Embedded Inductive Sensor System in Helping Industrial Machine Maintenance Problems

Sivaraos[1], M.R. Muhamad[1], T.S.Liang[1], Kadirgama[2], M. Shajahan[1]
[1]*Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, Melaka*
[2]*Faculty of Mechanical Engineering, University Malaysia Pahang, Pahang*
sivarao@utem.edu.my

***Abstract*— The inductive sensor / proximity sensor was preliminarily initiated to be used as a micro level limit switch where its potential in speed measurement was not taken advantage by the industries. Thus, looking into its potential significant contribution, this paper presents the performance of a non-contact inductive sensor which was used to remotely measure the high speed rotational spindle with high degree of accuracy. The sensor was used to generate pulse correlating the rotational speed of a machine. An experiment was conducted using a self-designed test rig to investigate its performance in counting the machine spindle speed which can help to ease the machine maintenance task for technical supports. The measuring was monitored by a specially designed LCD display, connected to an electronic circuit and a microcontroller. The test result shows that the inductive proximity sensor yields up to 95% in terms of rotational speed accuracy. The setup was made to suit a single monitoring system, while the modular based for multiple systems that integrate different operations are in progress.**

***Index Terms*— Inductive Sensing, Microcontroller Application, Remote Measurement, Rotation Measurement, Preventive Maintenance.**

I. INTRODUCTION

The inductive proximity sensor is an important embeddable component used in manufacturing lines which are capable in alternating the switch to on and off function without any form of physical contact [1]. In the modern industrial production floor, it is ideally positioned to perform many tasks by detecting the connection(s) without the actual mechanical contact, which is also classified as wear-free [2]. These types have been used by industries since 1970s to detect position, measure displacement, alignment, and vibration of a target without physical contact [3]. Sakthivel et al. [4] has used inductive sensor as a guiding tool for removing metal shrapnel during surgery. Kim et al. [5] applied inductive sensors for dental implant stability evaluation, while, Hrvoje et al. [6] used in monitoring motor spindle parameter in the ship.

Fericean et al. [7] developed a new type of inductive sensor for industrial automation, whereas Bae et al. [8] proposed the use of inductive sensor in automatic weld seam tracking. Gaydecki et al. [9] implement inductive sensor in imaging steel- reinforcing bars embedded within concrete successfully. Tan et al. [10] applied the inductive sensor in non-contact measurement of water surface level. Although there are many previous research regarding inductive, but the evaluation of the performance of inductive sensor in rotational speed measurement was not widely addressed.

This paper presents the performance analysis of inductive sensor, especially for machines with rotating spindles where the particular points can be taken to capture the signal. Therefore, this methodology is highly potential to be applied onto maintenance management system by integrating wireless communication system. For this reason, high accuracy performance is required and some fine-tuning is essential. The engineering experiments witnessed that the modified inductive proximity sensor integrated with a microcontroller was able to capture the rotational speed up to 10, 000 rpm without any problem. The sensor was also able to generate a bell shaped pulse which is easily interfaced with the microcontroller for the measurement and control purpose.

II. METHODOLOGY

The conventional inductive sensor was used to perform switching or measuring the gap of metallic spinning spindle. Figure 1 shows the main elements in an inductive sensor including coil/inductor, oscillator, trigger/compared circuit, and output amplifier.

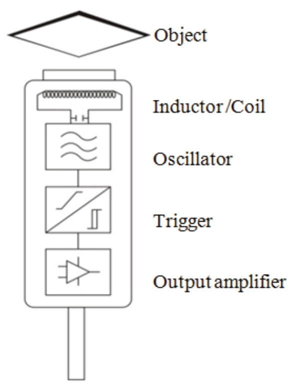

Figure 1: Block Diagram of Conventional Inductive Proximity Sensor

Principally, the oscillator generates high frequency electromagnetic field with coil or inductor, and when the metallic object is placed closer, the force generated by the inductor is disrupted. This causes the magnetic field to decrease allowing the trigger to differentiate the condition, especially when a metallic object is placed closer causing the switching output signal to occur [11,12]. Lastly, the output amplifier would amplify the output signal to be utilized as per the designed methodology.

In order to generate pulses with inductive sensor, where the pulse's frequency is directly proportional to the rotational speed, a metallic registration mark is placed bulging on the rotating device [13]. Figure 2 (a) shows the proximity sensor placement and Figure 2 (b) shows the pulse generated when the spindle is rotating.

