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RESEARCH ARTICLE

DEVELOPING LOW-COST TORQUE MEASUREMENT SYSTEM

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ABSTRACT. **Torque measurement is critical in industrial, experimental, and medical applications. Various methods for torque measurement have been introduced in the literature, and application-specific solutions have been developed. The present work proposes a hybrid method using a rotary encoder to measure angular displacement and challenges related to external light conditions and resolution limitations to overcome. Experimental setups demonstrate the system's ability to successfully measure rotary mechanisms' transient (starting and stopping) torque without noise, providing a cost-effective, numerically accurate solution. Experimental studies have shown promising results.**

1. INTRODUCTION

Electric motors are widely used as an environmentally friendly alternative to internal combustion engines in the vehicle industry, conveyors, cranes, and production machines in industrial production, refrigerators, washing machines, fans, and vacuum cleaners in household appliances, wind turbines, propulsion systems of spacecraft, medical devices, curtain, door, window control in smart home automation, drills and saws in electric vehicles [1]. Especially in industrial applications, motor torque measurements are needed for performance optimization by optimizing motor efficiency and output, preventing overload and damage by ensuring operation within safe limits, quality and consistency in production, and energy optimization. In addition, torque measurements are gaining importance for precise control in medical devices and aerospace applications.

Torque can be defined as the measure of the rotational force applied to an object about an axis [2]. Looking at the literature, various methods developed for torque measurement stand out. Mathematical simulation, dynamo-meter, Strain Gauge method, current and voltage measurement, optical methods, piezoelectric sensors, and hall effect sensors are the most widely used methods in the literature [3, 4].

Mathematical simulation is a cost-effective solution that does not require physical components and installation, enables safe testing under extreme conditions, and can model a wide range of scenarios and

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conditions [4, 5]. However, the results depend on the accuracy of the model and input data. In addition, unexpected real-world conditions are ignored.

The dynamo-meter is one of the most widespread methods because it offers direct physical measurement by connecting to the shaft of the motor, is applicable to a wide range of motors and machines, and provides reliable and repeatable results [6, 7]. However, it is more expensive than many other methods, requiring equipment, physical space, installation, regular maintenance, and calibration.

In the Strain Gauge method, a strain gauge is connected to the motor shaft, and the torque is calculated by measuring the stress in the motor shaft. It stands out with its high accuracy, precise measurement, and small size [8]. However, the disadvantages are that they are easily damaged, require careful installation and calibration, and are affected by environmental factors such as temperature and humidity.

In the current and voltage measurement method, torque is calculated by comparing it with the performance curves of the motor. As such, it is easy to apply and understand and is cheaper than other methods [7]. However, the fact that it requires calibration and works with less accuracy than direct measurement methods prevents it from being used in every field.

The advantages of optical methods are that they measure torque without physical contact, are suitable for high-speed applications, and allow highly accurate measurements. However, they have disadvantages such as more complex setup and calculations, more expensive compared to electrical methods, and being affected by external light conditions [9, 10].

Piezoelectric sensors generate electrical signals under mechanical stress and are used for torque measurement. The high-frequency response makes them suitable for dynamic measurements. Long-term stability in measurements, wide measurement range, and relatively small size are its advantages [11]. However, cost, sensitivity to temperature and vibrations, and the need for specialized and complex electronic circuitry for signal processing make it difficult to use.

The advantages of the Hall effect sensor are that it performs non-contact measurement, is robust against environmental conditions, and can be used in various applications [12], while its disadvantages are that it requires careful calibration, has a limited measurement range, is affected by magnetic fields and its performance changes with temperature.

The proposed method uses a rotary encoder to overcome issues with external light conditions and resolution limitations. The system provides an effective measurement of starting and stopping torque, offering an accurate, cost-effective solution. The disadvantage of the presented method is that it needs an inertial moment of the system.

2. Related Work

In previous studies, there are applications where existing methods are customized according to the application. In the study presented by Ashwindran et al., an Arduino-based system was developed to measure the torque of wind turbines [13]. The system consists of two subsystems, including a photo interrupter (primary) and a load cell (secondary). The developed system has been tested in both laboratory and simulation environments and has been shown to provide reliable results. The study is proposed as a cost-effective solution for the measurement of rotating machine torques.

