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Design, Construction and Performance Analysis of Dynamic Torque Transducer

by

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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. To fulfil the lack of standard device, this research concentrated on fabricating non- contact torque transducer device using easily accessible materials. The research primarily focuses on developing electronics and mechanical systems required to measure dynamic torque. Hollow Aluminum shaft is taken as torque transducer specimen with coupling facility. Strain gauges are attached on surface of specimen shaft in Wheatstone bridge arrangement such that strain gauge produce potential difference while the shaft experiences strain. Arduino NANO as I/O device, HX711 ADC module as signal amplifier, HC05 as Bluetooth module for wireless measured signal communication. For calibration, Torque is applied to specimen by coupling it with motor generator dynamic torque measurement apparatus (DL 10055ETM) which manufacture by DE LORENZO. Linear regression is used to predict value of applied torque. The torque transducer device is calibrated by applying different torque value under variable rotational speed of shaft. Consistency of data under varying speed for a particular torque is analyzed by plotting the data obtained during calibration, in graph. For a particular rotational speed and applied torque, strain signal transmitted by Bluetooth module of Arduino arrangement is recorded and obtained values are plotted in graph against applied torque. Linear approximation of the obtained relation, in MATLAB software, gave calibrated relation between torque and strain gauge sensor signal.

Measurement of dynamic torque at high rotational speed, using locally available resources was deemed possible based on consistent data received during the project implementation. 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.

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CHAPTER ONE: INTRODUCTION

Torque is a vital physical factor that plays a major role in determining the quality of a product. According to Figure 1.1, torque can be simply defined as measurement of the forces that act to rotate an object.

The object rotated about an axis, which is called the pivot point O, when subjected to a force, F. Moment arm can be defined as the distance ‘r’, between the point where force acts and the pivot point, and ‘r’ is a vector quantity. Magnitude and direction of Torque can be calculated by Eq. (1) (F.P. Beer, 1992). Torque is measured in N-m which is equal to torque produced when 1N force is applied on a point at distance r from pivot (F.P. Beer, 1992).

Both dynamic and static torque measurements can be explained by this definition. In general, torque can be defined as:

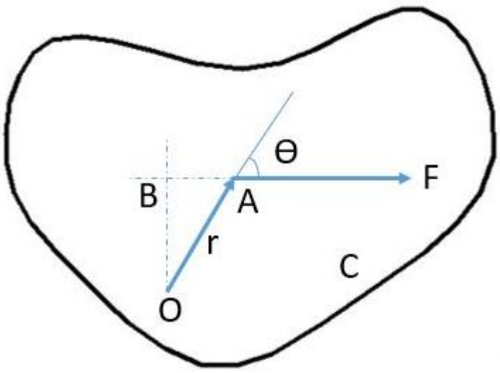

Figure 1. 1 Definition of torque

$$\vec{T} = \vec{r} * \vec{F} \qquad (1)$$

In the one dimensional case

$$\vec{T} = \vec{r} \cdot \vec{F}\mathrm{Sin}(\theta) \qquad (2)$$

Where,

θ = Angle between the r (position vector) and F (force vector)

Torque can be calculated in the case of a shaft with power (P) and rotating with angular velocity (ω), using formula;

$$T = \frac{P}{\omega} \qquad (3)$$

Simply multiplying force and length does not completely define torque and this statement begins an actual step towards metrology to suitably deal with right calibration and measurement of torque. A new field in metrology, measurement equipment for standard torque and its traceability, started in late 1900s.(Khaled, 2016). In the first part, length and force measurements are two different issues of metrology; each of which has its own difficulties and problems. In second case, when they are collective for torque measurements, new problems and troubles rise.

When a shaft is subjected to a torque or twisting a shear stress is produced in the shaft. Shear stress differs from zero in the axis to maximum towards outside shaft surface.

In solid circular shaft, shear stress in a given position can be deduced from:

$$\tau = T\frac{r}{J} \qquad (4)$$

Where,

τ = shear stress, T = twisting moment

r = center to stressed surface distance at a given position

J = Polar Moment of Inertia of Area

When shaft is subjected on torsional moment, shear stress and normal stresses are occurs. Principle plane are the plane where shear stresses are minimum and the stress normal to principle plane is called principle stresses.

By the Mohr circle method equation of normal stress is

$$\sigma_{1/2} = \frac{\sigma_x+\sigma_y}{2} \pm \sqrt{(\frac{\sigma_x-\sigma_y}{2})^2 + \tau_{xy}^2} \qquad (5)$$

In pure torsion,

$$\sigma_x = \sigma_y = 0$$

Hence, the normal stresses are,

$$\sigma_{1/2} = \pm\tau_{xy}$$

When torques are applied to shaft's ends, normal stresses, σ, oriented at the ±45° directions reach the maximum value, numerically equaling to the maximum shear stress, τ_{max} while the shear stresses become trivial values (F.P. Beer, 1992).

1.1 Background

For a rotating system, the torque transducer or sensor is a device that measures the torque, which includes equipment such as turbine, grinder machine, power generation machines, or rotor. Static and dynamic torque measurements fall among the two general categories, torque measurement can be classified. The moment twisting a stationary object can be termed as measured toque in a static measurement system (M.Hilal Muftah, 2013).

In another case, object is rotated due to the applied toque in dynamic measurement system. Measuring toque in a static system deems easier than in a dynamic system. This is because for the latter, it is difficult to transmit measurement signal between rotating and stationary parts (Krimmel, 2022). Angle of twist, Force and displacement, power or shear stress can be used to obtain the torque magnitude. Improving load values in deflection analysis and controlling mechanical power for industrial purposes are the two main reasons for measuring torque. These values help in the design of rotating systems to ensure appropriate and acceptable capacity so as to avoid failure under shear stresses emanating from applied torque (Khaled, 2016).

A rotary torque meter or torque transducer measures torque in a rotating shaft. The rotary transducers sense torque with high-precision strain gages is mounted on or embedded in the rotating turbine shaft, these respond to shear forces with changing electrical resistance. When configured in a Wheatstone bridge arrangement, sophisticated electronics convert these signals into torque values (Morris, 2001).

Usually, either torque sensors or torque tools can be used to measure applied torque. Torque tools are generally found in workshop and those tools have primary function to assemble different parts by exerting suitable forces generated by screwing bolts and nuts. On the other hand, to check, sense and control the applied torque, torque transducers are used. The torque transducers are used in process control for calibration and checking fastening equipment such as powered torque drivers and runners (M.Hilal Muftah, 2013).

Power output from Micro hydro power plants ranges from 2KW to 100KW, the speed of turbine shaft can go upto 1500RPM and torque produced on the shaft ranges from 1 Nm to 600 Nm (Alternative Energy Promotion Centre, n.d.). Dynamic torque measurement makes it easier to analyze power plant performance and provide a basis for automatic feedback system during its working condition (Peter Sue, 2012). Dynamic torque measurement devices available in the market are difficult to afford due to their high cost, so many micro hydro plants do not constitute torque measurement devices. To fulfil this lack, a prototype Strain Gauge type Non-Contact Dynamic Torque Transducer has been fabricated, which is economical and easier to install.

1.2 Objectives

1.2.1 Main objective

The main objective of this research is to design, construction and performance analysis of dynamic torque transducer

1.2.2 Specific objective

The proposed research has following objectives

- Select and design components that can be used to construct the torque transducer.
- Calibration of the constructed torque transducer.
- Performance testing of the constructed transducer.

1.3 Problem statement

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. Hence, slip rings are to be used to transmit signal or power between receiver, which is stationery, and rotating strain gauge (M.Hilal Muftah, 2013). It is effective to measure torque on shaft rotating at low to moderate rotating speed using strain gauge since high rotating speed might severely degrade the performance (F. Hajdu, 2012). Further, in case of heavy duty application which continuously deal with extreme temperatures, vibration, dust and dirt, accuracy and reliability of output torque measurement might get compromised. Premature failure can be caused due to excessive vibrations and wear, as brushes used tend to have limited life. In same manner, electrical connections of slip rings and bushes can be affected by high temperatures, promoting corrosion. Slip rings provide limited dimensional flexibility for torque measurement. Since, commercial slip rings are expensive on their own the torque measurement becomes costly.

CHAPTER TWO: LITERATURE REVIEW

A torque sensor or torque meter can be defined as a device used for measuring and recording torque on a rotating system like bicycle crank, gearbox, rotor, crankshaft, transmission or engine. Torque measurement can be classified into two categories, static torque and dynamic torque measurements. For static torque measurement, strain gauge is applied to a shaft or axle as torque sensors or torque transducers in most common way (Goszczak, 2016). Static torque measurement can be carried out using simpler instrument arrangement, since the shaft or axle is at rest or uniform motion, as compared to dynamic torque measurement where shaft or axle is constantly subjected to acceleration or deceleration. Therefore, in case of dynamic torque measurement, the torque effect of rotary shaft is transferred to static system after converting the effect of torque into electric- or magnetic signals (M.Hilal Muftah, 2013).

Earliest technology involved measurement of torque using bridge circuits or strain gauges mounted on shaft specimen (Goszczak, 2016). The technology focused on measurement of voltage change produced by deformation of strain gages as a result of deformation of shaft due to applied torque. When the technology was developed slip rings were used to transfer the measurement signals of Strain Gauge Bridge present on rotating shaft (M.Hilal Muftah, 2013). Slip rings promised higher accuracy in low and moderate speeds but required to be monitored carefully for insulation faults in order to avoid measurement errors (Valentin Mateev, 2021).

Later on, torque sensor was introduced which used AC voltage and rotating transformer to facilitate better maintenance-free and stable signal transmission. With huge development of electronics, the signal noise and disturbances were minimized by using digital signals instead of classical analog signals and as the electronics components were far smaller they were attached directly to transformer (Lin, 2012). Recent development in torque measurement include apparatus enabled to measure both static and dynamic torque for larger frequencies. Using encoder belts and magnetic sensors the arrangement detects and measures the deformation on shaft due to applied torque. The technology is advanced, accurate and versatile.

Dynamic torque meter is usually used to measure the torque being transmitted between two machines in connection. There are several varieties of torque meter couplings, which are used for continuous on-line torque monitoring (Morris, 2001). Torque meter designs are faced with the task of detecting a physical change due to torsion in the coupling while the shaft is rotating. Therefore, the dynamic torque measurement is necessary to perform through no contacting means and get the torque information to a stationary output device via slip ring or wireless device (Goszczak, 2016).

2.1 Torque measurement

Torque measurement is fundamental importance in all rotating bodies and applies to the rotation of shafts in devices such as pumps, rotational cutting equipment, gearbox shafts, vehicle axles, and electric motors. Torque measurement is also a necessary part of measuring the power transmitted by rotating shafts like hydro turbine. For the dynamic torque measurement is more complex than static torque measurement. By measuring the dynamic torque at real time further it can use to design the feedback system.

2.1.1 Torque measurement methods

In general, torque measurement can be divided into two groups: direct and indirect measurement of the torque (Goszczak, 2016). Direct methods involve measurement of some physical values (usually elastic strain) which varies according to the torque value and after calibration value of Torque is directly given by detector (S.M, 2019) (M.Hilal Muftah, 2013). Whereas, indirect methods measure some physical values which can be used to calculate torque. For example, to calculate torque by determining physical values such as, force acting on arm whose length is known. The torque measurement methods are categorized as shown in Figure 2.1. Based on the direct toque measurement method there are different types of sensor used. For the toque measurement, different types sensors based transducers are used. Dynamic torque transducer sensors many divided into strain sense types and angle of twist sense types. The different type of torque transducers classification are shown in Figure 2.2.

For tension measurements, strain gauge, surface acoustics wave, magnetic elastic, piezoelectric, etc. type sensors are used to construct the dynamic torque transducer. For the twist measurement, optical and induction type sensors are used to construct dynamic torque transducers.

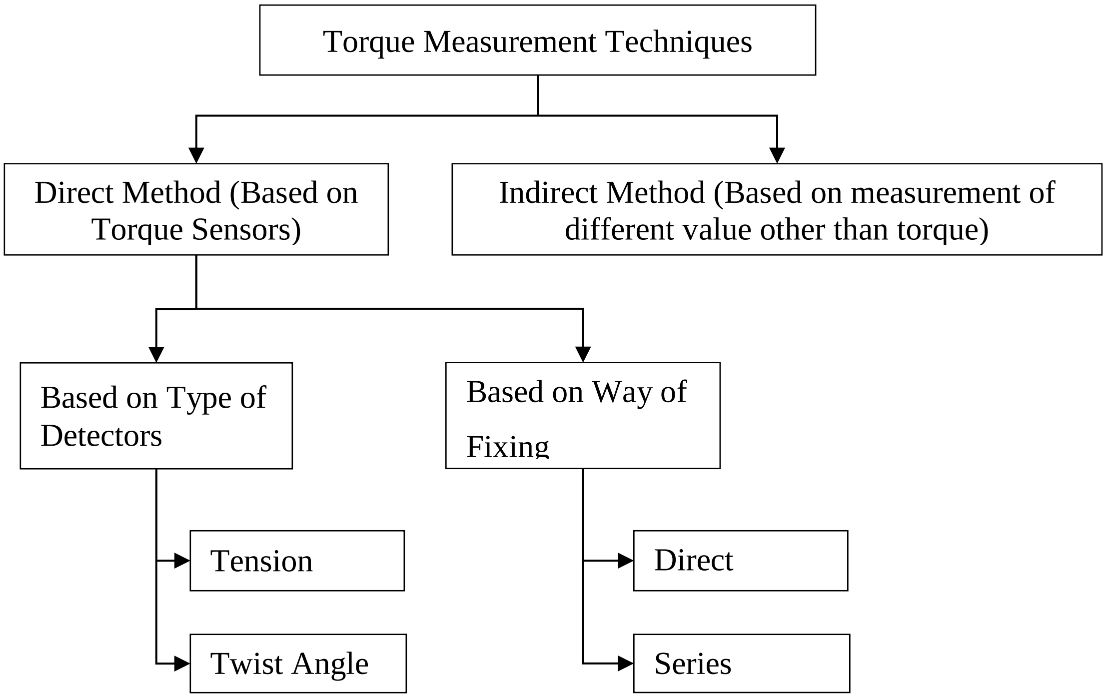

Figure 2. 1 Classification of torque measurement methods (Goszczak, 2016)

2.1.2 Torque sensor

Torque measurement sensor converts torque measurement i.e. reaction, dynamic or rotary into any other physical variable, in this case, into electrical signal that can be measured, converted and standardized.

