Development of Wireless Clamp-on Torque Transducer for Rotating Shaft

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***Abstract*—This paper presents wireless clamp-on torque transducer based on twist angle deformation measurement system using strain gauges. Firstly, the model of a torque measurement system based on the twist angle with strain gauges sensing structure is studied and developed. Secondly, for the system verification, the proposed model is presented as a case study. In this study, both the mechanical and electronics designs are discussed and analyzed. Particularly, using finite element analysis technique the mechanical sensitivity and maximum stresses of the torque sensor are examined. While the readout electronics of the system is verified experimentally by laboratory tests. The torque sensor has the capability of ±50Nm with 0.023 V/Nm of sensitivity under static torque measurement. Finally, the performance of the developed scheme is examined by carrying out simulations followed by experiments.**

***Index Terms*-*RF wireless telemetry, torque measurement, strain gauges, rotating* shaft**

I. Introduction

Nowadays, torque has the essential prerequisite for precisely controlling rotating mechanical devices used in many industrial applications including product development, testing analysis, quality test, and safety or optimal control. Meanwhile, it has been important to establish a suitable torque measurement system that can easy to install, increase the strength, operational capability, and lifespan of rotating mechanical devices. Commonly, torque can be obtained by measuring strain, the angle of twist, stress (magneto-elastic methods) [1] and sensors which are based on surface acoustic waves [2], Piezoresistive [3], Hall-Effect [4] and capacitance [5]. Many varieties of methods have been proposed in the context of these torque measuring techniques [6]. Thus, the strain gauge method based on strain measurement has been widely used in industrial applications due to low cost and high sensitivity.

Numerous scholars made a great contribution to this research area such as M. Hilal Muftah *et. al*. established an improved torque measurement method based on strain gauge with high load ability [7]. In order to achieve the transient torque of an automotive powertrain Zhang. N. et. al. developed a novel wireless transducer by using strain gauges on the surface of the rotating shaft [8]. Similarly, Radionov A.A implemented on-line elastic torque monitoring system consist of two bridged resistance strain gauges [9]. Placement of strain gauges have also a direct relation to the sensitivity of the torque measurement, Qingsong Xu, designed a large-range rotary stage whereas, conducted FEA to enhance sensitivity and best positioning of strain gauges [10]. Micro-electromechanical systems using strain gauges are also introduced in various applications for torque measurement [11], [12].

In aforementioned methods of torque sensors strain gauges have to be glued directly on the rotating shaft. Moreover, the problem with glued strain gauges is that they are very hard to paste accurately and its mechanical capability is also questionable. Another type of these sensors required an additional piece between the rotating shaft and load. Because of the required additional part shaft needs to be cut and assembling a wired torque measurement unit into the system is a rather complicated, time-consuming, and in some cases even impossible task. In addition, it affects the strength and operational capability of the system [13].

In this paper, a wireless clamp-on torque measurement system is studied, the benefit includes, wireless transmission, fast installation and no need to install additional part with a rotating shaft. The installation is carried out directly on the surface of the rotating shaft. This measurement system utilizes pre-calibrated strain gauges rod, where strain gauges are aligned precisely on the rods by the assembly of a collar around a rotating shaft. And signal conditioning circuit with STM32 is used to control the system and transmit measured torque signals through wireless emitter (NRF2401) to achieve non-contact torque measurement. Furthermore, the mechanical sensitivity and maximum stress on rods and collar are analyzed using ANSYS 15.0 finite element analysis software. After the various analysis of the mechanical design and operational verification of the electronics readout design, the sensor was placed in a test setup and static analysis was conducted using a torque wrench. Finally, the key findings of the paper are concluded.

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II. Development of Wireless Clamp-on Rotary Torque Transducer

A. Mechanical Design Considerations

In this work, the proposed mechanical design is based on measuring the twist angle of the rotating shaft under torsion, when the torque between the two cross-sections is constant, and the diameter of the shaft remains unchanged, then the twist angle between the two cross-sections can be mathematically expressed as (1).

$$\emptyset = \frac{TL}{GI_p} \tag{1}$$

In (1), the Ø, T, and L represent twist angle, applied torque (Nm), and the length of the shaft (m) respectively, the G denotes the shear modulus of elasticity (N/m^2), and I_p expresses the polar moment of inertia (m^3).

