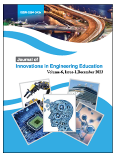

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Institute of Engineering
Tribhuvan University

Design, construction and performance analysis of dynamic torque transducer

Dipesh Karki[a,*], Hari Bahadur Dura [a] and Laxman Poudel [a]

[a]*Department of Mechanical and Aerospace Engineering, Pulchwok Campus, Institute of Engineering, Tribhuvan University, Lalitpur, Nepal*

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Abstract

Most of the dynamic torque measurement devices present are not easy to afford and accurate for higher shaft speed, at the same time, especially in case of Micro-hydropower stations where dynamic torque fluctuates and requires constant monitoring. To fulfill the lack of standard devices, this project concentrated on fabricating non-contact torque transducer devices using easily accessible materials. The project primarily focuses on developing electronics and mechanical systems required to measure dynamic torque. Hollow Aluminum shaft is taken as a torque transducer specimen with a coupling facility. A strain gauge is attached with the specimen shaft in the Wheatstone bridge arrangement such that the strain gauge produces an electrical signal while the shaft experiences strain. Arduino NANO as an I/O device, HX711 ADC module as a signal amplifier, HC05 as a Bluetooth module for wirelessly measured data communication. For calibration, torque is applied to the specimen by coupling it with motor-generator dynamic torque measurement apparatus (DL 10055ETM) which is manufactured by DE LORENZO. Linear regression is used to predict the value of applied torque. The experimental data obtained using the proposed torque transducer prototype has made it clear that it is possible to measure and analyze real time digital data of dynamic torque produced on specimen shaft rotating in high speed, wirelessly, using locally available resources.

1. Introduction

Product quality is determined by using one of the very important physical parameter, torque. Torque measurement plays a vital role in all rotating bodies, which can be applied for rotating shafts in most of the devices. Magnitude of the Torque is calculated with parameters such as angle of twist, shear stress, force and displacement [1] [2]. Two main reasons behind wide application of torque measurement include, mechanical power control in industries and improvement of load values in deflection analysis. While designing rotating systems, these values prove vital to ensure acceptable and appropriate capacity of system so as to avoid failure due to shear stresses arising from applied torque [3].

Static and Dynamic torque are two categories in which torque measurement can be classified. If Dynamic and Static torque measurement are compared, the latter is relatively easier since the measured shaft or axle is static, whereas the shaft or axle is rotating during measurement of dynamic torque [4].

Torque measurement sensor is a type of transducer, specifically a torque transducer that converts a torque measurement (reaction, dynamic or rotary) into another physical variable. Such sensors can be categorized as shown in Figure 1 [4].

It is difficult to measure the torque in rotating shaft. In frequently used strain gauge type torque transducers it is challenging to receive the signals from the attached strain gauges [3]. Hence, to transmit power or signal between the rotating strain gauge and the stationary signal receiver, slip rings are used [3]. Measuring torque on a rotating shaft using strain gauges with slip rings is effective only when the gauge is operated in a low-to-moderate rotating speed. Higher rotating speeds will severely degrade their performance.

Hence in this case, the torque effect is modulated into some form of electric signals, using strain gauge glued with shaft in Wheatstone bridge pattern that can be mea-

*Corresponding author:
carkey.dpsh03@gmail.com (D. Karki)

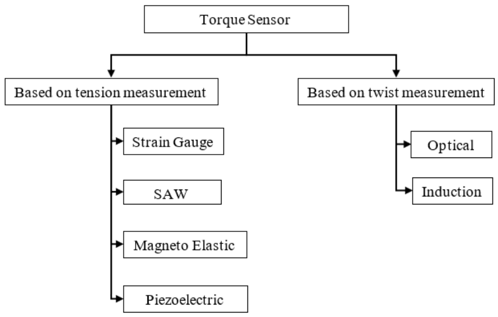

Figure 1: Classification of torque measurement sensors

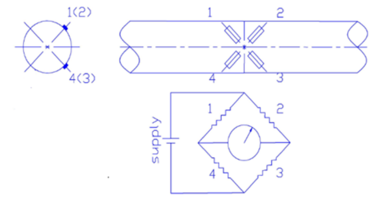

Figure 2: Alignment and connection of strain gauge to glue on the shaft (Strain gauge 1 and 3 are compression and Strain gauge 2 and 4 tension during the clockwise rotation shaft)

sured, converted and standardized. Signals from the rotary shaft are transmitted via wireless technology, to static system [3].