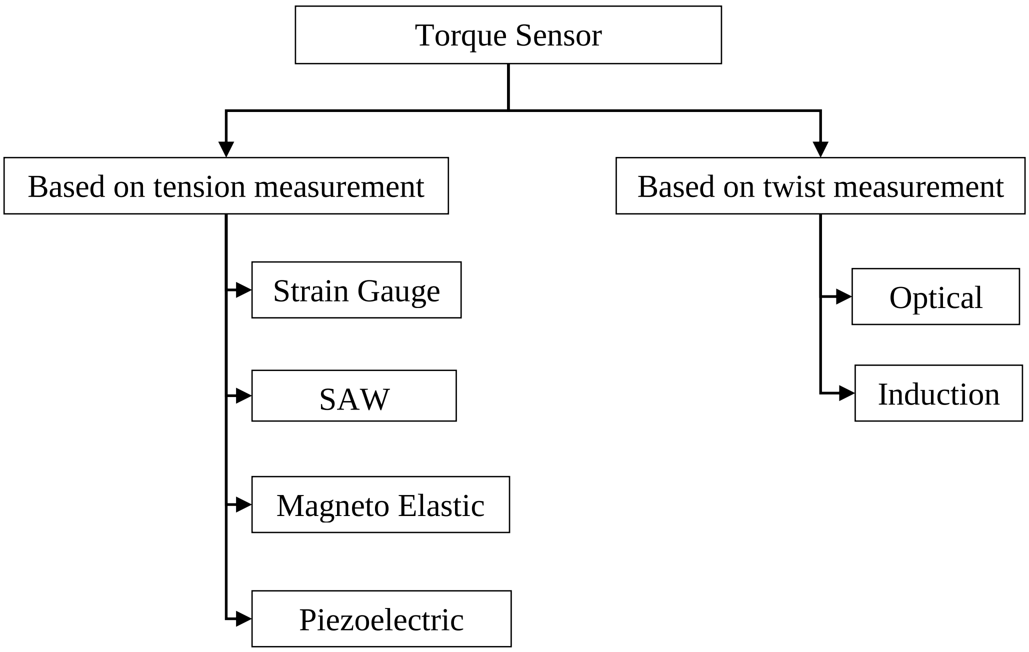

Figure 2. 2 Classification of torque measurement sensors (Goszczak, 2016)

- Strain gauges – Based on resistance change in strain gauges with elongation.
- Surface Acoustic Wave –Based on Change in resonant frequency of sound waves with deformation and which value help to calculate the torque
- Magneto elastic- Change in permeability of ferromagnetic material is used to measure torque.
- Piezoelectric reaction torque sensors –Strain is caused due to twisting of quartz discs placed between metal plates which generates electric charge on the surface of sensors.
- Optical – Optical sensors are placed near the ends of torsional elements. As the relative twist is produced the amount or nature of optical signals change and the change is used to calculate torque.
- Inductive –Coil placed in torsional element twist relative to each other. Change in inductance is measured and torque is derived.

2.2 Low cost torque transducers

Torque measurement technology had not formally begun up until Robert Hooke formulated Hooke's law. After almost two decades later in 1830's Hunter-Christie explained the working of bridge circuit. Up until 1945 sensors measuring rotating torque using inductive measuring systems were already available in the market and for the first time slip rings were used to transfer measurement data from SG-bridge in 1952. With the advancement in technology, SG-technology also improved with integrated digital sensor electronics where the electronics with transformer is attached to the rotating shaft and fixed parts remain in the housing outside (Krimmel, 2022).

Decade's long development of SG technology improved the measurement accuracy and widened its application but the technology remained costly and difficulty in transmitting measurement data also remained. Further, SG technology also had limitations for measuring data at low and medium frequencies, installation difficulty in cylindrical surfaces, noise exposure, requirement of trained professional for installation and need for regular calibration. To overcome these limitations non-contact methods were developed which were categorized into two types' tension measurement and twist angle measurement. In 1966 RG Karpov first experimented on contactless torque measurement by considering twist angle due to torque applied. The rotating shaft was mounted with two sprockets on both sides made of magnetic materials. Detector is placed near each of the two sprockets unattached to the shaft. The distance between socket and shaft changes as torque is applied to the shaft which is detected by magnetic pole detectors. Finally, torque value is measured based on the pulses generated by the detector (Jun Liu, 2013).

Conventionally slotted discs were mounted and rotated along with the test material and as the torque was applied the discs moved with respect to each other which changed the pattern of light pulses originally created by the two discs. The system was easy to install and could easily be fitted to existing systems (Sarmad Shams, 2012) (Hazelden, 1993).However, requirement of large rings in the test specimen is not always an option and installation of such type of rings claim higher costs. Laser technology was explored later as a contactless method for measuring torque and research paper was first presented in 1991 and the research was further analyzed for axial shaft vibration effects and shaft tilt sensitivity (T.H. Wilmshurst, 1993).

Contactless torque measurement using optical torque sensor was further explored using birefringent material. The torque sensor is based on the principal of birefringence effect shown by optically anisotropic materials where shaft is coated with photo-elastic layer. Birefringent materials split the polarized light beam into two perpendicular beams along the direction of principal stresses (Peter Sue, 2012). With the application of torque the two light beams have different velocity in the principal direction due to change in refractive index of coated material which implies one of the beams get delayed, also known as retardation. The retardation causes phase shift which is directly associated with principal stress and hence, torque is calculated based on the phase shift of beams (F. Hajdu, 2012).

2.2.1 Optical sensors in torque measurement

To reduce the cost and ensure flexibility of torque measurement systems researchers have developed system for measuring torque using zebra-tapes and optical sensors. The technology can be applied to measure torque in both variable and static conditions. A recent research published back in 2018 used two zebra tapes glued on both ends of cylindrical shaft and two independent optical sensors placed on fixed non-rotating supports (Hazelden, 1993). The setup includes optical sensor, OPTEK OPB739RWZ using visible red light to read zebra tape pattern and pulses are acquired using I/O device USB-6211 DAQ which is driven by Lab VIEW software (Sarmad Shams, 2012). When the torque is applied the zebra tape pattern changes position since shaft twists with torque. The twist angle is measured by comparing the optical probe signal of stationary zebra tape with optical probe signal of twisted zebra tape on the other end. Hence, the torque applied is determined based on phase shift seen in optical signal received from twisted zebra tape. Received signals were processed using two methods: Rising edge detection method and cross-correlation method (Zappalá, 2018).

Further, absolute angular shift (θ_a) due to applied torque can be calculated as:

$$\theta_a = \frac{2\pi}{60} n\Delta t \quad (6)$$

n = RPM

Δt = time shift between two optical sensor

2.2.2 Magnetic sensor in torque measurement

For the measurement of dynamic torque and speed at high rotational speed with reliable readings, magnetic sensors are used. Magnetic sensor is based on magnetic elastomer material and measures twist angle which can be used to derive torque. The magnetic sensors generate pulse while shaft is rotating or at static condition. When dynamic torque is applied to the shaft, magnetic pulse shift phase. The difference in phase or time can be used to find angle of twist and finally torque can be derived. Since, the sensor remain stationary and do not come in contact with the shaft, the torque transducer remain comparatively less expensive (Valentin Mateev, 2021).

2.2.3 SAW sensor for torque transducer

The shortcomings of conventional methods of torque measurement have led to the development of a technology based on surface acoustic wave transducers. If the transducer is attached to a drive shaft, the deformation of the substrate and hence the change in resonant frequency will be related to the torque applied to the shaft. In other words, the transducer, in effect, becomes a frequency-dependent strain gauge. This means torque sensors that incorporate the SAW transducer technology are well suited for use on rotating shafts and other moving elements, and can provide data continuously without the need for the inherently unreliable brushes and slip rings that are often found in traditional torque measurement systems (Lin, 2012). New type of torque transducer has been developed by SAW transducer technology (covered by Patents), which offers many benefits. Benefits include shorter length of shaft, which translated to higher shaft stiffness; lower inertia and capability of higher operating speed. Since, the electronics are not attached to the shaft new torque transducers are responsible for noise immunity, higher resolution and accuracy and substantial capacity to withstand overload. These sensors are capable of measuring torque from 1Nm to 13000 Nm, accurately and are able to deliver real time results. SAW torque transducers have been in use long enough though they have been developed recently, and their application in diverse fields have proven them as convenient and reliable technology that can even be used in challenging operating conditions (Lin, 2012).

2.2.4 Strain gauge sensor in torque measurement

Numbers of sources have introduced strain gauge theory depicting two commonly used strain gauge versions, named as semiconductor and resistance versions. Approximate linear relation between strain applied and change in gauge resistance is provided by wire resistance strain gauges, while semiconductor gauges only show linear behavior under tensile strain.

For developing torque measurement systems wire resistance strain gauges utilize the fact that, with the change in wire length, cross-sectional area and resistivity, the resistance changes given by formula R = ρ*L/A. Sensitivity of strain gauge us defined by k = (dR/R)/(dL/L) where denominator of the formula can be defined as axial strain, ε. Establishing Poisson's ratio, υ and using the first equation and can deduce to yield k = 1+2υ + (dρ/ρ)/ε (Paul Beard, 2011).

Hence, it can be inferred that, Poisson effect, level of strain and piezo-resistive factor, are sources affecting gauge factor. Uniform gauge factor is exhibited by Constantan type and Copper-Nickel alloys. Value of gauge factor is affected by strain gauge adhesive type and its application method, Gauge geometry and thermal effects giving rise to need for in-shaft calibration. Thermal dependency of calibrating strain gauge is affected by three main factors arising due to difference in temperature which includes gauge factor changes, strain experience by gauge and gauge resistance. Similarly, equivalent strain is given by the equation:

$$\frac{dR}{R}\frac{1}{k_0} = \varepsilon + \Delta\theta\{\frac{\alpha_t}{k_0} + (\alpha_{gauge} - \alpha_{specimen})\}$$

K_0 = gauge factor at gauge temperature

α_t =Thermal coefficient of resistivity

α = coefficient of thermal expansion

θ = temperature

Second term in the above equation becomes negligible when gauge material is selected such that it has appropriate thermal expansion properties under limited temperature range (Paul Beard, 2011). Further, electronic circuits are used for compensation of unwanted strains for wider temperature range. Strain gauges are arranged in Wheatstone bridge arrangement where four resistors represent active strain gauges.

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 $(dR/R)/\varepsilon = k$ (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 ε_1, ε_2, ε_3, and ε_4 are the strains associated with strain gauge 1, strain gauge 2, strain gauge 3, and strain gauge 4, respectively.

For strain gauge glued with balance Wheatstone full bridge pattern

$$\sigma_{1,2} = \pm\frac{1}{4} * \frac{E}{1 - v^2} * (1 - v) * \varepsilon_i$$

Shear stress increase from center (τ_{min}=0) to maximum at surface (τ_{max})

$$\tau_{max} = 2\varepsilon_{45^0} G$$

For full bridge circuit

$$\tau_{max} = 2\varepsilon_{45^0} G = \frac{1}{2} * \varepsilon_i * G$$

Where ε_i is indicated strain value for the full bridge circuits and G is the shear modulus

For torsion moment (torque) can calculated by using the τ_{max} according to equation

$$T = \frac{T_{max}}{D/2} * J = \frac{\frac{1}{2} * \varepsilon_i * G}{D/2} * J$$

$$\varepsilon_i = \frac{D * T}{G * J}$$

Strain of a single strain gauge for balance Wheatstone bridge circuit is given by

$$\varepsilon = \frac{\varepsilon_i}{4}$$

Hence, it is evident that to achieve maximum bridge sensitivity when two gauges are mounted in the direction of maximum tensile strain and remaining two gauges along the direction of maximum compressive strain. The principal strain axes are aligned in $\pm 45^0$ to the longitudinal axis of shaft in case of shaft under pure torsion which determines the mounting arrangement for torque measurement (M.Hilal Muftah, 2013).

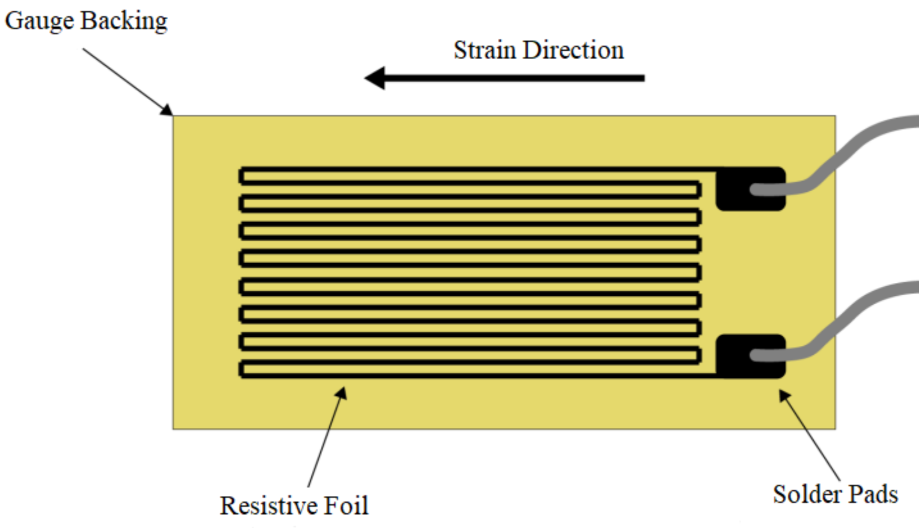

Figure 2. 3 Strain Gauge

The glued resistance strain gauge is proper for a wide variety of environmental conditions. It can measure strain in jet engine turbines operating at very high temperatures and in cryogenic fluid uses at temperatures as low as -269 degree Celsius (SHAFT STRAIN GAGING GUIDE, 2021). It has high sensitivity, low mass and size, and is suitable for static and dynamic applications. Strain gauge elements are available with unit resistances from 120 to 5,000 ohms (SHAFT STRAIN GAGING GUIDE, 2021). Gauge lengths almost 0.2mm to 100mm are available commercially in market (S.M, 2019). The three main attentions in gauge selection are: working temperature, the type of the strain to be sensed, and constancy requirements. Similarly, application success is guaranteed by right selection of grid alloy, bonding agent, carrier material and protecting covering. For torque measurement, complete bridge strain gauges are available in market.

2.3 Torque transducer for micro hydropower

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 (Alternative Energy Promotion Centre, n.d.). Most of these turbines are fabricated in Nepal (Alternative Energy Promotion Centre, n.d.). 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 2.4. 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 (Futek Advance Sensor Technology Inc, n.d.). 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.