Equation (1) is the characteristic equation for the proposed method. In this method, the pre-calibrated measuring rods are clamped at each end by a counterbalanced collar around a shaft as shown in Fig. 1. When the rotating shaft is subjected to torsion, the twist angle of the rotating shaft and measuring rod will be same and it will produce the same deformation. Thus, deformation can be measured by the strain gauges bridge fixed on the measuring rod. Furthermore, to process the strain gauges signal, circuit on the collar is utilized to amplify and convert the bridge signals. Afterward, these signals are sent out by the NRF2401 transceiver to the receiver circuit that is fixed on the ground.

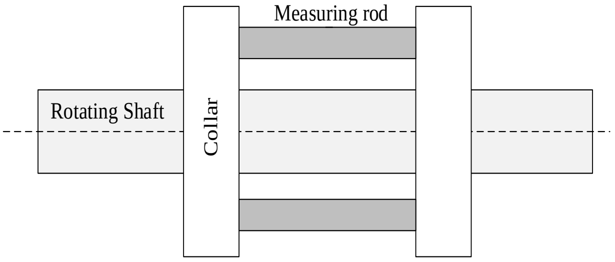

Figure 1. Proposed model design.

B. Finite Element Model Setup

The FEA was carried out to analyze the maximum stress on the measuring rods for the better placement of strain gauges and for sensitivity analysis. Prior wireless torque measurement systems use strain gauges, which have to be glued directly to the surface of the rotating shaft. In the field conditions, it is very hard to place strain gauges precisely. In the proposed method, the strain gauges are placed on the surface of measuring rod. To select the best position for strain gauges, ANSYS workbench 15.0 was used to analyze the maximum stress point on the measuring rods. Material for clamp collar is Al6061 and measuring rods material is SS304. The design parameters for the simulation are Clamp collars having inner diameter 17mm and outer diameter 57mm with a thickness of 15mm. Three rods having length 130mm with 10mm diameter. The simulation results showed that the deformation of each bar is consistent, and the location of the maximum stress on the rods appears to both ends of the rods. Hence we can make the biggest stress locations as the strain gauges paste position and it is indicated by a white outlined box in Fig. 2.

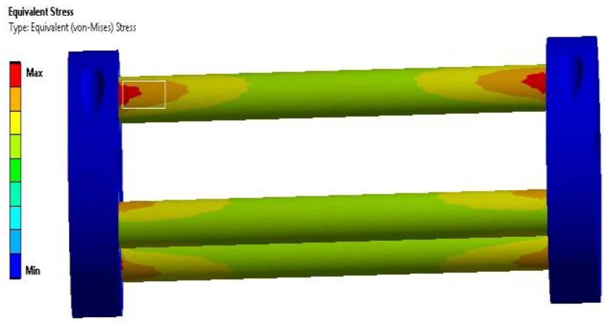

Figure 2. Simulated model with strain gauges placement location.

C. Readout Electronic Circuit

The proposed electronic circuit is mainly composed of the transmitter circuit and the receiver circuit. These circuit modules are shown in Fig. 3.

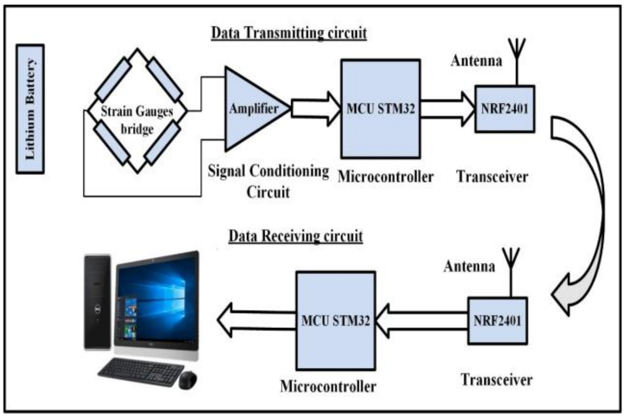

Figure 3. Readout electronic circuit.