Power output form Micro hydro power plants ranges from 1KW to 100KW, the speed of turbine shaft can go up to 1500RPM and torque produced on the shaft ranges from 1 Nm to 600 Nm [5]. Dynamic torque measurement makes it easier to analyze power plant performance and provide a basis for automatic feedback system during its working condition. Due to their high cost, it is difficult to afford dynamic torque measurement devices available in market and hence many micro hydro plants are installed without the device. To fulfil this lack, a prototype Strain Gauge type Non-Contact Dynamic Torque Transducer has been fabricated, which is economical and easier to install.

The main goal of the work presented in this paper is to propose a strain sensor based torque transducer for measuring dynamic loading on a rotating shaft. This torque transducer provides live frequency output signal, for transmitting in-operation torque measurement. In this research, a prototype for dynamic non- contacting torque transducer for micro hydro has been proposed.

2. Research methodology

2.1. Experimental Setup

Strain gauge is a type of sensor that convert mechanical effect into an electrical signal. For this experiment, BF350-3 AA resistive strain gauges sensor have been used. 6463 aluminum was selected as torque transducer shaft material for this experiment. Strain gauge is affected by the change in temperature which will produce error on measurement. To overcome such type of error Wheatstone bridge aided to gain accurate measurement [6]. The shaft has 30mm outer diameter, thickness 3mm and 120mm length. Four strain gauges (R1, R2, R3 and R4) are attached to the rotating shaft in the form of a Wheatstone bridge circuit [2] [7]. They are adjusted precisely at 45 degrees with the shaft axis in opposite directions, as shown in Figure 2. When torque is applied to the shaft, the shaft gets twisted to the direction of rotation, thereby producing shear strain. This causes elongation in one gauge pair along opposite direction and compression in other gauge pair along opposite direction [1]. These changes in the strain gauges lead to an increase in the circuit resistance due to tensile strain produced by one pair of gauges and a decrease in the circuit resistance due to the compression strain produced by the other pair. This results in an unbalanced bridge, which produces an electrical output corresponding to the applied torque.

The output voltage from bridge can be deduced from

$$\frac{dV_0}{V_i} = \frac{R_4 dR_3 - R_3 dR_4}{(R_3 + R_4)^2} + \frac{R_1 dR_2 - R_2 dR_1}{(R_1 + R_2)^2}$$

Where R_1, R_2, R_3, and R_4 are resistance of glued strain gauge respectively. Here, $R_1 = R_2 = R_3 = R_4$ and $\frac{dR}{R\varepsilon} = k$ (gauge factor).

$$\frac{dR}{R} = k\varepsilon$$

Where,
ε = strain, and k = gauge factor of strain gauge.
By match resistance of strain gauges, the resistance of each bridge leg is balanced and if gauge factors are assumed identical, bridge sensitivity can be deduced from

$$\frac{dV_0}{V_i} = \frac{k}{4}(\varepsilon_3 - \varepsilon_4 + \varepsilon_2 - \varepsilon_1)$$

where $\varepsilon_1, \varepsilon_2, \varepsilon_3$, and ε_4 are the strains associated with strain gauge 1, strain gauge 2, strain gauge 3, and strain gauge 4, respectively. Strain on the glued strain gauge is directly proportional to the applied torque. The change in voltage is measured due to strain on the strain gauge, which is indicative of the applied torque. Applied torque is calculated by calibrating the change in the output voltage.

Stationary, serial monitor is used to acquire voltage signal produced by glued strain gauge as a result of applied torque. Produces voltage signal is transmit to 24 bits HX711 analog to digital convertor [8]. These converted digital signal is transfer to Arduino Nano and further signal is communicated with serial monitor wirelessly via HC05 Bluetooth module. Shown in Figure 3 is constructed transducer for dynamic torque measurement. Coolterm is use as the serial monitor to receive and store the signal data for performance analysis and for calibration. After calibrating the output signal, applied torque was measured [9].

