figure, it is only when the angular spacing is larger than 9.15° ($r \times \Delta \phi = 6.15$ mm), that the response tapers to zero in between the traces. On the other hand, the peaks are barely identifiable when the angular spacing, $\Delta \phi \approx 6^\circ$ ($r \times \Delta \phi = 4.05$ mm). This is primarily due to the fact that when $\Delta \phi$ approaches limit $D/2r \approx 4.6^\circ$, the individual traces will not be resolvable in the response. With the angular spacing of $\Delta \phi \approx 7.5^\circ$ ($r \times \Delta \phi = 5.08$ mm), the dynamic range is reduced to around half the maximum range obtained when $\Delta \phi \approx 10^\circ$ ($r \times \Delta \phi = 6.8$ mm). The spacing of $\Delta \phi = 7.5^\circ$ is selected here as a compromise between resolution and dynamic range (sensitivity). As it will be shown later, with this spacing, a signal-to-noise ratio of more than 20 is obtained.

**IV. ROTOR PROTOTYPE CHARACTERIZATION**

Following the analysis reported in the previous section, a rotor radius $r = 38.5$ and consisting of 48 printed copper traces each with a length of 3 mm and width of 0.25 mm and with an angular spacing of $\Delta \phi=7.5^\circ$ was fabricated (c.f. Fig. 5).

The response of the waveguide-fed circular aperture to the rotating rotor was measured using the N9918A FieldFox Handheld Microwave Analyzer. With the white straight line of the rotor in Fig. 5 corresponding to the $0^\circ$ reference, the circular aperture stator was placed 1 mm above the copper trace in the $0^\circ$ direction. The stator was positioned such that the trace is $45^\circ$ to the direction of the incident electric field. The rotor was attached to the rotating object as shown in Fig. 6. The rotating object (and by implication, the rotor) was rotated in a clockwise direction through an angle of 22.5° at 0.15° step size so that 4 traces eventually passes underneath the circular aperture as the rotor rotates. The measured $|S_{nr}|$ response is shown in Fig. 7. The response agrees accurately with the simulation results. The normalized results show that the result conforms with the simulation result with the peaks occurring at multiples of 7.5°. The slight variation in amplitude has to do with the slight non-uniformity in the planar surface of the rotating object under test. The four peaks recorded correspond to the four traces that

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**Fig. 3.** (a) Simulated $|S_{nr}|$ as a function of $L$ for various values of $w$, and (b) effect of the trace width on $S_{nr}$ at 25.4 GHz.

**Fig. 4.** (a) Diagram of the rotor with four traces, and simulated response for (b) various trace widths (c) and trace interspacing.

Due to the mutual interaction among the traces, the results obtained using $\Delta \phi=7.5^\circ$ do not show that $S_{nr}$ reducing to zero in between the traces. This is essentially because $\Delta \phi$ in this case is less than $D/r \approx 9.15^\circ$ (i.e., two traces could be accommodated within the footprint). The reduction in the dynamic range due to the trace interspacing over the

In general, the trace width should be very small relative to the wavelength in order to make $\Gamma_\perp \approx 0$. Furthermore, to attain high angular resolution, the trace width should be as small as possible. However, using very thin trace reduces $\Gamma_\parallel$ as well. Our simulations and measurement showed that limiting $w$ to a value less than 0.075$\lambda$ will not impact the dynamic range of the sensor.

The interaction between the stator and the rotor with multiple traces was simulated to highlight the effect of trace width and trace interspacing. In the simulation, four uniformly interspaced copper traces were centered along the circumference of a circle of radius $r = 38.5$ mm on a PCB as shown in Fig. 4(a). The circular aperture was placed at $d = 1$ mm above the rotor and initially centered above one of the traces. The angular separation between the traces was fixed to $\Delta \phi=7.5^\circ$. The PCB was then rotated by incrementally increasing the rotor angular displacement $\theta$ so that each of the copper traces passes underneath the waveguide. The transmission cross-polarization coefficient $|S_{nr}|$ was recorded as a function of the rotor angular displacement $\theta$ for various trace widths as reported in Fig. 4(b). As expected, the response revealed four peaks at four different angular displacements corresponding to the position of the traces. The obtained results suggest that the trace width $\leq 0.5$ mm will not change the realized dynamic range significantly.
passes under the circular aperture during rotation.