(a) Bridge signal conditioning circuit

In the non-contact torque measurement, it is hard to obtained twist angle deformation with a complex environment, the changes in shaft shearing strains are very small and occur at rapid rates, therefore, measuring the resultant twist angle is a difficult diagnostic task. And the sensor output signals are very weak and accompanied by various noises. Therefore, the circuit should have the function of signal filtering, high signal amplification and so on.

In the proposed bridge signal conditioning, amplification is carried out in two stages. AD623 and AD620 op-amp are selected in the circuit. They are high input impedance differential amplifiers that can add signal filtering circuit as a front-end input. AD623 is selected to increase, the gain up to 800, and the second amplifier AD620 can increase the gain up to 200. The filter circuit is designed in differential mode with AD623 and common mode with AD620, and their cutoff frequencies are selected as 30Hz and 630Hz, respectively. The diagram of proposed bridge signal conditioning circuit is shown in Fig. 4.

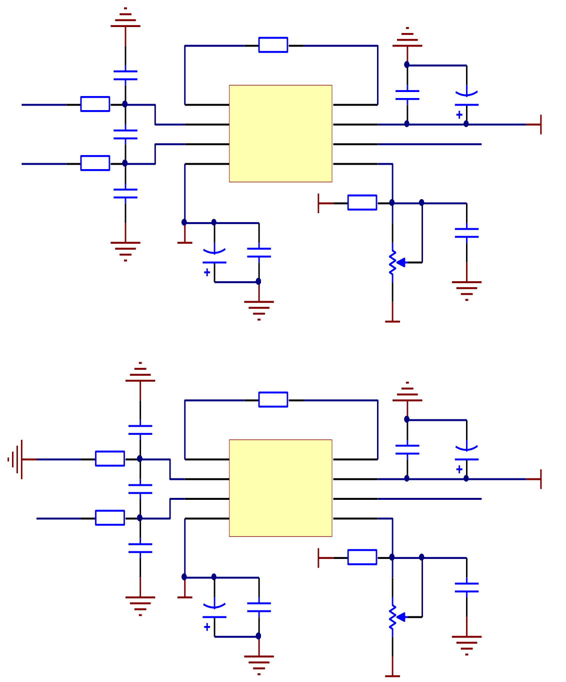

Figure 4. Bridge signal conditioning circuit.

(b) Master-slave microprocessor and wireless module

The microprocessor is the main part of a developed system that must have functions such as ADC, serial port, multiple digital interfaces, etc. To meet the system requirements STM32 is selected as the master chip, with 12-bit ADC and various high-frequency digital interfaces. In non-contact torque measurement, the most critical part is to achieve RF signals transmission which needs high communication speed, high transmission distance, high signal strength and other characteristics. Therefore, the NRF2401 module is used with 100mW communication power, 2Mbps transmission rate, 2Km transmission distance, and strong anti-interference.

III. Results and Discussion

In this section, the results of the simulation study and designed readout electronics are presented to verify the proposed model of the wireless clamp-on torque transducer.

A. Simulation Study

Numerous simulations were performed to investigate the parameters affecting the torque sensor sensitivity behavior, such as diameter and length of the measuring rods. Three different diameter rods were studied, $D1 = 10mm$, $D2 = 12mm$, and $D3 = 14mm$. The analysis showed that rods having diameter $12mm$ and $14mm$ behaved less sensitive when compared to the rod having diameter $10mm$ as shown in Fig. 5.

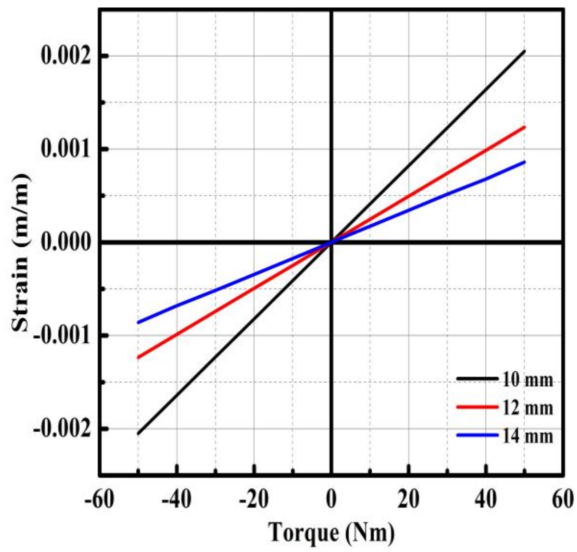

Figure 5. Torque vs. Strain with diameter variations of rods.