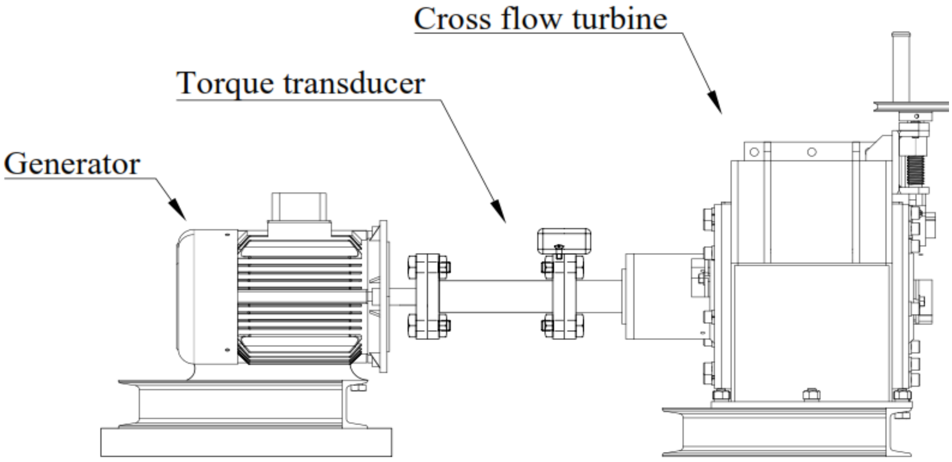

Figure 2. 4 Schematic digram of dynamic wireless torque transducer alignment for microhydro powerplant

2.4 Calibration

Torque is the measurement of elastic deformation of a body and a device which includes torque calibration, indicating device and the torque transducer can be defined as torque measurement device (Accreditation, 2000).

Torque calibration and measurement devices can broadly be classified into three categories; torque wrench tools, calibration devices used for calibrating torque wrench tools and torque measurement transducers (DKD-R, 2020). These three classification form a pyramid with torque wrench tools for daily use in workshops, at the bottom of pyramid as shown in Figure 2. 5. Further, moving upwards it is found that the pyramid devices have higher accuracy and the pyramid steps are associated with calibration meaning devices in upper part of pyramid are used to calibrate devices in lower stages (DKD-R, 2020).

Standard specifications define the procedure of performing calibrations in order to ensure parallel calibration results independent of whichever calibration laboratory it is performed. DIN-ISO 6789, ISO 6789, EA 10/14 and DIN 51309 BS 7882 are some of the most followed standards (Accreditation, 2000).

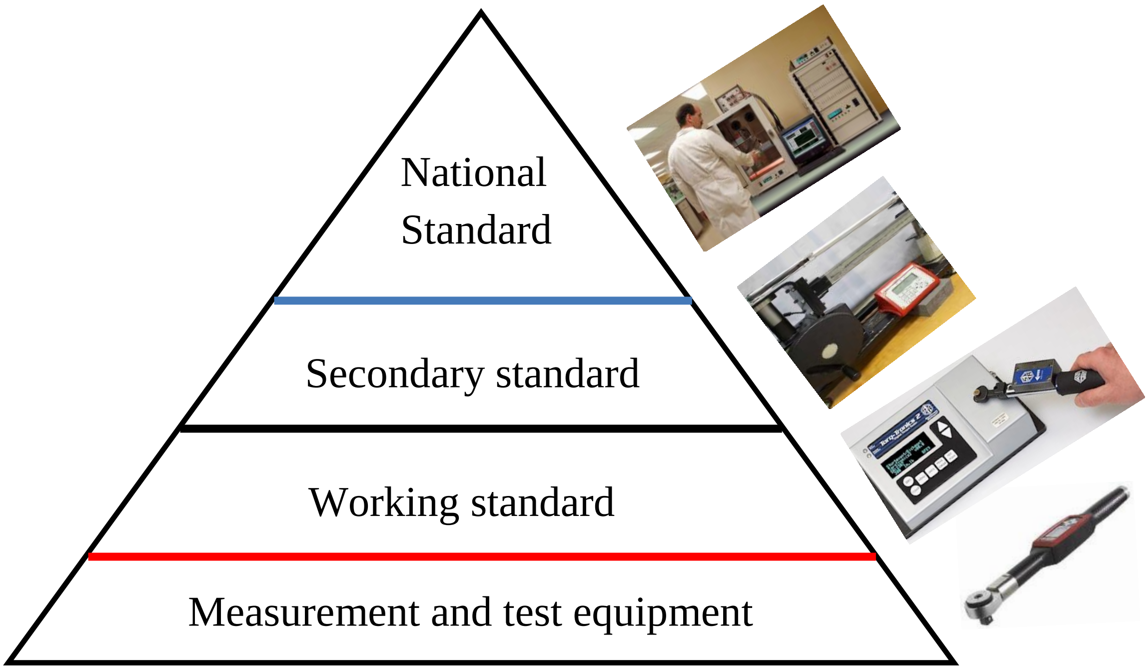

Figure 2. 5 Calibration Pyramid

2.5 Limitations

Torque applied and angle of twist produced are directly proportional to each other and they show linear behavior. As any measurement device is not accurate due to vibration, environmental condition, instrument errors and so on. Hence, the measurement device might not show linear behavior which results in linear uncertainty.

Linear uncertainty of torque transducer is associated with non-linear behavior observed during the calibration across the range of an assumed linear function. ISO GUM (Guide to the expression of uncertainty in measurement) has recommended two methods of measuring uncertainty. Type A uncertainty measurement can be performed using statistical estimation of calibration data regression. Type B analysis is performed using Monte Carlo method where real-world influencing methods are considered (International Organization of Standardization, 2008).

Performance datasheet of locally available electronics components are not completely reliable. Precision of data, resolution and accuracy are not consistent. The results of calibrating machine might also have anomaly in measurement due to the fact that the standard machine are of older technology and have lower precision.

CHAPTER THREE: METHODOLOGY

This paper is primarily concerned with proposing a torque transducer based on a strain sensor. For the purpose of in-operation torque measurement, the proposed torque transduce provides a live output signal. To fulfil this, some literature review has been done on the topic of torque transducer. The research outline is shown in Figure 3. 1.

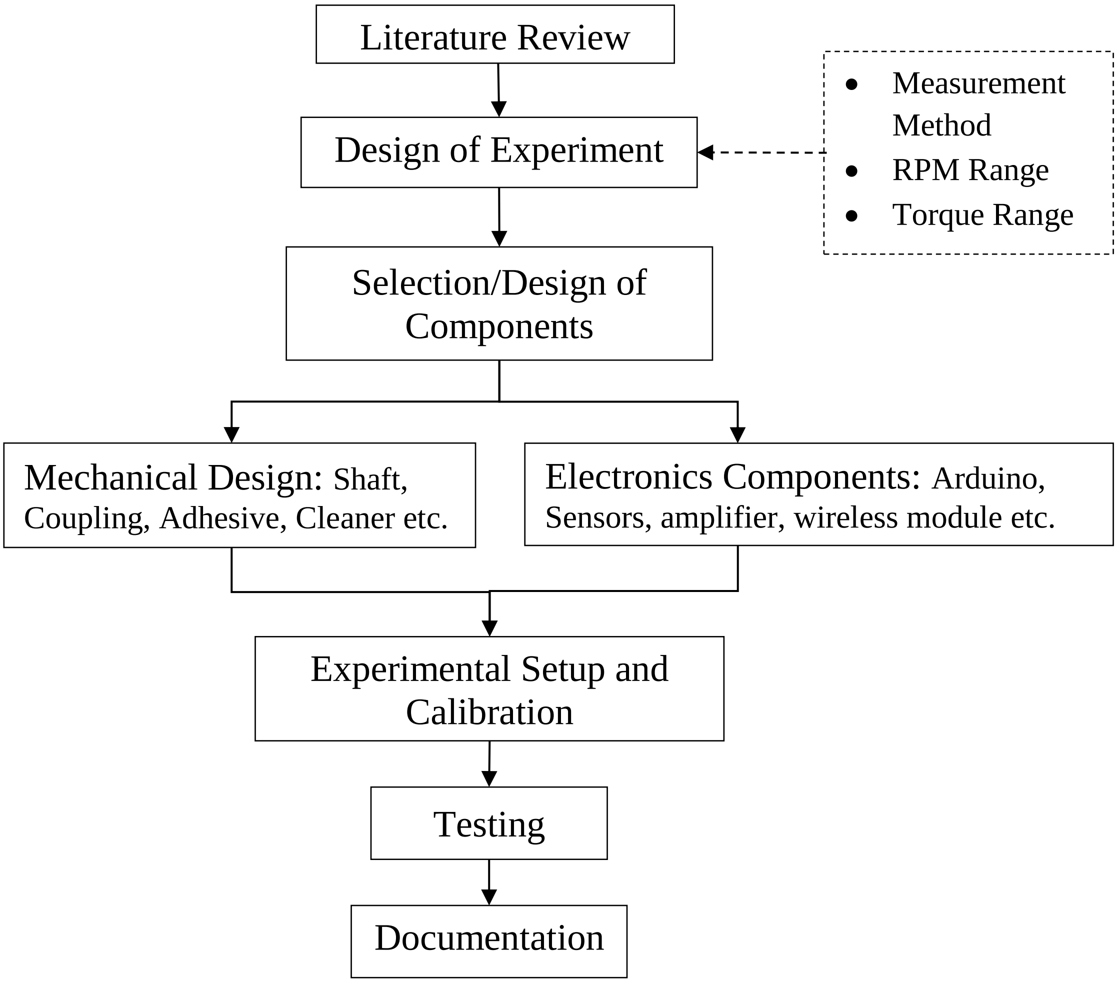

Figure 3. 1 Research outline

The design of torque transducer depends upon the calibration facility. Based on the calibration facility, the method of torque measurement is selected such that, cost of experiment, data accuracy and ease of installation are considered. Further, selection of torque measurement method depends on Torque range and RPM of rotating shaft, which is up-to 10Nm and 1500 rpm respectively in case of proposed project's experimental setup. Selection, Fabrication and Procurement of components of the setup is to be done based on torque range and RPM. Selection of design component is divided into two categories mechanical component and electronics components. Torque transducer shaft is designed such that, it does not cross elastic limit and significant strain is developed while applying torque which is to be measured, otherwise torque transducer does not show linear behavior. Since, the shaft will be rotating with high RPM, the use of slip rings is not suitable due to higher experimental costs and inadequate data provided by slip rings at high RPM. Hence, electronics components are selected such that wireless live signals are transmitted by the setup while rotating along with the shaft. For experimental setup, shaft is coupled with torque producing machine (generator and motor), using coupler, and electronics components are attached to shaft such that they rotate along with the shaft. Torque producing machine is operated to obtain live Torque, RPM and strain signal data. The output data is analyzed to develop approximate relation between Torque and strain signal (from Arduino Data). The data obtained is simplified and further coded, such that output received from setup is easy to analyze. Iterations are carried out until reliable data is obtained. The results and conclusions are well documented.

3.1 Experimental setup

After designing complete transducer component setup, hollow torque transducer shaft was fabricated in local market. The electronic components; Arduino, Amplifier, Bluetooth module were procured from the local market. Strain gauge sensor is properly glued on the shaft and gauges are wired in Wheatstone bridge pattern. For the torque transducer the electronic components 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 6cm x 6cm PCB board and this board is fixed into 10cm x 10x 6cm box. The box has facility to hold battery, to power the Arduino and switch is placed outside box face for convenience. Overall box can be attached with transducer shaft using bolts. The complete transducer device is align and coupling with generator and motor dynamic torque measurement setup. Here transducer power switch on before the power for testing machine and Android smart phone was connected. After all component were carefully installed, calibration and testing was conducted. Which is shown in Figure 3. 2.

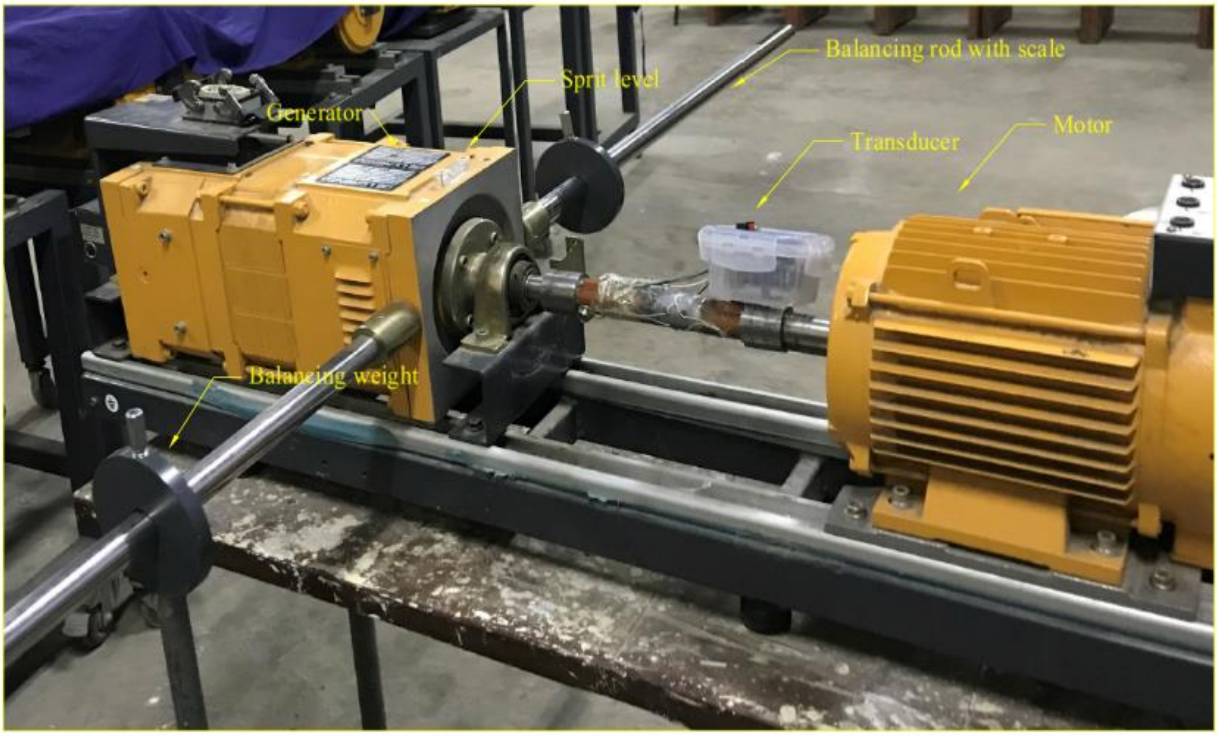

Figure 3. 2 Torque transducer inline couple with generator and motor dynamic torque measurement setup for calibration

3.2 Working Principle

This experiment involves with the measurement of torque using strain gauge sensor. Four strain gauge with Wheatstone bridge pattern are glued on the torque transducer shaft using adequate adhesive. Stationary, serial monitor is used to acquire voltage signal produced by glued strain gauge as a result of applied torque. The signal is transmitted to Arduino and further wireless signal is communicated with serial monitor via Bluetooth module.