Brusamarello et al. presented a system mounted on an aluminum alloy wheel for automotive applications [14]. In the developed system, the signal received from the strain gauge is amplified and filtered, and then analog-to-digital conversion is performed and sent to a remote computer via the ZigBee transmission module. The first dynamic tests of the system calibrated with static loads were performed under flat road conditions.

Bayraktar and Güldaş presented a study on the measurement and optimization of thrust and torque forces in unmanned aerial vehicles, especially quadrotors, and applied regression analysis in Matlab/Simulink environment to experimental measurements to minimize errors in trajectory tracking [15]. According to the results of the study, cubic and quadratic force equations give better results in trajectory tracking than other methods. The device sold by Surkon Makine Ltd. has been developed to measure the opening torque of bottle caps [16].

Caruana et al. presented a torque measurement system for use between the crankshaft of an internal combustion engine and an AC motor. A fully blind strain gauge and an electronic amplifier are used in the study. In the developed system, data acquisition can be performed up to 40 kHz by writing to an SD card via an Arduino board. The system was experimentally calibrated and mechanically tested up to 3000 rpm with no data loss [17]. This paper has shown that a low-cost system can be developed to measure torque between internal combustion engines and AC motors.

In the study presented by Sutyasadi, it was aimed to develop an effective control algorithm using a low-cost controller such as Arduino for the control of an aluminum robot arm that can be used in education due to the high cost of industrial robot arms [18]. In this study, computational torque control, PID, and cascade PID control were used to control the shoulder joint of the robot arm. According to the results obtained, computational torque control showed better results than PID and cascade PID control algorithms.

In the reviewed studies, measurement systems are designed according to the area of use and purpose. In this study, we focus on the development of a low-cost system to measure the torque of asynchronous electric motors at start-up.

3. Methodology

Indirect torque measurement methods can be realized in different ways depending on the specific situation and the available means. One is by measuring the angular displacement or rotational speed of the shaft. This information is then used to calculate the torque from the moment of inertia equation.

In the present work, a hybrid method is proposed. Since optical systems are affected by external light conditions and have low resolution, the angular displacement information is measured with a rotary encoder. The encoder generates 1024 pulses at one revolution. The encoder used is shown in Figure 1 (a).

Accordingly, the total angular displacement between two pulses is calculated as $2\pi/1024$ radians. The encoder has a 3-channel output, and accordingly, the pulse sequence from channels A, B, and Z can also provide information about the direction of rotation of the motor if necessary. Figure 1 (b) shows the relationship between the output information of the channels and the period.

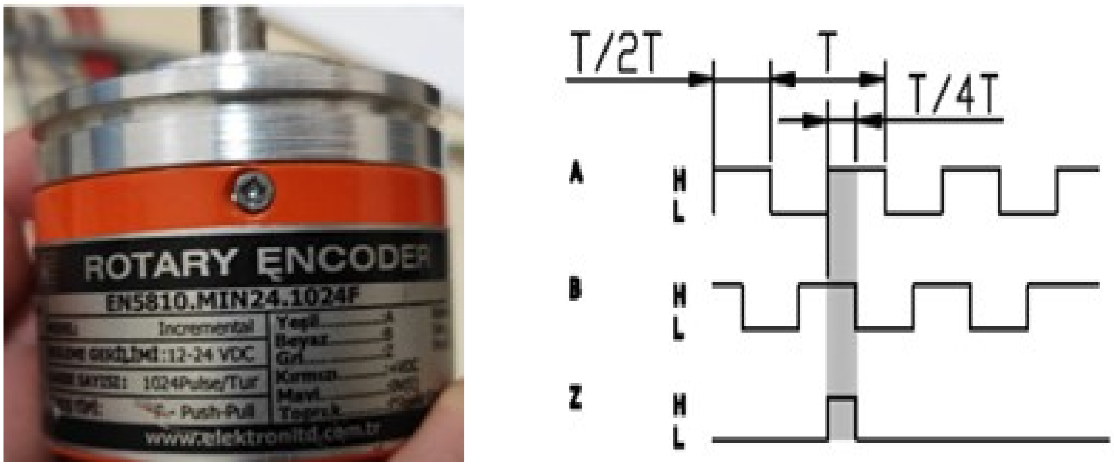

FIGURE 1. **(a). Used rotary encoder, (b) Output pulses and period relation for A, B and Z channels respectively.**

Angular velocity is defined as the change of angular displacement with respect to time and is defined in Eq. 1.

$$\omega = \frac{d\theta}{dt}. \tag{1}$$

The unit is radians/second, where ω (omega) represents the angular velocity. When the starting or stopping torque of an electric motor is to be calculated, the speed is variable. For this reason, the times of logic 1 and logic 0 outputs from channel A or B allow the motor speed to be calculated. Figure **??** shows the angular displacement and speed. In the SI unit system, the unit of angular path is radian and denoted by θ.