(a) Effects of length variation

The size of the sensor varied incrementally. The design parameters for this simulation are $D1 = 10mm$, $L1 = 100mm$, $L2 = 110mm$ and $L3 = 130mm$. The results demonstrate that the length of the rods has a significant direct relation to the strain, the strain being doubled or halved, as shown in Fig. 6.

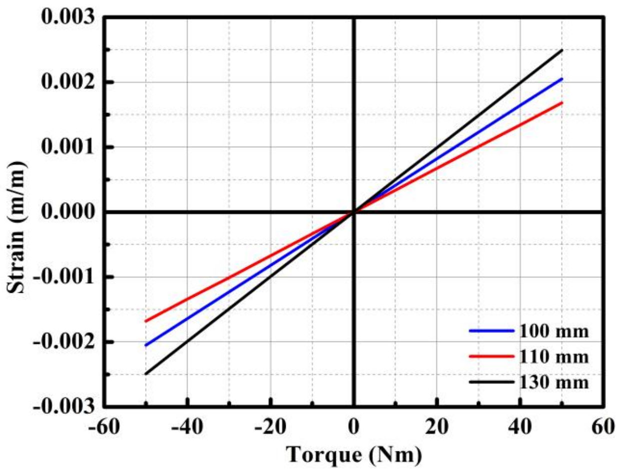

Figure 6. Torque vs. Strain with length variations of rods.

After sensitivity analysis of the proposed model, a parametric study was conducted using different torque values ranging from $1Nm$ to $50Nm$. These input values were separated with a step size of $5Nm$. The reason for choosing these steps was to observe the linearity of the mechanical sensing structure in the lower ranges with high resolution. Fig. 7. Shows the change in equivalent von Mises stress with respect to the applied torque over the full range of $1Nm$ to $50Nm$.

Fig. 8 shows the simulated von Mises stress on the proposed torque sensor model to ensure that the torque sensor model was well within yield strength point.

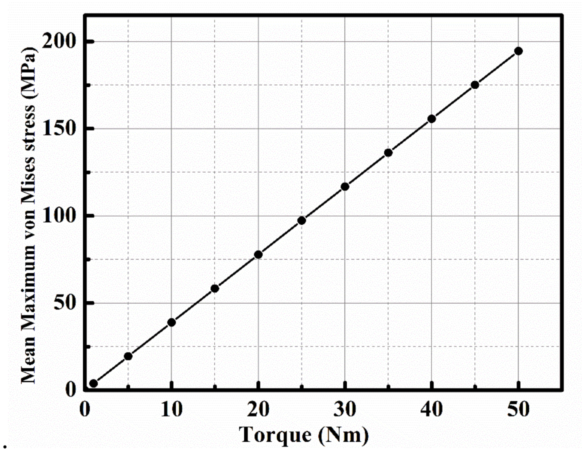

Figure 7. Torque vs. Mean maximum stress.

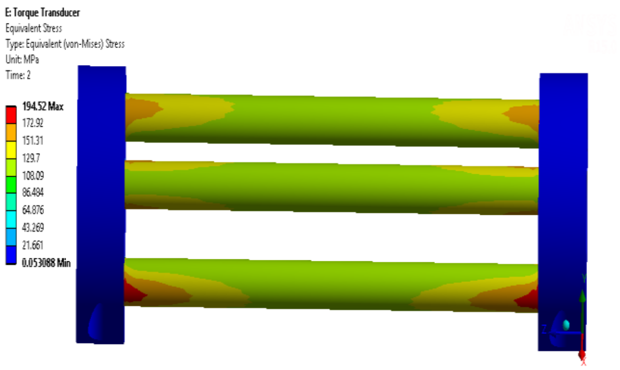

Figure 8. Torque vs. Surface von Mises stresses at 50nm.

B. Readout Electronics

In this subsection, to obtain the experimental results of the developed method, the sensor was placed in a test setup and static analysis was conducted using a torque wrench for the operational verification of the electronics readout design. The setup used for this verification is shown in Fig. 9.