The strain gauge is a type of sensor that convert the mechanical effect into an electrical signal. The strain gauge is affected by the change in temperature which will produce error on measurement. To overcome such type of error Wheatstone bridge helped and provide accurate measurement. Four strain gauges (R_1, R_2, R_3 and R_4) form a Wheatstone bridge to measure the applied torque. The strain gauges Wheatstone bridge connection shown in Figure 3. 4.

The Wheatstone bridge’s output voltage (Vout) can be formulated as in equation (7)

$$V_{out} = (\frac{R_1}{R_1+R_2} - \frac{R_4}{R_3+R_4})V_{in} \quad (7)$$

The output voltage of Wheatstone bridge is zero when $R_1*R_3 = R_2*R_4$ and all the resistance have the same value.

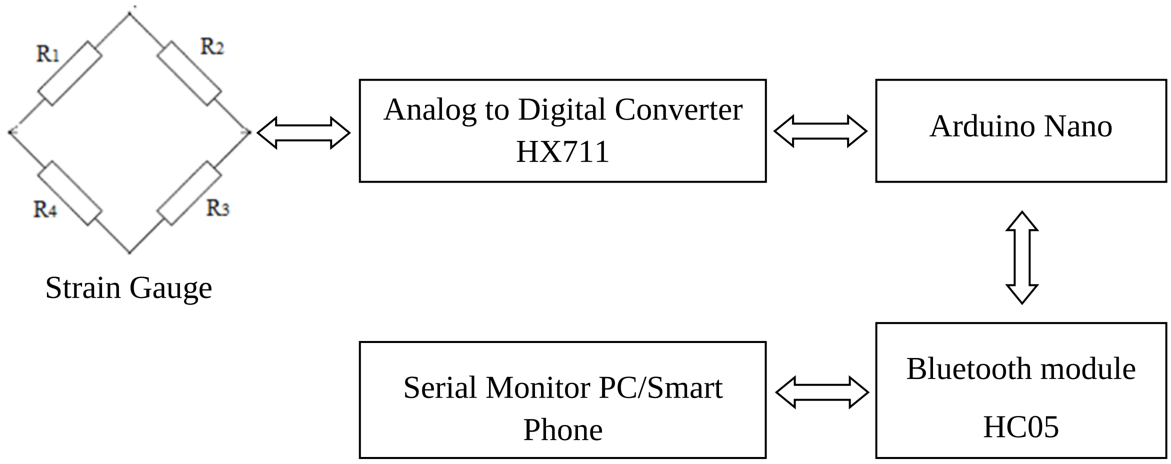

Figure 3. 3 Working principle of strain gauge torque transducer

Components used in torque measurement by using strain gauges include strain gauge, amplifier (HX711), Arduino, Bluetooth module and serial monitor. A strain gauge convert's applied torque into electrical signal (S.M, 2019). The sensor is attached to a rotating hollow shaft that deforms when a torque is applied. Four strain gauges are attached to the rotating shaft in the form of a Wheatstone bridge circuit. They are adjusted precisely at 45 degrees with the shaft axis in opposite directions, as shown in Figure 3. 4. 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. 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 (Sadik Kamel Gharghan, 2017). This results in an unbalanced bridge, which produces an electrical output corresponding to the applied torque. The produced electrical signal is transferred to an Analog to Digital converter (HX711) and this converted digital signal is transferred to Arduino and Arduino transfers the signals to a stationary serial monitor via wireless connection using the HC05 Bluetooth module. The measurement signals transformation process is shown in Figure 3.3.

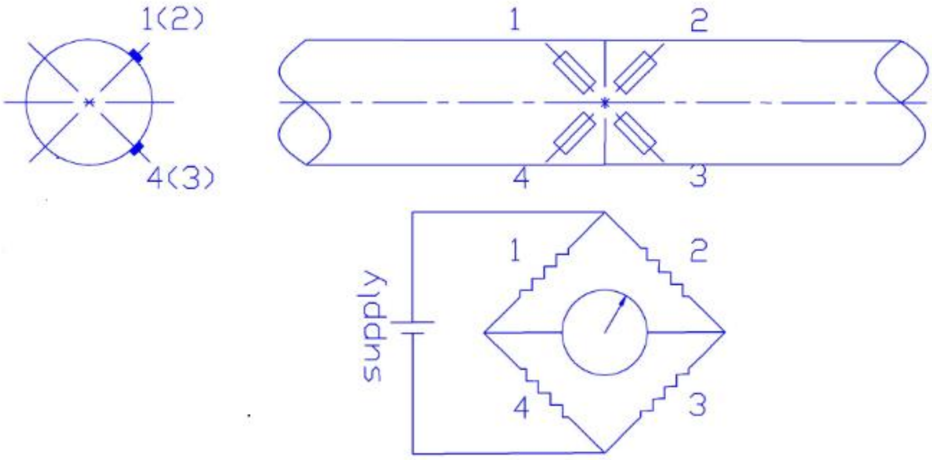

Figure 3. 4 Strain gauge alignment on shaft

During the torque measurement, an output signal (voltage) from strain gauge connected by Wheatstone bridge connection is an analog signal with a few millivolts. To amplify the signal and transform the analog to digital, an HX711 ADC (analog to digital converter) is used.

HC05 Bluetooth module is used as a wireless signal transmission from the bridge of the resistive strain sensor. Digital signal from the HX711 is transmitted to Arduino thereafter it is communicated wirelessly with serial monitor (Sadik Kamel Gharghan, 2017). The measured signal can be used to calculate applied torque.

Figure 3. 5 Dynamic torque transducer (constructed in this research)

3.3 Components

For torque transducer, strain gauges for making four resistive elements are bonded to the shaft. Two gauges are aligned with the direction of tension (stretch) and the others two are aligned with the direction of compression. The following component are required to measure the torque using strain gauge sensor method.

- Transducer shaft
- Sensor (Strain gauge)
- Arduino for signal processing
- Display unit (Laptop)/smart phone
- HX711 ADC (Analog to Digital convertor)
- Bluetooth module (HC05) for wireless serial communication
- Power Supply for Arduino
- Mounting/coupling component
- Cleaning agent
- Adhesives Chemical
- Connection cable
- Torque transducer calibration sets

3.3.1 Transducer shaft

When torque is applied to a cylindrical shaft, it produces twist. The angle of twist is governed by torsional equation as shown below:

$$\frac{\tau}{R} = \frac{T}{J} = \frac{G\theta}{L} \tag{8}$$

Where,

τ = Shear stress G = Modulus of rigidity

R = Outer radius of shaft J = Polar moment of inertia

T = Torque Ɵ = Angle of twist

L = Distance between fixed end Cross Section and twist end cross section,

From the above equation it can be deduced that, to acquire significant strain on attached strain gauge with definite torque hollow shaft with ductile material is suitable for the experiment. In this research an aluminum hollow pipe is used. But as the radius is reduced, shear stress value may cross the elastic limit causing plastic deformation. For this experiment, in order to acquire significant strain on attached strain gauge within elastic shear stress limit and with limited torque, some assessment is done on torque transducer shaft dimension.

As torque transducer shaft material 6463 aluminum is taken for this experiment and dimensional assessment was performed to acquire significant strain within available torque value. Torque transducer shaft is designed such that for maximum torque shaft remains within elastic limit and produces significant stain with minimum torque.

Assessment on variable shaft diameters is performed according to locally available and calculations show that significant strain is produced on hollow shaft with outer diameter of 30mm and thickness 1mm. Further, to obtain significant strain for the given hollow shaft following properties were assessed

Table 3.1 Traducer shaft property

Outer diameter of shaft	30mm
Internal diameter of shaft	28mm
Length of shaft	120mm
Polar Moment of Inertia	19175 mm^4
Modules of elasticity	68GPa
Shear modulus	26GPa
Tensile strength	150MPa
Tensile yield strength	90MPa
Shear strength	97MPa
Fatigue strength	69MPa

Torque value on 50% loading

$$\frac{T}{J} = \frac{\tau}{R}$$

$$\frac{T}{19175} = \frac{35}{15}$$

$$T = 44741 \text{ Nmm}$$

From the above calculation it is conclude that the maximum 44.74 N-m is the safe load for this transducer shaft.

Strain gauges are attached on shaft with Wheatstone bridge neatwork. The strain gauges are alien such that two of the strain gauge on tension and other two on compression when rotation is applied to it which is shown in Figure 3. 6.

Figure 3. 6 Strain gauges glued on surface of shaft and connection as Wheatstone bridge pattern

3.3.2 Analog to Digital Converter

During the torque measurement an output voltage from connected Wheatstone bridge is analog signal with low value. To amplify the low value signal, booster is required. To amplify the measured voltage in possible range of receiving device and convert the analog to digital, an HX711 ADC (analog to digital converter) strain booster is used.

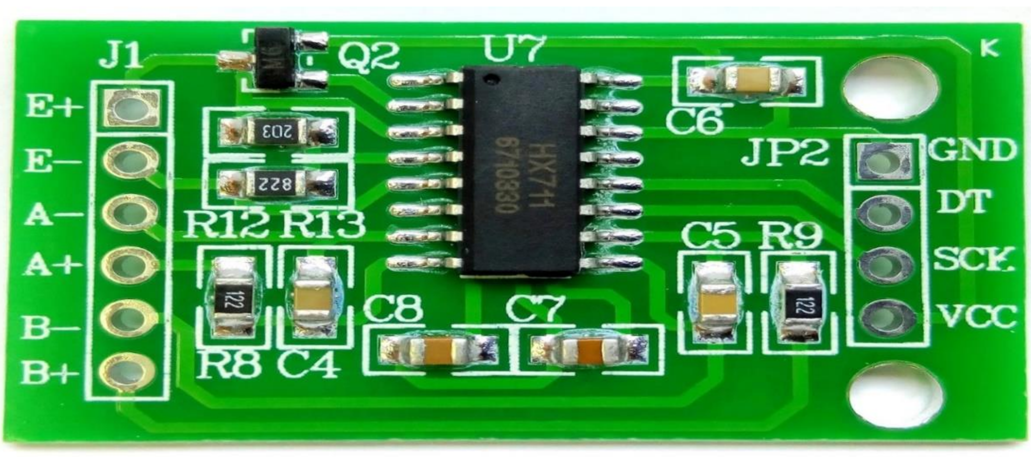

Figure 3. 7 Analog to Digital converter (HX711)

HX711 is 24 bit ADC. It has 24 bit resolution which means it can assign the input sensed voltage in the range 0V-5V any value in the range 0-16777216. In other word, it has 16777216 different levels assign to the sensed continuous voltage value.
As the ADC has 24-bit resolution, it assigns the maximum measured voltage to its maximum level. For instance, if the analog voltage value is 5 volts, the ADC maps this analog value 16777216.

HX711 measured analog voltage = $\frac{\text{ADC value} * 5}{2^{24}}$ Volts

The HX711 has a resolution of:

Resolution = $\frac{5}{2^{24}}$ = 0.298μV

This means it can detect changes as small as 0.298 μV.

3.3.3 Strain gauge sensor

For this experiment, BF350-3 AA resistive strain gauges sensor have been used. This resistive strain gauges sensor has 350–ohm nominal resistance. The resistance varies when a force is applied, using torque or any other means. The strain gauge exhibit small changes in resistance. By measuring the change in the sensor's resistance, a measurement of the force applied can be calculated. Specification of strain gauge is tabulated as shown in table 2.

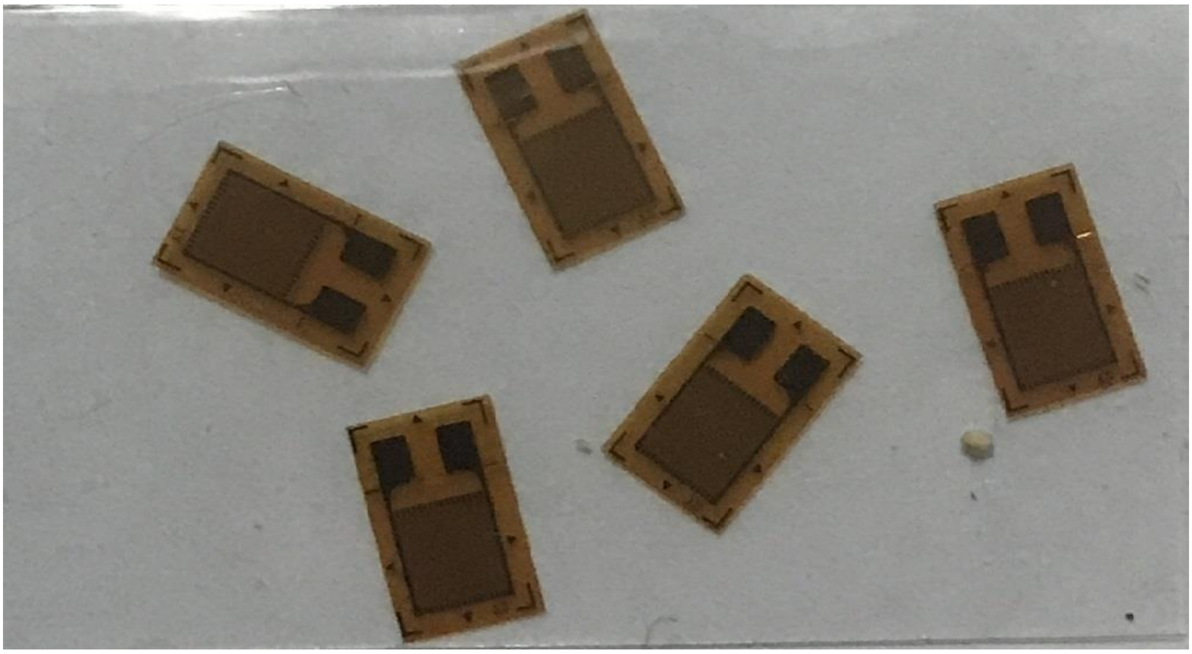

Figure 3. 8 Strain gauge (BF350-3AA)

Table 3.2 Strain gauge sensor specification

Model	BF350-3AA
Resistance	350Ω
Basal Material	Epoxy-modified phenolic
Basal material thickness	32±1(μm)
Grid material	constantan
Insulation resistance	10000Ω
Sensitivity coefficient	2.1
Sensitivity coefficient dispersion	≤±1%
Transverse effect coefficient	0.4%
Strain limits	2.0%
Fatigue life	≥1M
Size	7.1 x 4.5 mm(L*W)
Working temperature	-30°C to +80°C

Strain gauge is comprised of metallic wire, semiconductor material or foil bonded to the strained surface using fine epoxy film. Strain is passed on to the grid material when carrier matrix is strained. Strain is marked by the alterations in electrical resistance of the grid. Shape of the grid is tailored such that maximal gauge resistance is provided while retaining gauge length and width to the minimum. Short length strain gauge are able to maintain accuracy in the range of +/-0.10%, comparatively cheap (E, 2018). These strain gauge have tolerable effect due to temperature changes and come with compact size, low mass and high sensitivity. Using bonded resistance strain gauges both static and dynamic torque can be measured. While attaching strain gauge to the stressed surface, it is mandatory that same strain experienced by the object is transmitted to the strain gauge (Strainblog, n.d.). While adhesive material used between strained surface and surface, the arrangement is affected by creep due to bond atrophy, temperature, and hysteresis due to thermoplastic strain. It is beneficial to use resins designed particularly for strain gauges, since numerous epoxy resins and glues are susceptible to creep (Strainblog, n.d.).