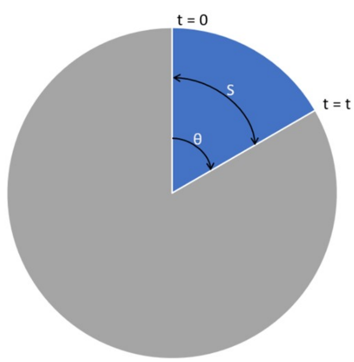

FIGURE 2. **Angular displacement.**

The relation between rotation and radian is given in Eq.2. 1 radian is defined as the central angle on a circle with an arc length equal to the radius, and Eq. 3 defines it.

$$\text{rotation} = 2\pi \text{ radian}, \tag{2}$$

$$\theta = \frac{S}{R}, \tag{3}$$

When the angular velocity is not constant, the rotational velocity variation depends on the rotational moment (torque) acting on the body in circular motion. The change of angular velocity with respect to time is defined as angular acceleration defined in Eq. 4 and denoted by α;

$$\alpha = \frac{d\omega}{dt}. \tag{4}$$

The relationship between angular velocity and torque is expressed by Eq. 5;

$$\tau = l * \alpha, \tag{5}$$

where τ is the torque, I is the moment of inertia and α is the angular acceleration. The moment of inertia measures a body's resistance to rotational motion. The moment of inertia is calculated depending on the geometry of the body and the position of the axis of rotation. For example, the moment of inertia of a cylinder or disk is calculated according to Eq. 6:

$$l = \frac{1}{2}mr^2, \tag{6}$$

where I is the moment of inertia, m is the mass of the cylinder and r is the radius. For bodies with more complex geometries, the moment of inertia is calculated using integration.

Considering the 16 MHz clock speed of the Arduino Uno, it is concluded that a processing cycle is completed in approximately 62.5 nanoseconds. However, considering that the response time of a digital input is completed in 3 processing cycles, a sampling frequency of approximately 5 kHz is obtained. In this case, the times of each logic 0 and logic 1 pulses at the encoder output can be detected fast enough. The flowchart of the algorithm for the measurement software of the designed system is given in Figure **??** in the appendix.

Then, from the sequential information received from the serial port, the period torque is calculated in the computer environment with the angular velocity, angular acceleration, and moment of inertia information obtained from the steady state of the system. The data taken from the serial port is saved as a CSV file and processed in Matlab. In addition to this, the data can be processed using Arduino. Since the data processing process is done after the measurements are completed, it will not pose any problems in terms of performance. This study setup is prepared for just measuring transient torque.

4. RESULTS AND DISCUSSIONS

The connection diagram of the designed system is given in Figure 3. When the existing 1.1 kW asynchronous motor is driven from the line and loaded with a Foucault brake via coupling connection, the speed of the motor can be read optically via a 4-leaf encoder, and the torque generated can be read from the indicators on the control panel via the load cell. However, the measurement system on the control panel cannot perform the relevant measurements due to insufficient response speed in situations where the torque changes dynamically and very quickly, such as starting and stopping.