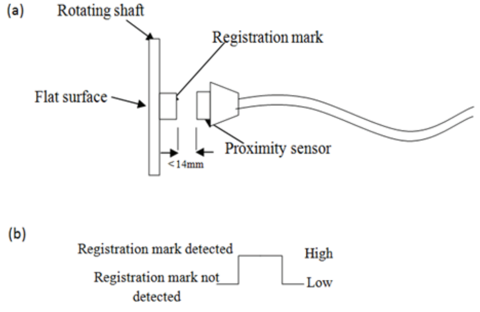

Figure 2: (a) The Placement of Proximity Sensor for Rotational Speed Measurement (b) Pulse Generated (Ideal)

As the spindle rotates, the registration mark will intermediately fall within the detection area of the proximity sensor and trigger the proximity sensor which will immediately switch the output signal from "Low" to "High". When the spindle rotates continuously, the output signal of proximity sensor would be in the form of a continuous wave with regard to and proportional to the spindle rotational speed.

A. *Rotation speed measurement method*

The measurement of the rotational speed can be done in several approaches [14, 15], one of the approaches is the frequency measuring method, where the readings are based on the number of pulses counted, N in a fixed time window (Tw). Figure 3 shows how a square wave is generated by the proximity sensor when the spindle is rotating with the number of pulses counted in a fixed time window determination. However, the applied time window affects the result of the calculation, where, the longer time window is applied, the more the number of pulses can be counted. Therefore, the relative measurement error for different time window is also analysed and reported in this paper. The following formula is applied to analyse the spindle rotational speed, *n*.

$$n = \frac{N \times 60}{T_w}(rpm) \quad (1)$$

If the number of pulses N increase by one, the rotation speed is:

$$n_1 = \frac{(N+1) \times 60}{T_w}(rpm) \quad (2)$$

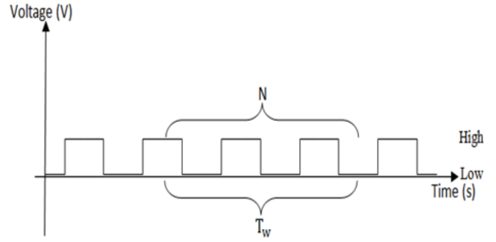

Figure 3: The relationship of N and T_w with Square Wave Generated by Proximity Sensor

The resolution, R is now calculated with:

$$R = n_1 - n = \frac{60}{T_w}(rpm) \quad (3)$$

As mentioned earlier, the relative measurement error n is very much dependent on the time window, as the resolution relies only on time window in this case. Hence, the relative measurement error can be calculated with:

$$P_R = \frac{R}{n} \times 100\% \quad (4)$$

Figure 4 shows the calculation of the resolution and the relative error for different values of the Tw using Eq. (3) and (4). The resolution and the relative error of the shorter value of T_w is higher compared to the longer Tw. Hence, the value of Tw to be applied in the formula would be long enough for better reading accuracy of the rotational speed measurement.

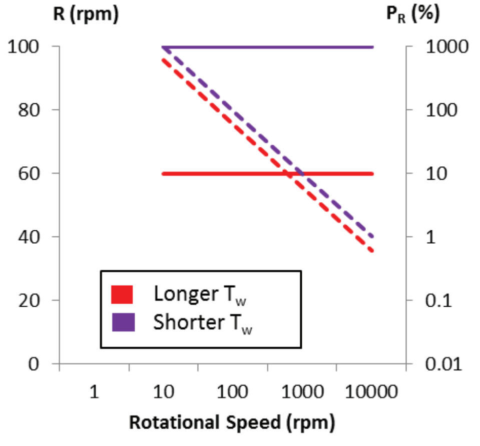

Figure 4: Investigation of Resolution R (Straight Line) and Relative Error P_R (Dotted Line) For Different T_w

B. Hardware and software descriptions

The electronic circuit of the proposed system includes the following components:

1. A long sensing distance proximity sensor with a constant DC voltage supply.
2. Microcontroller (PIC16F877A) based on rotational speed display.

The microcontroller was programmed to measure the rotational speed based on the pulse generated via the proximity sensor. All programming was done by using micros 8.2 Integrated Development System (IDE). The flow chart on the rotational speed measurement is as shown in Figure 5.