3.3.4 Arduino

Arduino Nano is the smallest dimension board which has breadboard friendly design. For easy attachment, Arduino Nano comes with Mini-B USB connector and includes pin headers which allow easy attachment with breadboard. Specification of Arduino is presented as shown in Table 3.3.

Table 3.3 Specification of Arduino

Board name	Arduino Nano	
Microcontroller	ATmega328	
USB connector	Mini-B USB	
Pins	Built-in LED Pin	13
	Digital I/O Pins	14
	Analog input pins	8
	PWM pins	6
Communication	UART	Yes
	I2C	Yes
	SPI	Yes
Power	I/O Voltage	5V
	Input voltage (nominal)	7-12V
	DC Current per I/O Pin	20 mA
Clock speed	Processor	ATmega328 16 MHz
Memory	ATmega328P	2KB SRAM, 32KB flash 1KB EEPROM
Dimensions	Weight	5gr
	Width	18 mm
	Length	45 mm

With easy to use software and hardware, Arduino is open-source prototyping electronics platform which can be used to develop digital devices that can provide output by receiving some input. C++ programming may be used to program or provide set of instruction to Arduino microcontroller to perform almost anything. To communicate with PC, the Arduino board includes a USB plug and wiring with external devices is possible due to presence of connection sockets. Arduino Nano is used for this project due to compact size.

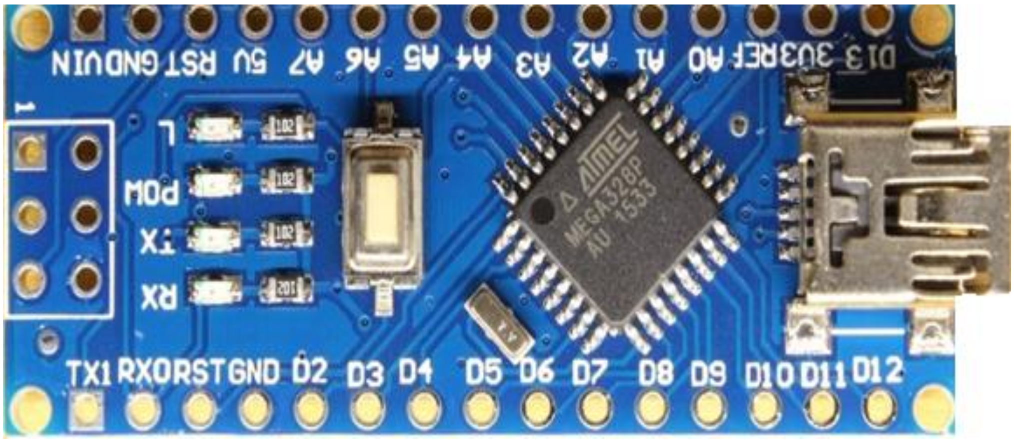

Figure 3. 9 Arduino Nano

3.5 Bluetooth Module

Among various mediums for wireless communication such as Wi-Fi, Zigbee, NRF and Bluetooth, Bluetooth protocol proves to become useful in the project due to its easy access, low cost, reliable and decent working range of 100m, data rate upto 1 Mb/s, and since it comes with baud rate functionality. HC05 Bluetooth module uses serial communication with operating voltage 3.6V to 5V and 3.3 voltage in RX pin for communication. Direct 5V supply to Bluetooth module might cause damage to the module. Between Arduino TX pin and module RX pin, resistance division circuit (5v to 3.3v) is used to prevent the module from damages and make it work properly, which is shown in Figure 3. 10.

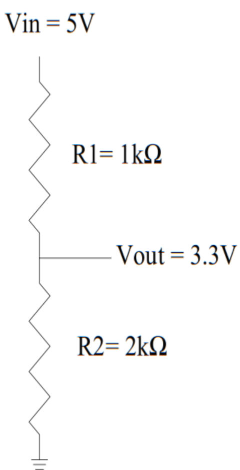

Figure 3. 10 Schematic of voltage divider

Formula for output voltage calculation is,

$$V_{out} = V_{in} \times \frac{R_2}{R_1+R_2} \quad (9)$$

In order to supply 3.3 V to data communication pin, voltage divider circuit with R1 (1kΩ) and R2 (2kΩ) is connected to 5V Arduino supply. Which is shown in Figure 3. 10.

Bluetooth serial port protocol module, is used to setup wireless serial connection which provides promotes ease in interfacing with controller or PC. HC05 Bluetooth module is used as a wireless signal transmission from the bridge of resistive-strain sensor. Digital signal from the HX711 ADC is transmitted to Arduino Nano thereafter it is transmitted to the Personal computer via HC05 Bluetooth module serial communication. HC-05 Supported baud rates are 9600,19200,38400,57600,115200,230400,460800 and 9600 is its default baud rate. Operating voltage is 5V and current 30mA with cover range 100m.

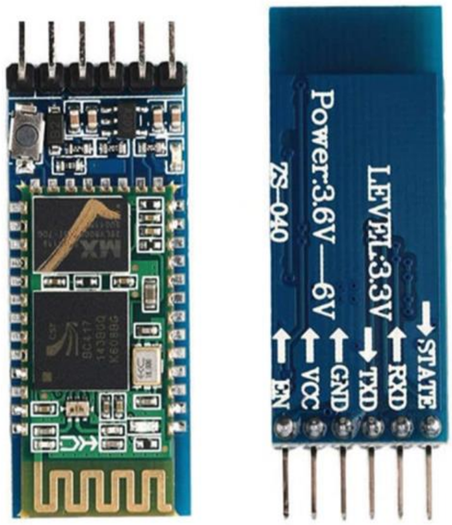

Figure 3. 11 Bluetooth module (HC05)

3.4 Strain gauge Installation

For the preparation of shaft surface, it was necessary to make sure that shaft is clear to any deformities and had smooth surface. Shaft preparation includes cleaning of shaft by removing any surface adhesives using cleaning agents. Sand paper with grit numbers 240, 360, 450 and 620 were used for shaft surface preparation to the point where it can be used as specimen. Shaft was then rinsed with soft conditioner along with neutralizer and finally wiped dry using cotton paper.

For adequate alignment of strain gauge shaft surface was first marked. As the strain gauge needs to be installed flat and square to the axis of shaft, reference line was essential. A piece of paper was wrapped around the shaft, the edges were aligned, line was drawn along the edges and finally straight reference line was marked on the shaft. Since, four strain gauge were to be aligned uniformly at 45 degrees, lines were drawn passing through the intersection point, making 45 degrees with horizontal in every direction. The strain gauge were glued with cellophane tape towards their top sides, to act as handle, and aligned onto the 45 degree lines for proper orientation. Strain gauge were the lifted, by lifting the tape such that strain gauge were no more touching the shaft surface. Thin even layer of catalyst was applied to the bottom surface of strain gage and let dry. While strain gage is still hinged back, bead of M-bond 200 adhesive was applied on the shaft surface where strain gage was to be attached. Strain gage was then pressed onto the shaft surface with single wiping motion of thump so as to rest strain gage on shaft surface, until it was properly attached and tape was carefully peeled back after few minutes (Strain Gage Installation, n.d.). Lead wires were soldered to the solder pads on strain gage and solder joints were cleaned using rosin solvent.

3.4 Circuit design

An output voltage received from connected Wheatstone bridge is in the form of analog signal with low value, during torque measurement. HX711 ADC (analog to digital converter) is used as strain booster. 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 µ (S.M, 2019) V (ALLDATSHEET.COM, 2021). 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 (Interfacing Bluetooth Module(HC05) With Arduino, n.d.). 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 (Interfacing Bluetooth Module(HC05) With Arduino, n.d.).

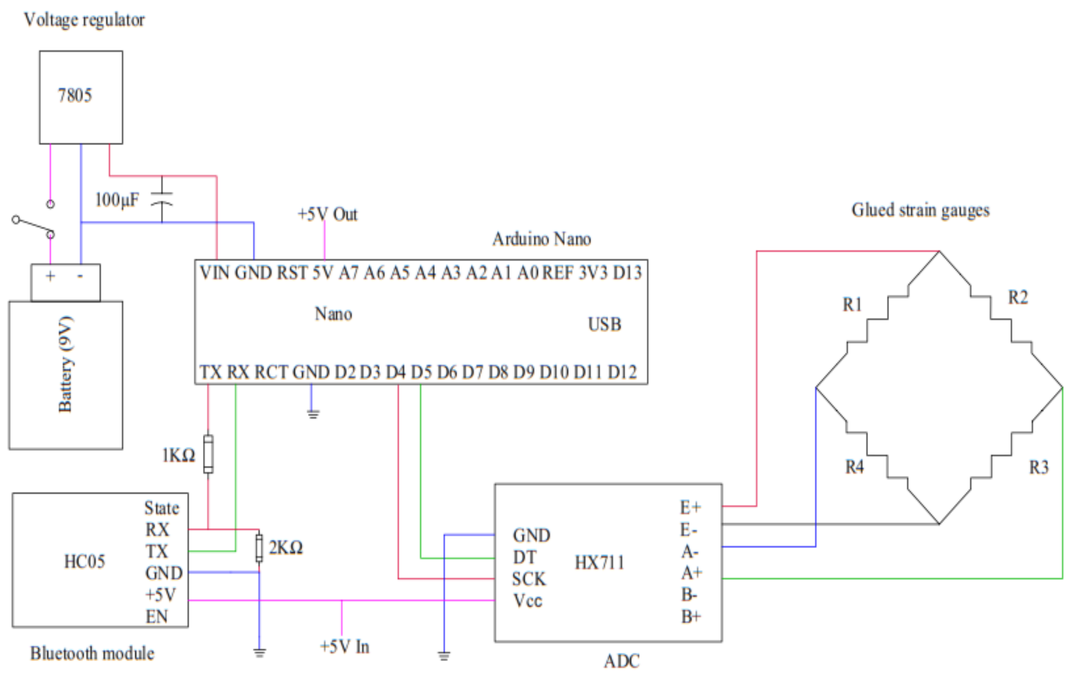

Figure 3. 12 Design of torque transducer electronics circuit diagram for electrical signal amplify and wireless signal communicate

For wireless serial communication the Bluetooth module is connected with Arduino. HC05 Bluetooth module has six pin available. The circuit connection are shown in Figure 3. 12.

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. 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. Required components connection diagram is shown in Figure 3.12. The complete circuit is made on a Printed Circuit Board.

For the torque transducer the electronic components 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 (printed circuit board) 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 3. 13. The box had facility to hold battery, to power the Arduino.

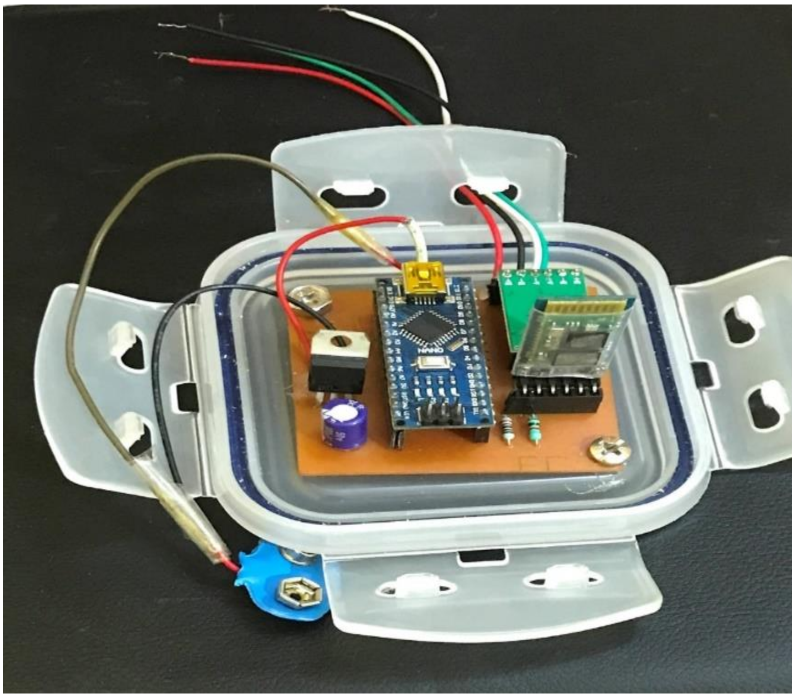

Figure 3. 13 Fabricated torque transducer electronics (connection as the Figure 3.12 and bolted to top of the transducer electronics box)

3.5 Torque transducer program in Arduino IDE

For this project, HX711 module was used with library named as “<Q2HX711.h>”. In terms of performance the use of this library was found to be the easiest and most stable to implement. The code is written to read strain gauge voltage variation through HX711. Digital pin D5 is initialize to receive the data pin (DT) of HX711 and similarly digital pin D4 is initialize to clock (SCK) pin of HX711.

After uploading the code, HX711 and HC05 are appropriately wired with the Arduino and it is also ensured HX711 is properly wired to the attached strain gauge. The code should provide output values that are communicated with Coolterm which is used as a serial monitor. The code should regularly output a value close to half of 2^{24}. This allows the strain gauge to measure both clockwise and anti-clockwise rotation. Data received in Coolterm can be used to calibrate the torque transducer. During the calibration the relation between strain gauge sensor value and torque value is deduced. The relation is coded on the Q2HX711.h header file and is uploaded to Arduino for torque transducer. The flow chart of coding is shown in Figure 3.14 and syntax is shown in Appendix B.