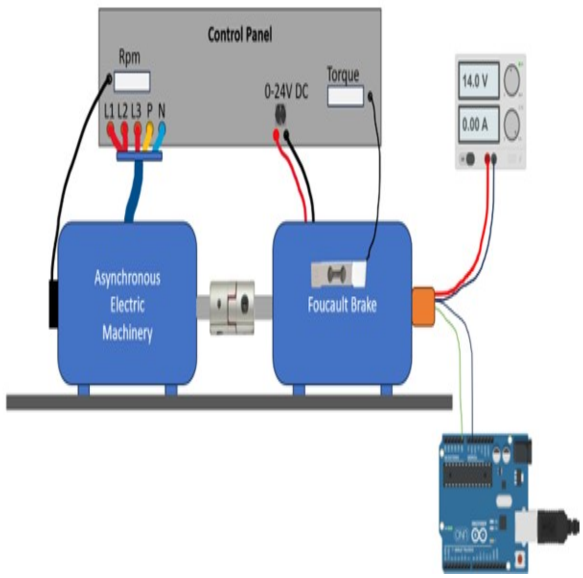

FIGURE 3. **Designed measurement system schema with real system.**

The bearing and coupling, whose design is shown in Figure 4, was produced on a 3D printer, and the 1024 pulse/revolution encoder shown in orange in Figure 2 was connected to the existing system. The encoder was fed externally with 14 V voltage, and the output was adapted to the 0-5V range with a voltage divider. It was tested separately on Arduino Uno and Mega boards. In cases where the system is required to react very fast, the measurements are saved in the microcontroller's volatile memory to minimize the error that may be caused by delays.

The moment of inertia of the existing system was determined experimentally. The steady-state torque of the system is measured and displayed on the panel via the load cell on the Focault brake. Therefore, the ratio of the torque measured on the panel to the acceleration measured by the 1024 pulse/rotation encoder gives the inertia value of the system. For this purpose, the angular path, velocity, and acceleration were calculated from the encoder, and the steady-state torque was found by proportioning it to the value on the control panel.

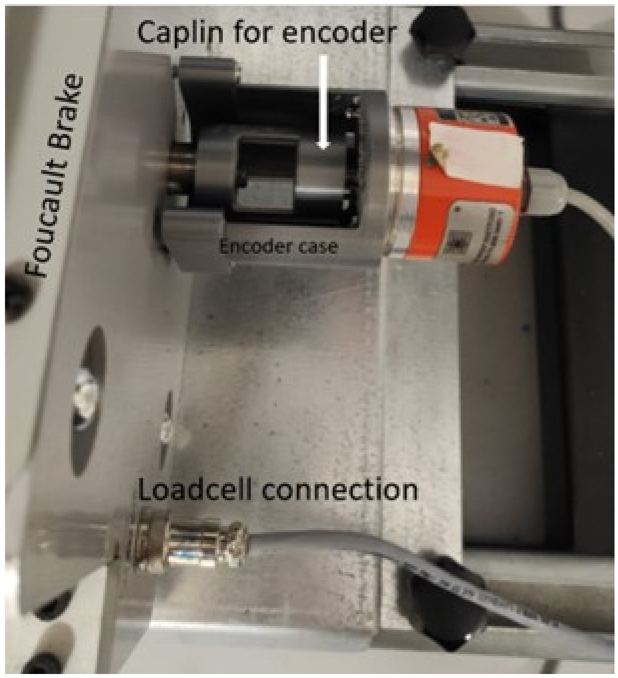

FIGURE 4. **Incremental encoder with foucault brake and connections.**

5. CONCLUSION

The moment of inertia is a measure of an object's resistance to changes in its rotational motion. It plays a crucial role in calculating torque in systems such as electric motors. Typically, it is determined experimentally due to the complexity of theoretical calculations, which may not account for all real-world factors.

Various methods for torque calculations are available in the literature, and a simple comparison of these methods is provided in Table 1.

With the system developed and successfully tested, the transient (start and stop) torque of rotary mechanism systems can be measured silently and successfully. With the proposed method, performance data of electric motors can be realized in a noiseless and numerical way that is cost-effective. The disadvantage of the system is that it requires calibration for measurements of systems with unknown moments of inertia.

The work in [6] has examined some of the situations that cause erroneous results in torque measurement systems. Accordingly, the use of data mining and machine learning methods to analyze the signals obtained in a steady state and to detect possible errors will be discussed in future studies.

TABLE 1. **Comparison of methods for determining moment of inertia**

Method	Advantages	Limitations
Pendulum Method	Simple setup, easy to conduct, good for basic shapes.	Accuracy depends on precise timing and knowledge of center of mass.
Rotary Motion Sensor Method	Precise measurements, suitable for complex shapes, direct data acquisition.	Requires sophisticated equipment like rotary sensors.
Torsional Oscillation Method	Good for symmetrical objects, directly uses torsional properties.	Requires knowledge of the spring constant, precise timing.
Angular Impulse and Momentum Method	Directly uses conservation of angular momentum, good for frictionless environments.	Requires a near-frictionless environment, sophisticated measuring tools.
Acceleration Method Using Known Masses	Flexible for different configurations, measures effect of added masses.	Needs precise measurement of angular acceleration, accurate force application.