A 30dB ERAVANT K-band 1832733025-KFKF-S1 low noise amplifier was connected to port 1 of the waveguide to amplify the received signal at port 1 of the waveguide. The amplified signal level is within the square-law region of the KRYTAR 302B Schottky diode detector. The operational input level for the diode detector ranges from -20dBm to +10dBm with an output voltage ranging from 1mV to 200mV. The detector output was sampled using the NI 9223 C series analog input module connected to the National Instrument (NI) cDAQ 9174. The sampling was done at a rate of 10ksamples/s for 10s.

Considering that the data is averaged over 100 sets of samples, the effective sampling rate is 100 samples/s. By setting the acquisition time to 10s and allowing for at least 4 traces to pass underneath the stator before estimating the speed, the resultant minimum speed is given as:

$$\omega_{\text{min}} = \frac{(N_{\text{min}} - 1)}{N_T} \frac{3}{4} \frac{f_{\text{rev}}}{\min} = 0.375 \text{ RPM}$$

where $N_{\text{min}}$ is the minimum number of traces required, $N_T$ is the total number of traces on the rotor and $T_{\text{acq}}$ is the measurement time. While $N_{\text{min}}$ of 2 is sufficient for the speed estimation, a value of 4 is used to reduce the estimation error at low speed.

The sampling rate for this work was determined based on the maximum speed of the object under test. The maximum speed of the available rotary object under test was $\omega_{\text{max}} = 50$ RPM, equivalent to 40 traces/s. In satisfying the Nyquist criterion, the sampling rate must be greater than twice the maximum speed. A sampling rate of 2.5$\omega_{\text{max}}$ equivalent to 100 S/s is sufficient to accurately recover the sampled signal. In order to improve the signal-to-noise ratio, averaging over 100 samples was carried out thereby effectively increasing the sampling rate to 10 K/S. Though the speed detection system is currently designed for a maximum of 50 RPM by limiting the acquisition sampling rate to 10 K/S. However, the system can actually measure up to 5000 RPM by increasing the sampling rate of the acquisition system to 1 MS/s.

The object under test was rotated at different speed settings including 0.4, 1, 2, 5, 10, 20, 40, and 50 RPM. The detector output voltage was acquired for 10s during the period of the rotation and the acquired data was analyzed using two different methods – the time domain method and the frequency domain method.

Prior to the speed measurement, the noise floor of the measurement system was also characterized. The setup is similar to Fig. 8 but with the rotary object not placed underneath the circular aperture but still on the same planar surface as the stator to account for the vibration noise due to the motor of the object under test. The RF was turned ON while the motor was rotating and the received signal from port 1 of the waveguide was sampled at the rate of 10 K/S for 2000 s (equivalent to 200 measurement cycles of 10s each). The measured rms noise of the measurement system was 440uV. This noise is primarily due to the vibration of the rotor as the rms noise with the motor turned OFF was measured to be 57uV.

VI. MEASUREMENT RESULTS

The acquired detector output voltages for the different speed settings were averaged over 100 consecutive samples and the resultant signals were processed in both time domain and frequency domain.

A. Time Domain Analysis

The detector output voltage for three different speed settings is shown in Fig. 9. The acquired voltages for the different
angular speed settings were averaged over 100 sets of sampled data and the resultant signals were processed in the time domain. For speed settings ranging from 5 – 50 RPM, a simple peak detection algorithm that relies on turning point detection was employed. This technique resulted in accurate peak detection. The red circles are the peak locations signifying the alignment of a copper trace with the center of the aperture of the stator. The speed was then estimated based on the equation below:

$$\hat{\omega} = \frac{(N_{\text{peak}} - 1)}{N_T \Delta T}$$

where $N_{\text{peak}}$ is the number of peaks detected, $N_T$ is the total number of traces on the rotor, and $\Delta T$ is the time difference between the first and the last detected peak. The worst-case speed estimation error for the 5 – 50 RPM speed settings was only 0.2% at 10 RPM rotational speed for the 10s acquisition time.

For lower speed settings, there are more samples within a trace cycle which results in multiple false peak detection as shown in Fig. 10. Hence, a more robust peak detection algorithm is required to detect the peak voltage within a cycle for a very wide range of speed settings from 0.4 RPM – to 50 RPM.