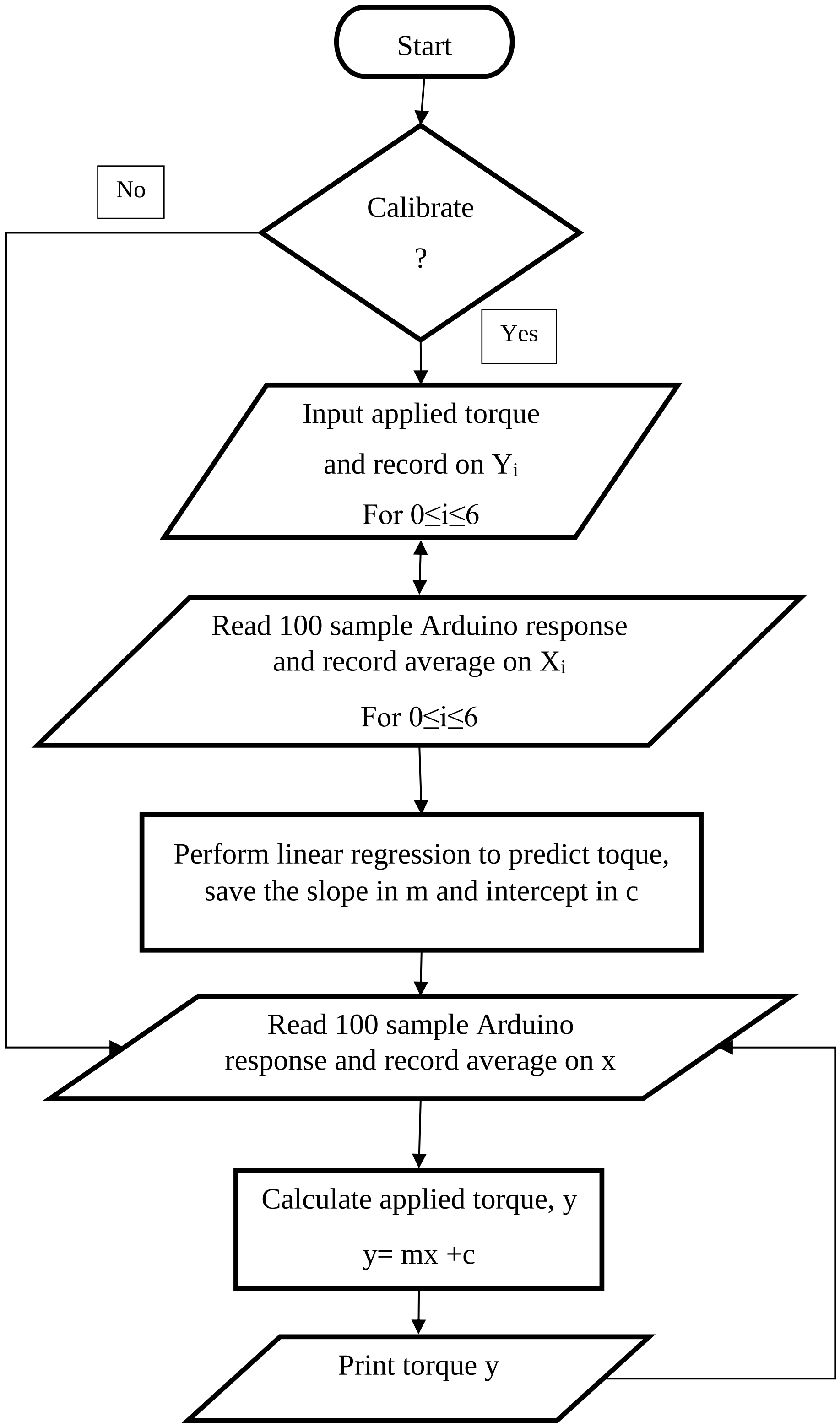

Figure 3. 14 Flow chart for signal reading and torque calculation

In order to make system user friendly, calibration option has been set in the torque transducer program. When the torque transducer is turned on, software asks to choose if calibration is required for torque transducer. If the input is ‘yes’, program follows calibration code along the algorithm where program asks for six known torque values as input and software stores the torque effect obtained from sensor attached with torque transducer shaft respectively. Also, software develops relation between independent variable sensor value and dependent variable Torque value using linear regression analysis technique. Program stores the relation until next calibration is performed. Further, in case input is ‘no’, program does not perform any calibration and is directed to measurement loop where it performs torque calculation based on previously calibrated data. To calculate independent torque value, average value of hundred dependent torque effect values, sensed by strain gauge sensor, are used.

3.5 Signal Processing

The Strain gauges are glued on the shaft as a Wheatstone bridge pattern. Strain gauge senses strain on the shaft while torque is applied. Strain is directly proportional to applied torque on the shaft in case of pure torsion. Strain on the gauge change output of Wheatstone bridge. The output voltage in bridge is very small. HX711 is used to amplify the voltage signal which has 24 bit resolution (ALLDATSHEET.COM, 2021). Total resolution is divided into two parts, half of the resolution is used for clockwise and half of the resolution is used for anti-clockwise rotation. The amplified digital signal is transferred to Arduino Nano on accessible form. After calibration these voltage signals can be used to calculate torque applied to the shaft. Here glued strain gauge sensor rotates with machine shaft. To receive signal on rotating condition, HC05 Bluetooth module is used which communicates with stationary laptop serial monitor. The signal data is store by coolterm serial monitor. Relation between applied torque and output signal is deduced. The relation is recoded on Arduino and transducer operate with wirelessly. The excitation and output of glued Wheatstone strain gauges are connected with the HX711 module. Arduino Nano is used as the Input-output device for HX711 ADC and HC05 Bluetooth module. Here Personal Computer or Android smartphone can use to communicate the measurement signals. The connection of these components is as shown in Figure 3.15.

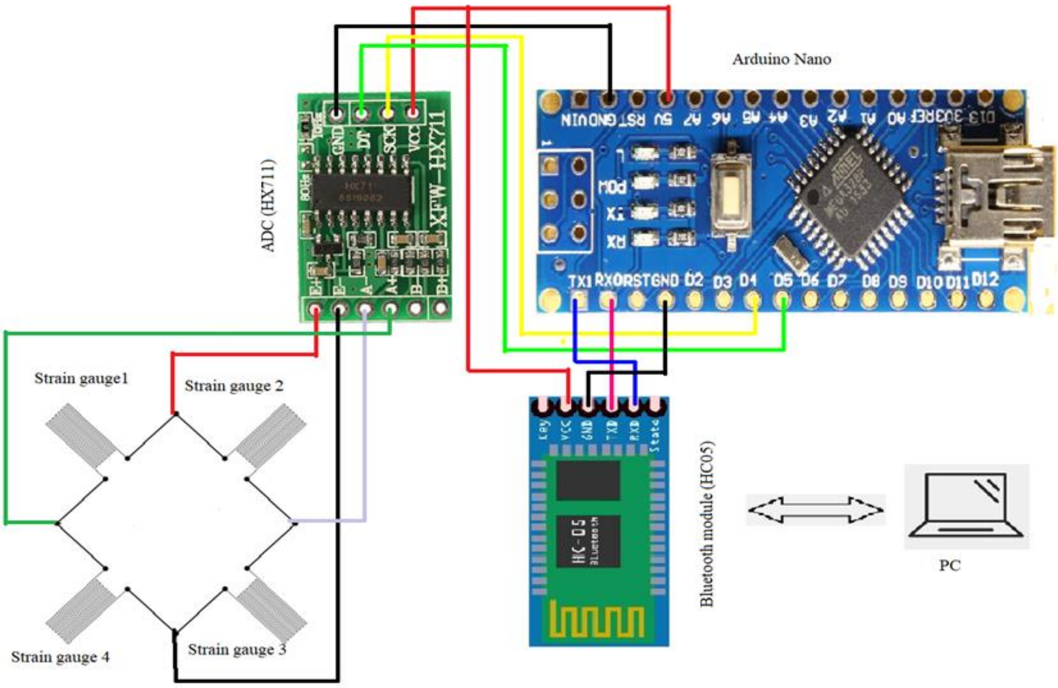

Figure 3. 15 Signal flow diagram

3.6 Linear regression

To determine the relationship between two or more variable regression can be used, which predicts change in dependent variable for specific change in independent variable by using the provided information about dependent and independent variable. Of the many forms of regression, linear regression is most common which concentrates on developing linear model for given values of independent variable for predicting corresponding values of dependent variable. If x is considered as independent variable (in this case Arduino Response) and y as dependent variable (in this case Applied torque), linear regression can be used on dependent and independent variables, to predict the values of dependent variable corresponding to value of independent variable.

$$y = c + mx$$

$$c = \frac{(\sum_{i=1}^{n} y)(\sum x^2) - (\sum_{i=1}^{n} x)(\sum_{i=1}^{n} xy)}{\mathrm{n}(\sum_{i=1}^{n} x^2) - (\sum_{i=1}^{n} x)^2}$$

$$m = \frac{\mathrm{n}(\sum_{i=1}^{n} xy) - (\sum_{i=1}^{n} x)(\sum_{i=1}^{n} y)}{\mathrm{n}(\sum_{i=1}^{n} x^2) - (\sum_{i=1}^{n} x)^2}$$

Where,

c = intercept of x and y

m = slope

3.7 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 3. 16. 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 (TEST BENCH, n.d.). 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 3.4. 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 three second for particular torque and RPM. In each sample reading, signal values have variation for a particular Torque and RPM. A number of experiments was done at different torque and different RPM.

Figure 3. 16 Torque measurement motor generator coupling (DE LORENZO)

CHAPTER FOUR: RESULT AND DISCUSSION

Literature review provides better picture of the experiment which runs throughout the project. Reading various articles, journals, explored website helped to find the right direction for the project. Further, lab for testing instrument was managed and test was scheduled. Hollow shaft was designed based on acquiring significant amount of strain with applied torque. Aluminum was chosen as shaft material and procurement was done from local market. Strain gauges were attached on Aluminum shaft. The connection between the strain gauges was Wheatstone bridge network. Two coupler for coupling torque transducer shaft to generator and motor were designed and fabricated. The shaft was assembled on generator and motor. The excitation voltage wire and output voltage wire of attached strain gauges were connected to the transducer circuit. The traducer electronic component were fixed on the transducer shaft. The orientation of portable electronics chips (i.e. HX711, Arduino, and HC05) were aligned such way that the chips tighten instead of getting loose. After the proper installation of complete components, the transducer was rotated and the strain value was stored in Coolterm serial monitor via Bluetooth communication. Various torque value and rpm were applied to the transducer and response of different condition were recorded for data analysis.

In this experiment, the response is affected by the different parameters. Majority of temperature effect is compensated by Wheatstone bridge circuit but it is not possible to completely eradicate the temperature effect which might produce error in transducer. Response of this torque traducer is affected by the vibration of machine and fluctuation on input power of motor. Here, the calibration torque meter is not completely precise due to which the torque transducer can further accumulate error.

Potential difference developed on bridge circuit depends upon the orientation of strain gauges. In this experiment, the arrangement is such a way that two strain gauges are in compressive and remaining two are in tension stress. But this arrangement may not ensure uniform stress on all strain gauges. The transducer shaft material properties also affects the response of the strain gauge sensor.

Torque transducer is affected by the accuracy and resolution of electronics component involved. Here HX711 ADC was used to amplify and convert the analog signal into digital signal. Arduino Nano was used as data transmission medium. HC05 Bluetooth module was used to communicate data wirelessly with serial monitor. Strain gauge’s stress limit, gauge factor, resistance, fatigue life and other properties affect the strain response of transducer.

4.1 Response of torque transducer with applied torque

The Figure 4. 1 shows the actual torque applied to the shaft and amplified potential difference of attached strain gauges. Amplified potential difference is the magnified form of potential difference produced in strain gauge due to strain. Torque applied to the shaft refers to the torque value provided by generator-motor coupling. For this experiment strain signals were received in every five second up to twenty sample for particular torque.

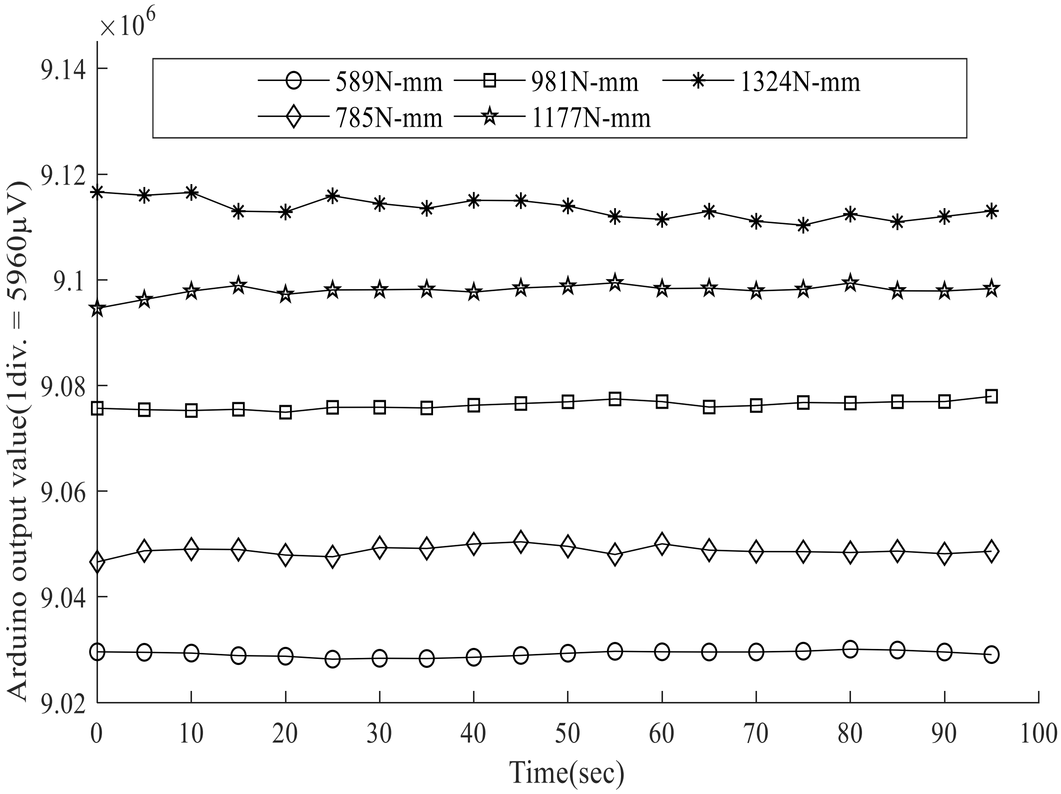

Figure 4. 1 Arduino reading vs time

Here experiment was done at different torque value. First of all, at 589Nmm torque the values provided by Arduino had lower fluctuation as compared to readings at torque value of 1324Nmm. In this experiment, at 589Nmm torque the RPM was 515 rpm and at 1324Nmm the RPM was 1355rpm. From this graph shows the signal is fluctuating at higher RPM. The data thus obtained was used for relation approximation between torque and strain signal, which in turn was used for calibrating the torque transducer.