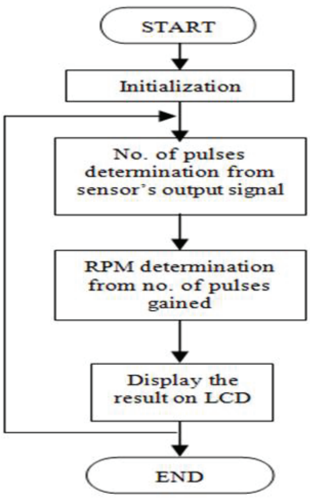

Figure 5: Programming Algorithm of Microcontroller

The program of the microcontroller is written using a commercially available package mikro-C 8.2, primarily to:

1. Count the number of pulses passed at input port of the microcontroller (PORT A) whereby PORT A is defined as a counter to count the number of LOW to HIGH transitions in the pulses applied at PORT A;
2. Determine the rotational speed in RPM by using Eq. (1) from the number of LOW to HIGH transitions in the pulses applied at PORT A;
3. Display the value of rotational speed on LCD 16X2 from the result of the determination.

III. Simulation

The established microcontroller program was simulated using Proteus 7 to verify the functionality of the program for the rotational speed measurement upon the ideal input pulse as a signal to the microcontroller. The schematic of the electronic circuit is illustrated in Figure 6, where the pulse generator plays a role as rotational speed signal and the LCD displays the result of the measurement. This gives an overview of the overall scenario of rotational speed measurement using proximity sensor and microcontroller via measuring frequency method.

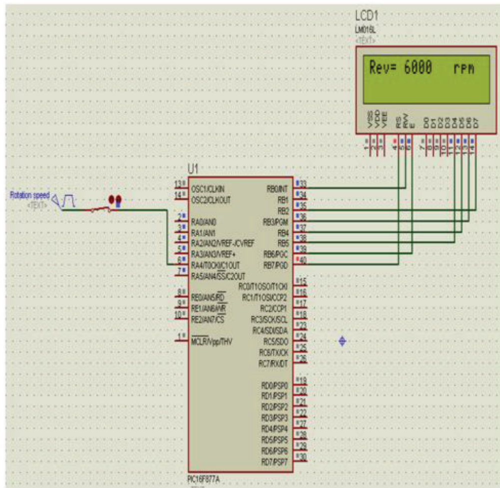

Figure 6: Schematic Circuit Diagram of RPM Measuring System

The signal from pulse generator is considered the output signal of the inductive sensor as the output signal of the inductive sensor is the square wave signal. The frequency of the signal is varied from 10 Hz to 100 Hz, which is significantly equal to spindle rotational speed ranged from 600 to 6000 RPM in order to validate the performance of the rotational speed measurement program. The observed results are illustrated in Figure 7.

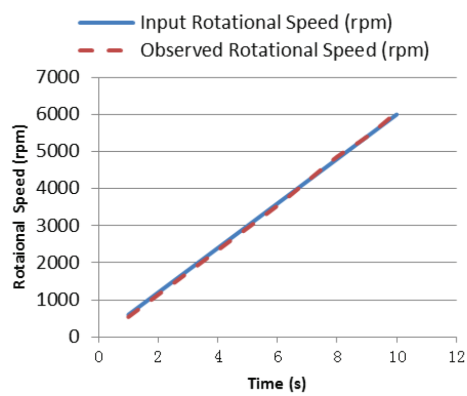

Figure 7: The Comparative Result of Input Rotational Speed and Observed Rotational Speed

Figure 7 shows that the observed rotational speed value was almost the same as compared to input rotational speed value. Thus, it proves the performance of the programmed codes together with its algorithm matches well even for very high rotational speed measurement while being able to generate smooth and well squared waves even by employing proximity sensor. However, there is an existence of slight deviation which probably due to the way the frequency was observed.

IV. Experiment Setup

A special test rig was designed in order to test the accuracy of the proximity sensor in the rotational speed measurement. Figure 8 shows the experimental set-up of the test rig which was designed to investigate the sensor performance before it can be employed for machine maintenance environment.

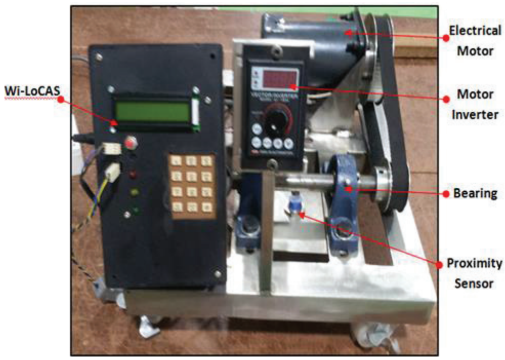

Figure 8: A Custom Made Testing Rig Using an Ac Motor for Proximity Sensor Performance Validation in Rotational Speed Measurement

The experimental investigation was initiated by rotating the spindle of a 240V AC motor at different speed. The metal bolt (bulge) on the spindle which acts as the registration mark enables the proximity sensor to generate pulse when the spindle is rotating aligning in-line both of them together. Initially, the proximity sensor was switched on while the output of the sensor was connected to the microcontroller. As the spindle rotates, the square wave signal was observed generated well by the proximity sensor according the rotational speed of the spindle. The output signal from the proximity sensor was then sent to PORT A of the microcontroller. The results of the measurement was made to display on the LCD screen. The speed of the motor was gradually varied from 300 to 1800 rpm by an integrated inverter with the incremental of 300 rpm for each cycle. At the same time, the original revolutions were also captured to make a comparison study. The result displayed on the LCD based on proximity sensor performance was then compared for each speed continuously.