Figure 3: Dynamic torque transducer (constructed in this research)

2.2. Circuit design

During the torque measurement an output voltage from connected Wheatstone bridge is analog signal with low value. HX711 ADC (analog to digital converter) strain booster is used. It has 24 bit resolution which means it can assign the input sensed voltage in the range of 0V-5V to respective value in the range 0-16777216, which means it can detect voltage changes as small as 0.298 μV [10][11]. In this experiment, the data is received in rotating condition. The circuit is held safely on the rotating shaft. For wireless communication, the Bluetooth module (HC05) is connected with Arduino. HC05 Bluetooth module has six pin available. In Bluetooth module, Vcc and GND pins are used for power supply to the module and RX and TX pins are used to receive and transmit data. The RX pin has to be connected to TX pin of Arduino and TX pin has to be connected to the RX pin of Arduino [12] [13].

Arduino is used as a data input and output device. The power is supplied to the circuit using a 9V battery. Arduino operates on 5v, hence 7805 Voltage regulator and capacitor are used [12] [13]. HC05 module has an internal 3.3v regulator. So, here resistance division circuit has to be used (5v to 3.3v) between Arduino TX pin and module RX pin using 1kΩ and 2kΩ resistor [13].

Required components connection diagram is shown in Figure 4. The complete circuit is made on a Printed Circuit Board.

For the torque transducer the electronic components

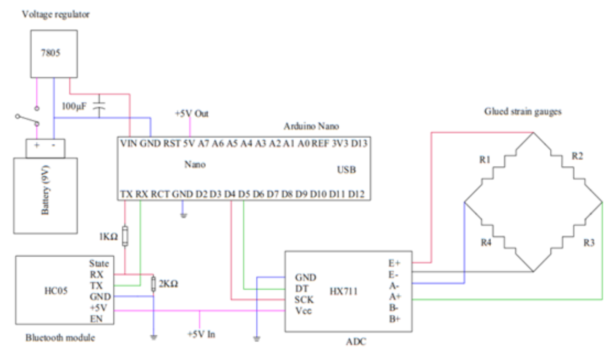

Figure 4: Design of torque transducer electronics circuit diagram for electrical signal amplify and wireless signal communicate

rotate along with the shaft, thus the electronics components fixed in such a way that they continuously transmit data to stationary serial monitor. The electronic components are wired in PCB board and this board is fixed into suitable sized box. The orientation of the portable type of transducer aligns the electronics component into the box such a way that centrifugal force helps to tighten the pin while the box is rotating. The constructed torque transducer electronics is shown in Figure 5. The box had facility to hold battery, to power the Arduino.

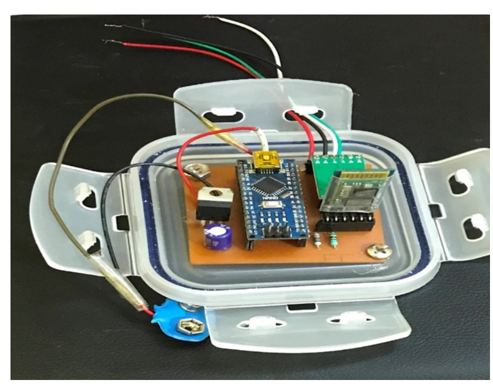

Figure 5: Fabricated torque transducer electronics (connection as the Figure 4 and bolted to top of the transducer electronics box)

2.3. Calibration

The dynamic torque measurement setup is available in Trivuban University, Institute of engineering, Paschimanchal Campus, Pokhara, Nepal. Here grid-connected induction generator (DL 2062 N) and induction motor (DL 1022/4) is used to calibrate the transducer which is shown in Figure 6. Both generator and motor have been manufactured by DE LORENZO. Motor shaft speed can be varied up to 1500 rpm and shaft torque can be varied in the range of 0 to 10 Nm [14]. A 6463 aluminum hollow shaft (outer diameter 30mm, thickness 3mm and length 120mm) with glued strain gauge as torque transducer is coupled between the induction motor and generator. Electronics components are aligned and fixed on the shaft as shown in Figure 6. At different RPM, torque is applied gradually to the rotating shaft producing strain on both shaft and strain gauge. These strain signals are transmitted to a stationary serial monitor via the HC05 module wirelessly. The strain value is obtained in amplified digital form and these signal values can be used to calculate torque on the shaft. Hence, torque is derived from the calculated strain value on the shaft.