4.2 Average response of torque transducer with applied torque

The Figure 4. 2 shows the relation between applied torque and response of torque transducer. Here nine set of torque are applied to the transducer at different rpm. Collection samples have different value on same torque. To calibrate the transducer, average value and standard deviation was calculated for every sample.

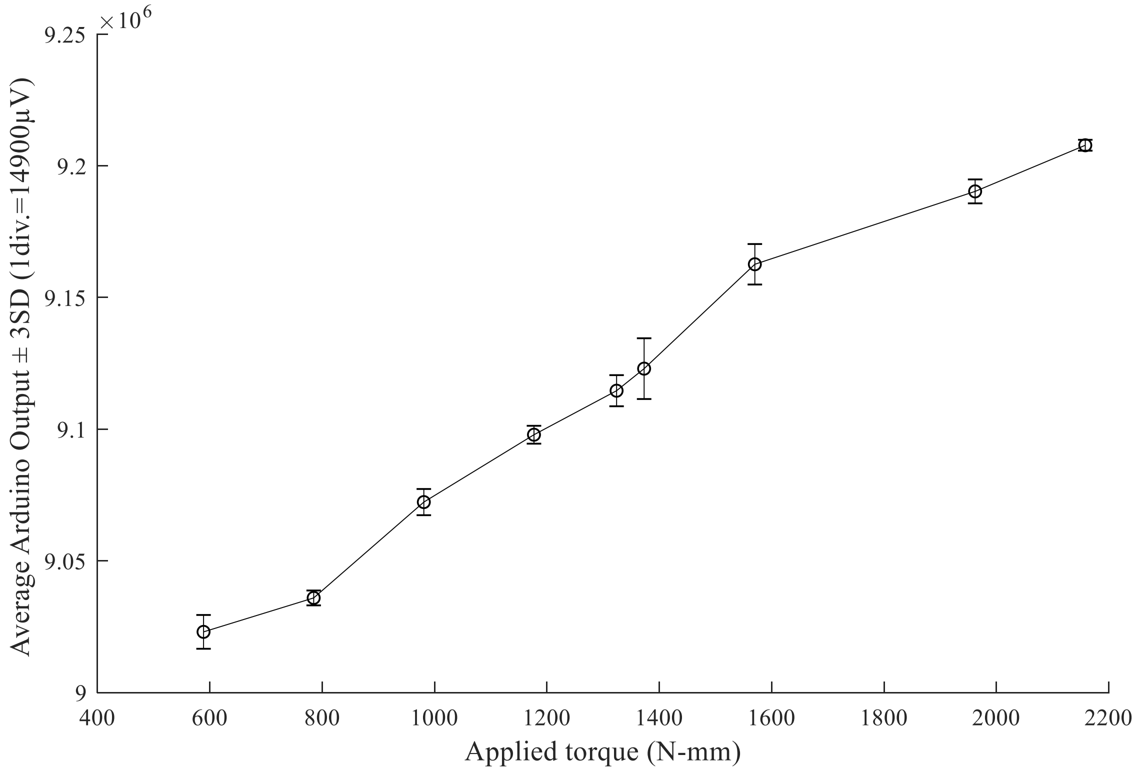

Figure 4. 2 Average Arduino output VS actual torque

According to Hooks law within the elastic limit the torque is directly proportion to the strain. From the Figure 4. 2 the strain response is not linear with the applied torque. In this experiment the linearity of response of Arduino with applied torque depends on the torque transducer shaft properties. Also, the response depends on accuracy and precision of electronics components. During the calibration of torque transducer it was difficult to accurately fix the applied torque for each experiment. Some variations were produce by grid line variation and vibration of machine.

The response data is up to 24 bits resolution. HX711 is responsible for data resolution. HC 05 Bluetooth module is responsible for wireless serial monitor communication. Arduino Nano as an input and output device was used to transmit data.

4.3 Calibration

To determine the relationship between two or more variable regression used, which predicts change in dependent variable torque for specific change in independent variable Arduino digital value response by using the provided information about dependent and independent variable. Of the many forms of regression, linear regression is most common which concentrates on developing linear model for given values of independent variable for predicting corresponding values of dependent variable. For a particular rotational speed and applied torque, strain signal transmitted by Bluetooth module of Arduino arrangement is recorded every five second upto twenty signals. The average of twenty signals is calculated, for different torque value different average value is recorded and thus obtained values are plotted in graph against applied torque.

Here calibrate the output torque from our experimental arrangement with torque reading of already available torque measurement setup. From these varying value average and standard deviation was calculated. Figure 4. 3 shows the regression line equation and R-square value is 0.95.

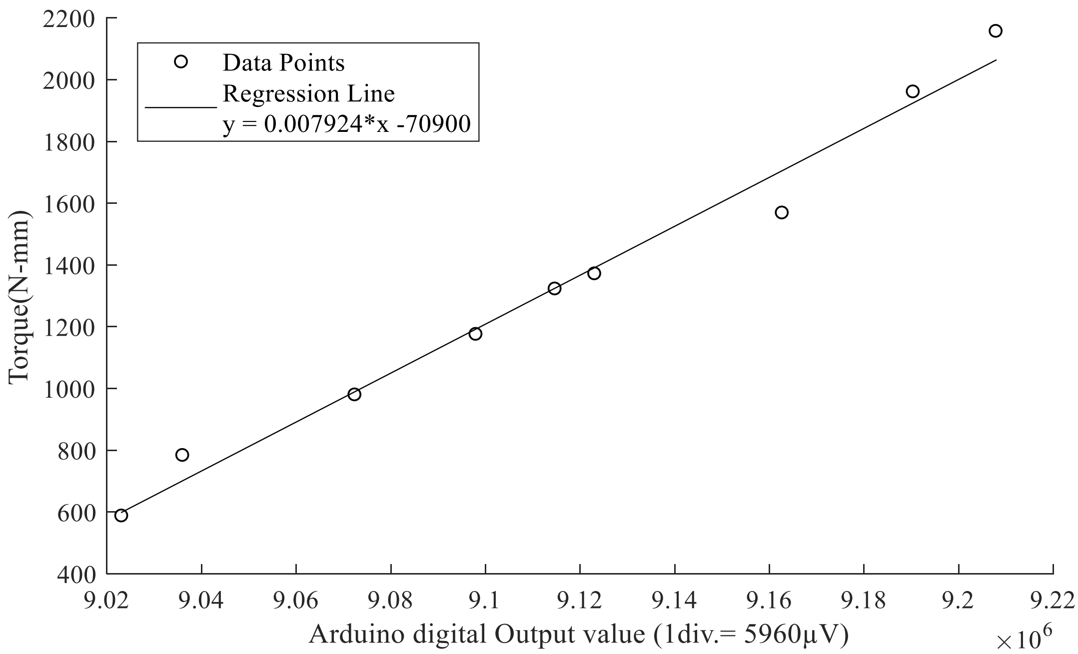

Figure 4. 3 Curve fitting

4.4 Response of average Arduino value on different RPM

Figure 4. 4 shows RPM vs Average Arduino output. Here by applying 589Nmm torque, three experiment at different RPM were performed. Similarly, three experiments were

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 was 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.

The variation of response with variation of RPM for particular applied torque, highly depend on stress strain behavior of the transducer shaft material. Also, strain gauge properties, electronics propertied, angle of alignment of strain gauge, adhesive quality etc. are cause of the response fluctuation. In this experiment, the calibration machine contain the vibration and this vibration is depend on the RPM, response is also effect by the calibration machine vibration.

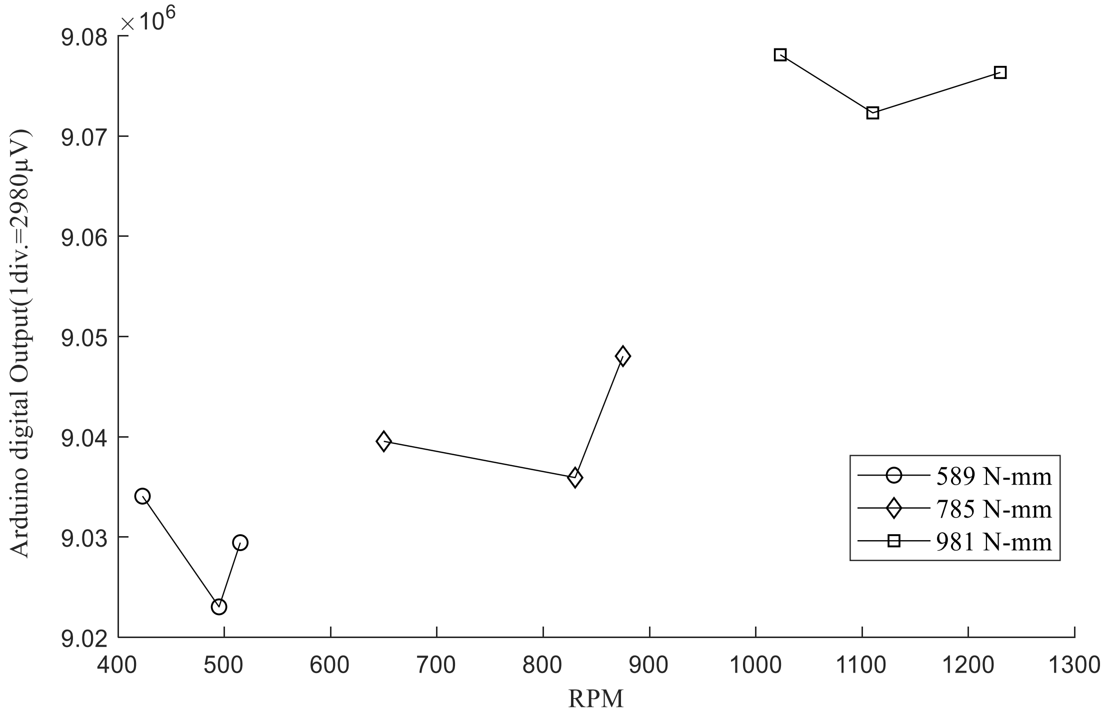

Figure 4. 4 Arduino average digital value output at different RPM (performance testing on different RPM for particular torque)

4.5 Toque transducer performance testing

From Figure 4.3, 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 only thereafter transducer electronic system is able to develop regression relation to measure the unknown torque. The data shown in Table 4 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. Form the Table 4.1, relative to the DE LORENZO reading, the mean absolute percentage error (MAPE) in the torque measurements of the proposed system is 3.73%, and the root mean square error (RMSE) is 129.

Table 4.1 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

4.6 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. Hence, this torque transducer comes with higher error margin. Further, the calibration frequency of prepared torque transducer device is higher.

4.7 Limitation

In this experiment, the transducer shaft is selected from the local market, the mechanical properties of the selected aluminum shaft were not reliable. The stress-strain behavior of the transducer shaft affects the repeatability of measurement. The available calibration machine also includes errors due to vibration on the machine while rotating at high speed. The calibration machine is included some errors provided by the manufacturer. During calibration, the applied torque did not be fixed precisely due to machine fault and supply line variation and this affect the calibration.

The selected component of this transducer component such as strain gauge, ADC, Arduino, Bluetooth module, transducer shaft, and strain gauge adhesive is procurement from the local market. These procured components did not have reliable data sheets so these components include some errors during the measurement.

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APPENDIX A: Torque Transducer Installation