V. Results And Discussion

The gained experimental results are as shown in Figure 9, where the agreements between the comparisons were fine. This proves established system can actually benefit the industries to detect in many ways by employing a simple proximate sensor, even for high rotational speed.

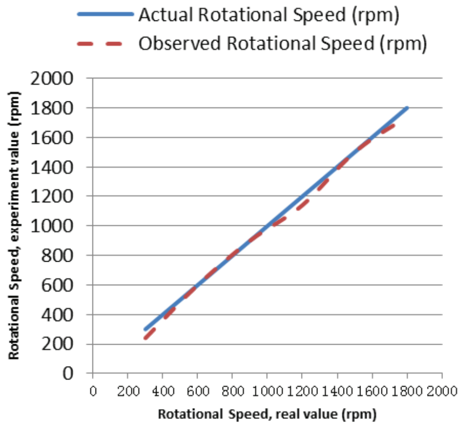

Figure 9: Experimentally Observed Rotational Speed by Proximity Sensor

The average relative error and the accuracy for analysis purpose are determined using Equation (5), (6), (7) and (8):

$$Error\ Percentage\ (\%) = \frac{actual\ value - observed\ value}{real\ value} \times 100\% \quad (5)$$

$$Average\ Error\ Percentage\ (\%) = \frac{Total\ Error\ Percentage}{Samples} \quad (6)$$

$$Accuracy\ (\%) = 100\% - Error\ Percentage \quad (7)$$

$$Average\ System\ Accuracy\ (\%) = \frac{Total\ Accuracy}{Samples} \quad (8)$$

Table 1 shows the readings of the comparisons of the actual and observed together with its accuracy level which were established using Eq. (5), (6), (7), and (8). The table's third column shows the error (in percentage), while the extreme right column shows the accuracy of the system based on the system performance validation result. The data sets reflect, most of the gained results proves that the accuracy of the proximity sensor in non-contact measurement rotational speed achieves almost 100%. This proves that the proximity sensor is reliable and much suitable for industrial applications, particularly for non-contact measurement rotational speed purpose. Another standing advantage of this sensor is that, even the two communicating surfaces are coated with grease or oil, it can still transmit signal. This is an added value, especially for industrial environment.

Table 1
Verification of Proximity Sensor Performance in Rotational Speed Measurement

Actual value (rpm)	Observed value (rpm)	Error (%)	Accuracy (%)
300	240	20	80
600	600	0	100
900	900	0	100
1200	1140	5	95
1500	1500	0	100
1800	1740	0.33	99.67
Average (%)		4.22	95.78

However, the trend of observed minimal errors could belong to random error type. This error is expected to be caused by the loss of pulses while measuring frequency as the value of the error is 60 rpm (equivalent to 1 pulse). The percentage of the error decreases as the rotational speed increases. This shows that the relative error can be reduced by increasing the measurement accuracy, if the rotational speed is increased via measuring frequency method.

The established system has been validated experimentally for detection accuracy, where the yield was 95.78% even at high speed spindle rotation proving the reliability of the system to be similar to the real machinery scenario. Therefore, the performance of the proximity sensor in this environment was proven with high degree accuracy results. These results show that the measurement of the rotational speed via non-contact measurement using the proximity sensor is direct and simple, and yet able to solve most problems faced by other approaches which may even be much expensive and not user friendly.

VI. Conclusion

An accurate, cost effective and flexible non-contact measurement method using proximity sensor was tested and validated in this paper. The initial function of the proximity sensor as a limit switch and micro switch is now successfully applied in rotation measurement purpose. After a series of experimental validations, the capability of the proximity sensor is proven on the rotational speed measurement method, resulting good order of accuracy. Therefore, it can be concluded that the approach is highly potential to be applied in any machinery application for measurement and control purposes. This comes to a good role, especially for maintenance alert system to ensure machines are well taken care for cost effective production without having too much of down time or lead time particularly due to machine break-down.

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