**B. Frequency Domain Analysis**

Speed estimation using the frequency domain method is more accurate and can cover a wider range of speed settings. Similar to the time domain analysis, the acquired detector output voltages for the different angular speed settings were averaged over 100 sets of consecutive sampled data, and the resultant signals were processed in the frequency domain using Fast Fourier Transform (FFT). The time-domain signals and their respective frequency spectra for each speed setting are shown in Fig. 11. The frequency in the frequency spectrum plot has been converted to speed in RPM with a conversion ratio of 1Hz = 1.25RPM obtained from:

$$1 \text{ revolution/minute} \equiv \frac{48 \text{ traces}}{60 \text{ sec}} \equiv \frac{48 \text{ trace cycle}}{60 \text{ sec}} = 0.8 \text{ Hz} \text{ or } 1.25 \text{ RPM} = 1 \text{ Hz}$$

This is considering that there are 48 traces/revolution of the rotor.

In all instances, the speeds were accurately detected with the frequency component at the speed of rotation having a magnitude ranging from 9 mVrms – 17 mVrms while the noise level remains as low as 0.44 mVrms. This results in SNR ranging from 20.45 – 38.64 (or 26.21 dB – 31.74 dB). The different speed values were accurately predicted within the 10s acquisition time. The speed sensor resolution using the FFT method over the 10s acquisition time is 0.1 Hz (or 0.125 RPM). Although the estimated speed values seem to be 100% accurate, the absolute speed estimation error over the 10s acquisition time is actually 0.05 Hz (or 0.0625 RPM). The reason for the seemingly 100% accuracy above was because all the speed settings were multiples of 0.125 RPM. However, for the case of 42.1 RPM speed setting, the estimated speed value was 42.125 RPM as shown in Fig. 12 resulting in an absolute error of 0.025 RPM and a relative error of 0.06%. In general, the maximum speed estimation error for the proposed system is therefore only 0.0625 RPM for the 10s acquisition period. As shown in Fig. 13, the estimation error increases to 0.625 RPM for 1s acquisition time (equivalent to 0.667 rotation cycle for 40 RPM speed).
Fig. 11. Speed estimation using Fast Fourier Transform (FFT) method.

Regardless of this imperfection in the object under test, the speeds were still accurately detected.

While all measurements have been carried out with a 10 s acquisition time, we can also demonstrate that we can accurately estimate the speed within a much lower acquisition time. For a 1s acquisition period, the maximum absolute estimation error is only 0.625 RPM for all speed settings that can produce four peaks in the detected voltage within the 1s acquisition time. These speed settings include 5 RPM and above.

Compared to the state of the art, the proposed speed sensor in this work addresses the shortcomings of the earlier reported microwave-based speed sensors. The reported sensor in [13] is limited by its PPR. Hence, the sensor resolution is 20 RPM within a 1.5 s acquisition time. Although a speed sensor with a shorter acquisition time of 1s and fine resolution of 0.072 RPM was presented in [12], the area of the rotor is a factor of 4 bigger. The proposed sensor in this work could also achieve a much finer resolution than the 0.125 RPM by increasing the rotor size.

Also, the suitability of the sensor in [12] to measure the speed at lower speed settings was not demonstrated. The acquisition time clearly defines the lower limit for the speed sensor and it is not clear what the speed limit is for a 1 s acquisition time. In this work, the proposed sensor can measure speed as low as 0.4 RPM and it is only limited in the upper range to 5000 RPM by the maximum sampling rate of the DAQ system which is 10 MS/s. We have also demonstrated a smaller absolute error of 0.0625 RPM.

VII. CONCLUSION

A fast and accurate angular speed detection system has been presented. The detection system utilizes a waveguide-fed circular aperture as a stator and a circular array of copper traces on an FR4 PCB as the rotor. Analysis of the waveguide-fed circular aperture to a copper trace was presented. The response of the waveguide-fed circular aperture to a rotating copper trace
was also presented. Furthermore, the response of the waveguide-fed circular aperture to a rotating circular array of copper traces was presented. It was demonstrated that a continuous pulse signal of equally spaced pulses could be generated by rotating a circular array of equally spaced copper traces placed close to the waveguide-fed circular aperture. 48 copper traces were printed on the FR4 PCB to form the sensor rotor. The multiple copper traces allow for fast detection of the angular speed. The design and analysis of the rotor for better sensitivity were presented. The detection mechanism relies on counting the pulses generated by the waveguide-fed circular aperture due to its interaction with the copper traces. The adoption of the frequency domain method for speed estimation also gives an accurate detection mechanism with an absolute detection error as low as 0.0625 RPM over a very wide range of rotor speeds. The speed detection system can detect angular speeds ranging from 0.4 – 5000 RPM with signal-to-noise ratios ranging from 20 – 38.

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