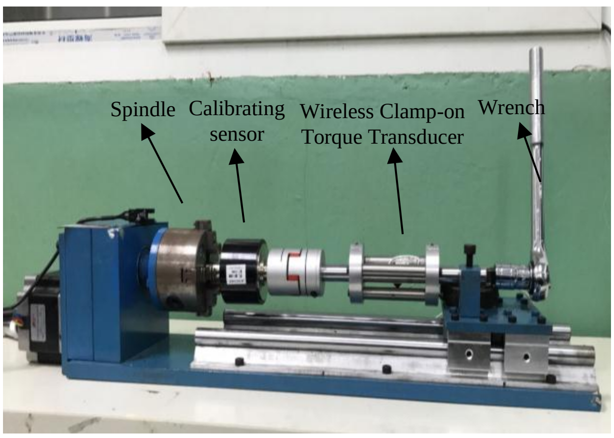

Figure 9. Experimental setup.

The test was conducted with designed readout to analyze the parameters affecting the torque sensor sensitivity behavior, such as diameter and length of the measuring rods as discussed in the above simulation results. The analysis showed that rods having diameter $12mm$, and $14mm$ has a significant direct relation to a strain, the strain being doubled or halved, as shown in Fig. 10. As well as the change in length, $L1 = 100mm$ and $L2 = 115mm$ behaved less sensitive when compared to the rod having length, $L3 = 130mm$ as shown in Fig. 11.

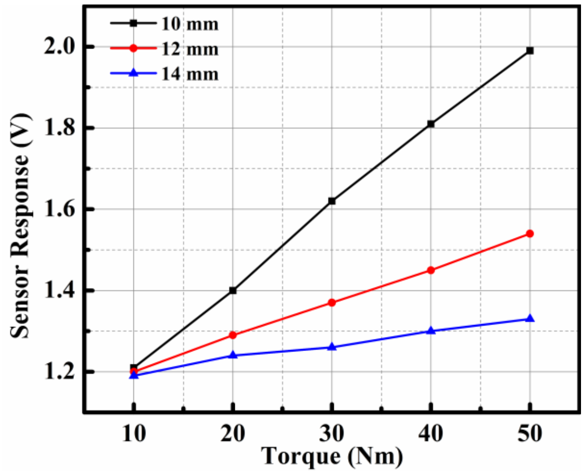

Figure 10. Torque vs. Sensor response with diameter variations of rods.

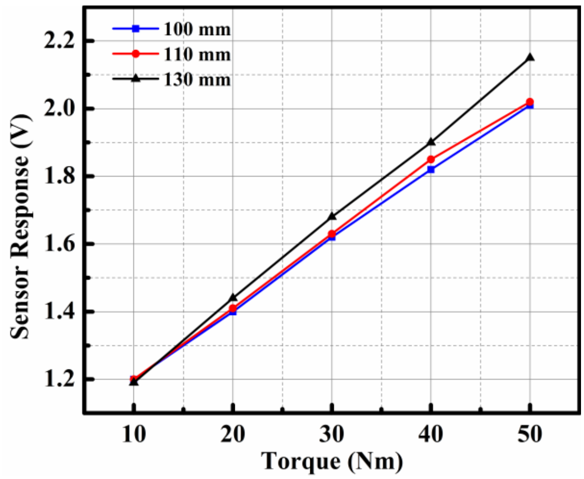

Figure 11. Torque vs. Sensor response with length variations of rods.

IV. CONCLUSION

In this paper, wireless clamp-on torque transducer based on twist angle deformation is established using strain gauges. The developed transducer can be easily clamped on the rotating shaft without disassembling of the mechanical components. Furthermore, wireless torque transducer can be measured without relying on the components such as slip rings, rotary transformers etc. To demonstrate the effectiveness of the proposed method, FEA simulations have been carried out on the developed transducer to obtain the precise position of the strain gauges and the mechanical sensitivity of the method. In addition, to validate the simulation results, experiments have been conducted on the wireless torque transducer which confirms the efficacy of the proposed method.

Furthermore, our design of the torque transducer based on the proposed method is scalable, such as a change in the mechanical dimensions of the sensor can lead to different range and sensitivity according to the application requirement. The developed wireless clamp-on torque transducer can be used for measure mechanical torque from rotating shaft and has a good application prospect.

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