Strain signal, upto 20 sample data, is logged in every

Figure 6: Torque transducer couple for calibration

three second for particular torque and RPM. Average strain is calculated for 100 samples of HX711 ADC output data as a result of applied torque, for a particular torque. Applied torque for particular Arduino response is measured on dynamic torque measurement setup. Linear regression is performed to average strained value and known applied torque which is plotted on the Figure 7. After calibration is completed the transducer will operate on calibrated relation to measure the unknown applied torque. The strain gauge type of torque transducer is affected by different factors such as transducer shaft mechanical properties, and environmental conditions so this transducer must calibrate when required and also electronics component also calibrates to different conditions.

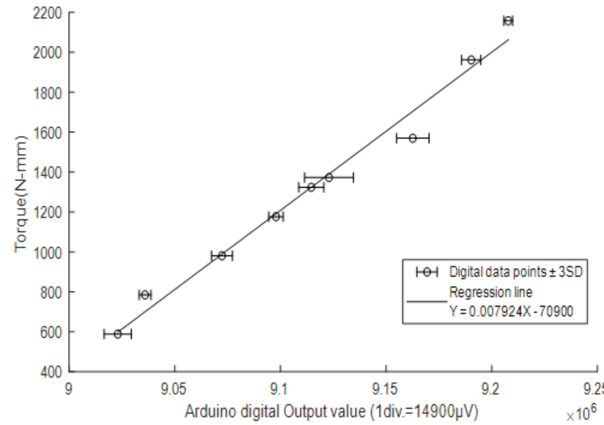

Figure 7: Applied torque vs HX711 output (HX711 is 24 bit analog to digital converter it assign the input sensed voltage in the range of 0V-5V, map to digital value to respective value in the range 0-16777216)

2.4. Torque transducer for micro hydro

Micro Hydropower are designed to produce power enough to fulfil energy needs of small population and the reason that most of the micro hydro projects do not require creation of dams or any flow controlling mechanisms, it becomes difficult to measure and monitor mechanical power output of turbine while shaft is rotating. More than thousand micro hydro power plants have been successfully installed all over Nepal and most of them are still working but with lower efficiency. Most of these turbines are fabricated in Nepal. Dynamic torque transducer is required for performance analysis of turbine and generator during installation and working condition. Non-contact type of dynamic torque transducer makes it easier for continuous performance analysis of turbine and generator, with its inline arrangement, easy installation and smooth data transmission. Since measured signals are transmitted via Bluetooth connection, this torque transducer is both economically and structurally feasible for micro hydro plants. Torque transducer can further prove its application for setting feedback mechanism, Guide for maintenance and operating micro hydro plant in higher efficiency. The alignment of transducer is shown in Figure 8. In this research mainly focused to construct the dynamic torque transducer with reasonable cost and torque range for micro hydropower of Nepal. The data obtained from the prepared torque transducer is real time and accessible digital data, which makes it easier to analyze the data, perform real time calibration and further integrate with feedback system. To measured dynamic torque for micro hydro, factory cost of dynamic torque transducer used for Micro-Hydro application is more than one hundred thousand excluding border cost, transportation cost etc. The total cost for constructed torque transducer in this research is totaled at twenty thousands. Designed types of torque transducer in this research will be suited for Micro-Hydro application both technically and economically.