DECLARATIONS

- **Conflict of Interest:** The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

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APPENDIX

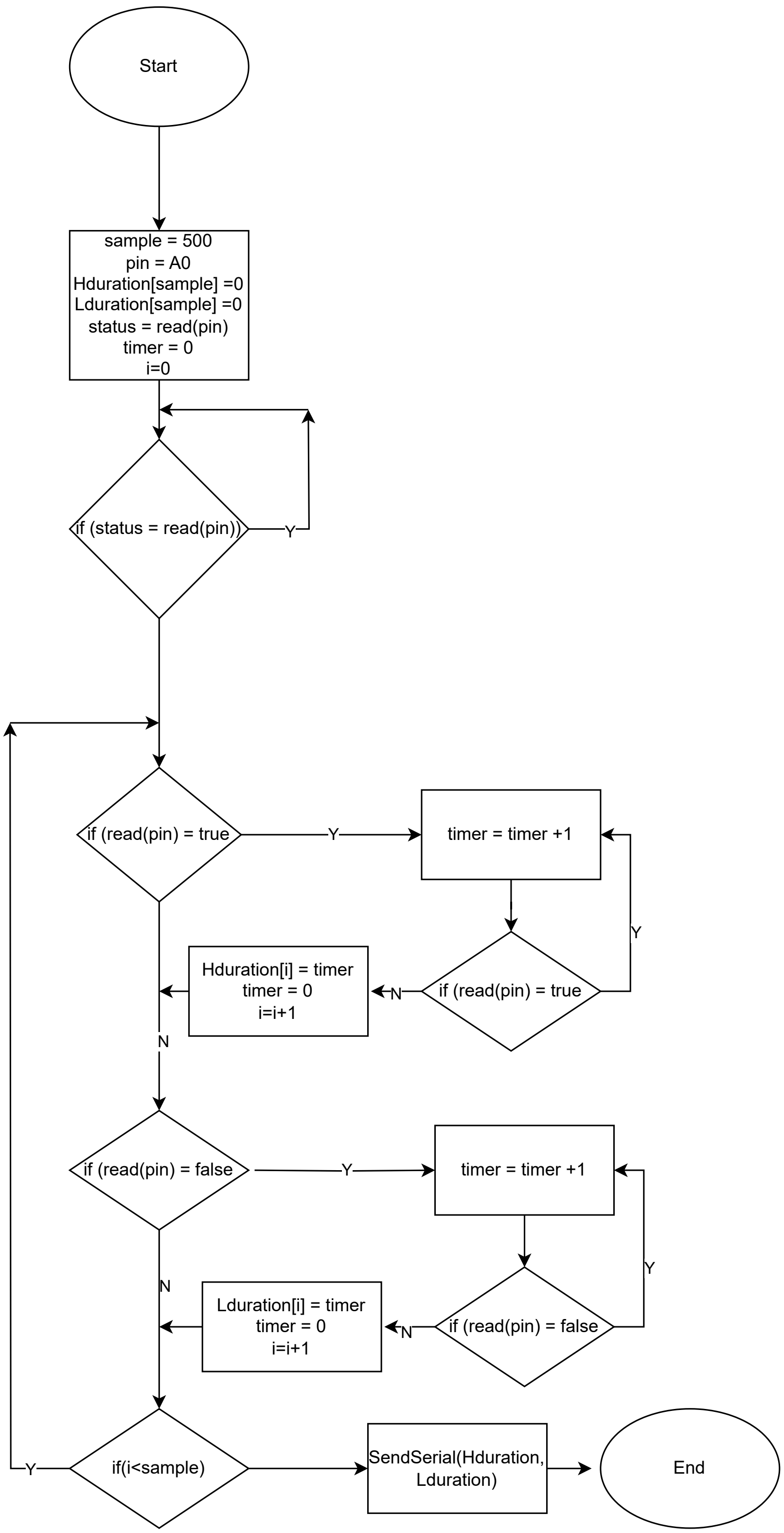

FIGURE 5. Flowchart for algorithm.