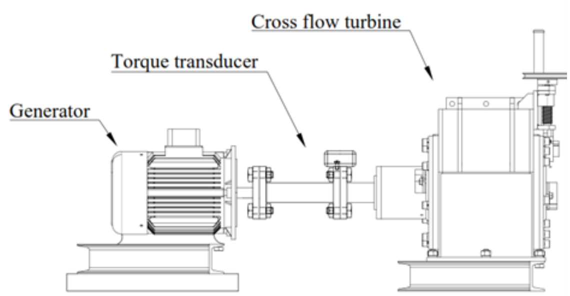

Figure 8: Schematic digram of dynamic wireless torque transducer alignment for microhydro powerplant

3. Results and discussion

3.1. Response of average Arduino digital output value on different rpm

Figure 9 shows RPM vs Average Arduino output. Here by applying 589Nmm torque, three experiment at different RPM are performed. Similarly, three experiments are performed at 785Nmm torque and 981Nmm torque. In ideal case these strain value must be same at different rpm and constant torque applied. But it is observed that in every experiment there is variation of strain value. The graph shows that the variation pattern of strain values is in same direction at different torque values i.e. in second torque application (785Nmm) the value decreases similar to first experiment and same thing happens in third torque value (981Nmm). In this graph the variation of Arduino value percentage is maximum at 785Nmm torque. The maximum variation is 0.33 percentage.

3.2. Torque transducer performance testing

From Figure 6, it can observed that produced electrical as a result of applied torque linearly varies with R square value, 95% on this experiment. This linearity relation is mostly affected by the stress-strain behavior of the transducer shaft. The repeatability of the electrical signal also depends on different parameters such as RPM, temperature, torque range, torque varying frequency and reliability of the electronics component, etc. For reliable measurement, this torque transducer has calibration option. For calibration, known torque needs to be applied

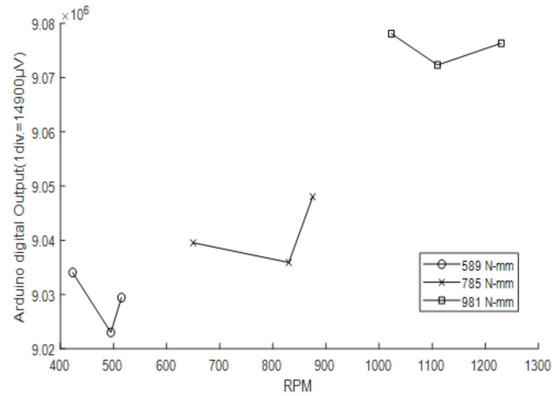

Figure 9: Arduino average digital value output at different RPM (performance testing on different RPM for particular torque)

only thereafter transducer electronic system is able to develop regression relation to measure the unknown torque. The data shown in Table 1 is torque transducer reading as received wirelessly by Bluetooth terminal HC05 application on Smartphone. DE LOLENZO torque is calculated by multiplying mass with required rod length, (determined by observing scale present on the rod), to balance the produced torque. Deviation between transducer torque and DE LORENZO torque is calculated with DE LORENZO as base torque. Ten experiments are performed for 650Nmm to 4905Nmm Torque which suggested -4.38 to 5.06 percentage deviation from DE LORENZO torque.

4. Conclusion

The consistency in data obtained during the project proved that it is possible to measure dynamic torque at higher rotational speed using locally available resources. The data obtained from the prepared torque transducer is real time and accessible digital data, which makes it easier to analyze the data, perform real time calibration and further integrate with feedback system. Locally available resources used in torque transducers do not provide highly accurate and precise data for measurements demanding standard data. Further, the stress-strain behavior of the transducer shaft affects the repeatability of measurement and the available calibration machine also includes errors due to vibration on the machine while rotating at high speed. Hence, this torque transducer comes with higher error margin. Further, the calibration frequency of prepared torque transducer device is higher.

Table 1: Performance testing of constructed torque transducer

SN	Transducer Torque (N-mm)	DE LORENGO Torque (N-mm)	Deviation
1	675	650	3.85
2	1009	981	2.85
3	1416	1471	-3.74
4	1876	1962	-4.38
5	2394	2452	-2.36
6	2873	2943	-2.37
7	3302	3433	-3.82
8	4113	3924	4.82
9	4595	4414	4.1
10	5153	4905	5.06

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