Figure A. 1 Strain gauge glued on shaft at 45^0 to the axis

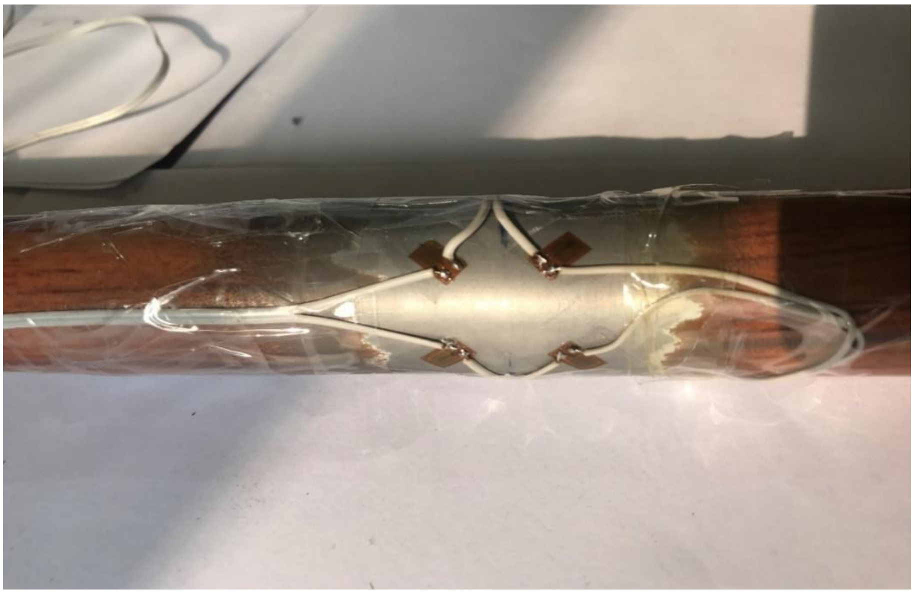

Figure A. 2 Strain gauge wired with Wheatstone bridge pattern

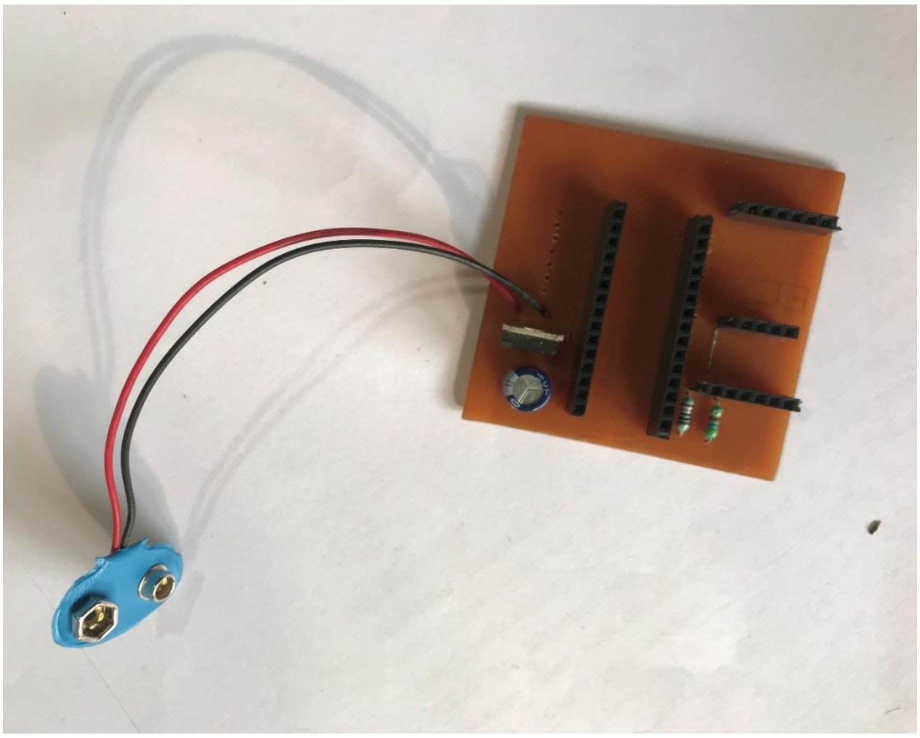

Figure A. 3 Printed circuit board for torque transducer

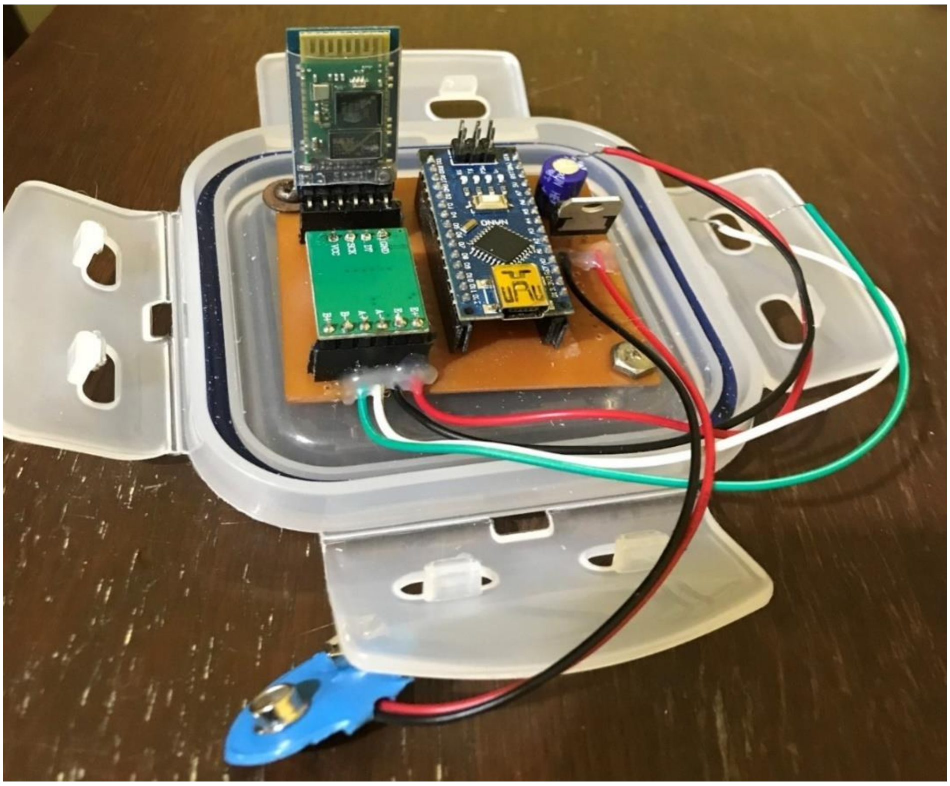

Figure A. 4 Transducer electronics on PCB and fixed on box top

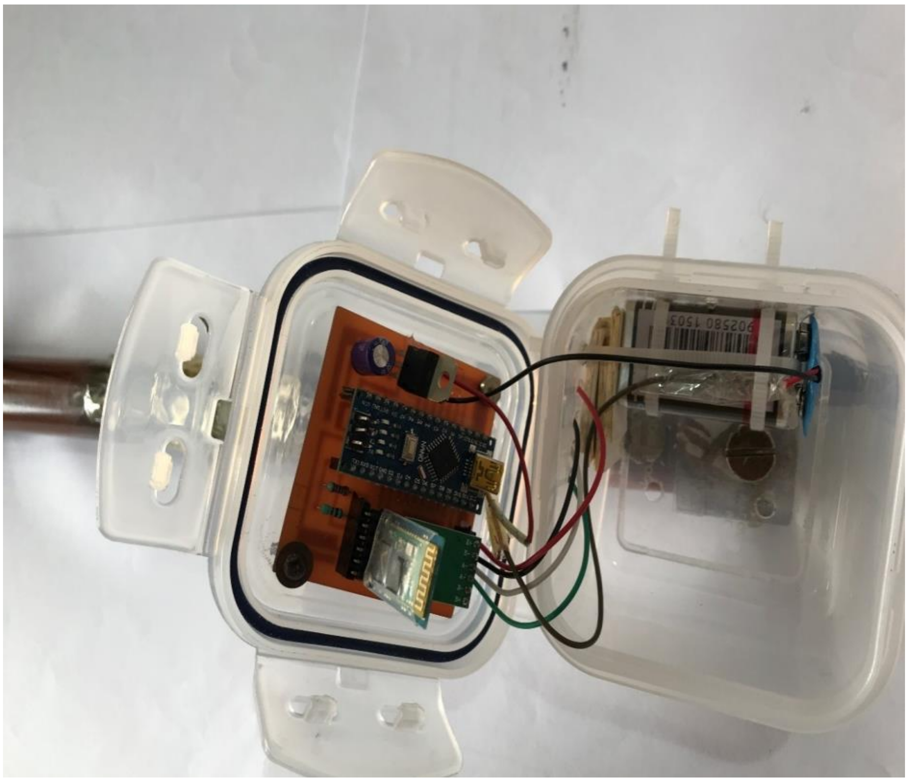

Figure A. 5 Transducer electronics with power facility

Figure A. 6 Power check and electronics hold on shaft

Figure A. 7 Load adjustment during the calibration

Figure A. 8 Constructed transducer

Figure A. 9 Torque transducer calibration

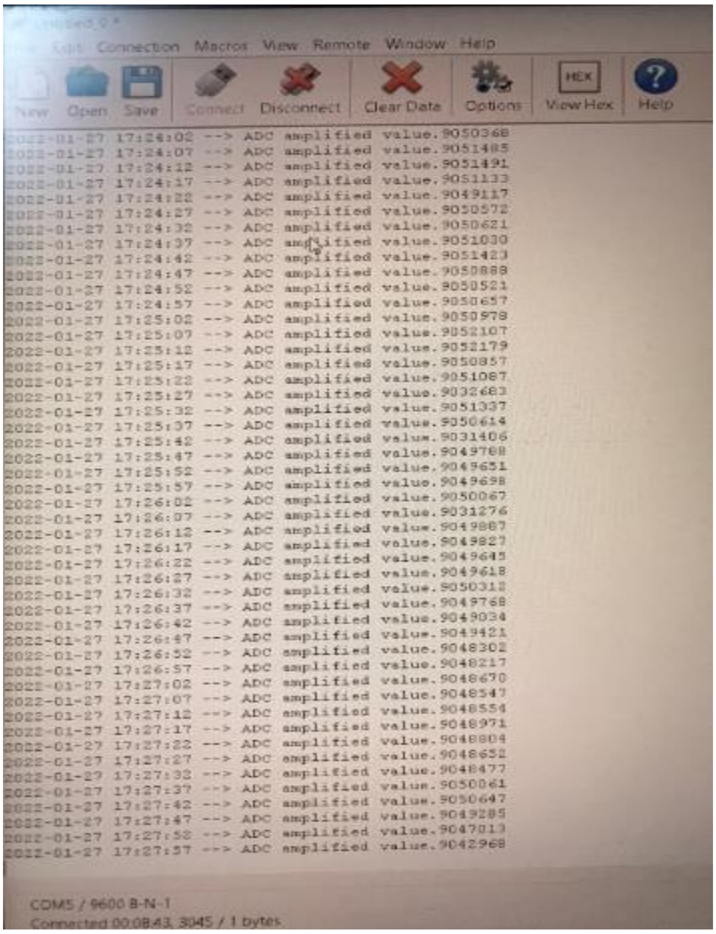

Figure A. 10 Arduino response serial data communication in Coolterm

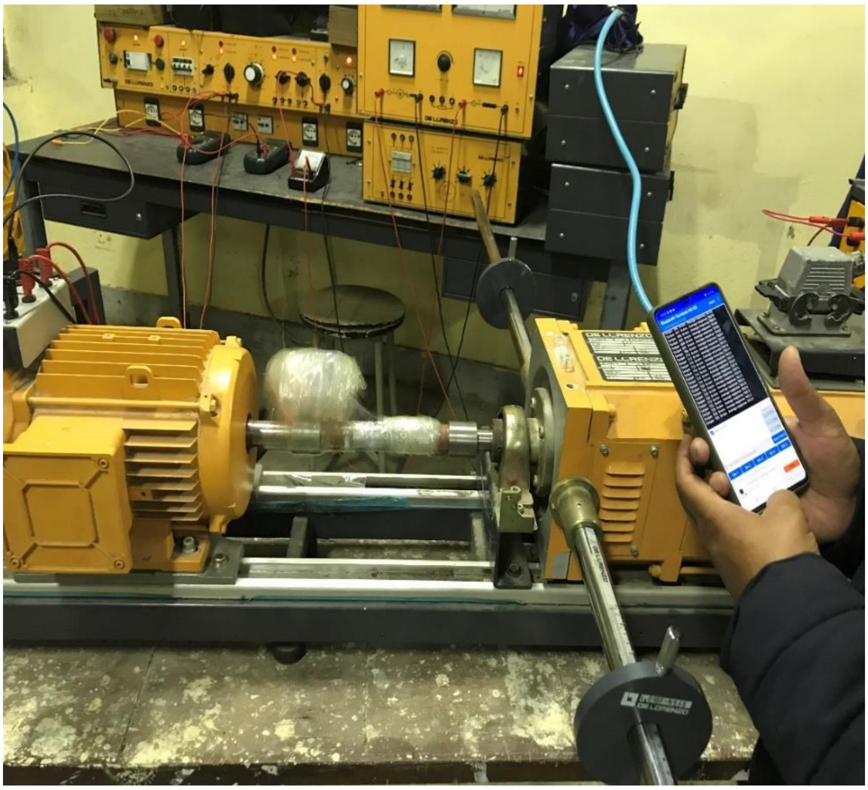

Figure A. 11 Transducer testing and measurement data wireless scrolling on smart phone

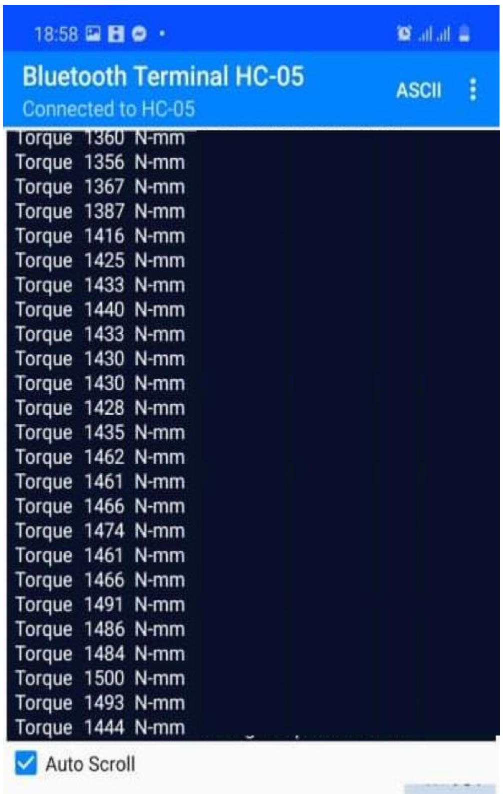

Figure A. 12 Torque transducer testing, data scroling on android smart phone

APPENDIX B: Transducer Program in Arduino IDE

```
#include <Q2HX711.h>
#include <EEPROM.h>

const byte hx711_data_pin = 5;   // connect HX711 data pin to D5 Arduino
const byte hx711_clock_pin = 4;  // connect HX711 sck pin to D4 Arduino

unsigned long Response;   // Arduino response
unsigned long sum;        // sum calculation for averaging 100 response
unsigned long c,m;      // c= intercept, m= slope
unsigned long  X, Y;
// x= strain value respone from HX711 deu to applied torque, Y= applied torque
unsigned int m_address = 0, c_address=8;       // to store calibration relation

Q2HX711 hx711(hx711_data_pin, hx711_clock_pin);

unsigned long strainValues[6];
// HX711 data out store in array during calibration
unsigned long torqueValues[6];
 // applied torque input store in array during calibration

boolean resume = false;

void setup() {             // put setup code here, to run once:
  Serial.begin(9600);       // burd rate
  Serial.print("Do you want to calibrate?\t");         // calibration demand
  while(Serial.available() == 0);                    // wait for input
  char input = Serial.read();                        // character read
  Serial.println(input);
  if(input == 'y') {
// sent y for new calibration and  other character for torque measurement on old calibration(
goes on void loop)
    for(int i = 0; i <6; i++) {
      Serial.print("Enter applied torque for y");
//  send applied torque value y1 to y6  in Nmm
      Serial.print(i+1);
      Serial.println(" in Nmm\t");
      resume = false;
      while(resume == false) {               // wait for  torque value input
      if(Serial.available() > 0) {
        float temp = Serial.parseFloat();       //
        if(temp != 0) {
          Serial.print(temp);
          torqueValues[i] = temp;      // input torque store in array
          resume = true;
          sum  =0;
          for (int i = 0; i < 100; i++)
//Take 100 readings of HX711 out put and average.  This loop takes about 100ms
```

```
        {
          Response = (hx711.read());        // read HX711 value
          sum = sum + Response;
//Sum for averaging to 100 HX711 data for particular torque input
        }
        strainValues[i] = (sum/100);       //  avverage of 100 sample
        Serial.print("Average value x:");
        Serial.println(strainValues[i]);
// HX711 out put store and print in array x1 to x6
      }
    }
  }
 }
 unsigned long s = 0;
 for(int i = 0; i <6; i++) {
   s = s + strainValues[i];       // total sum of HX711 output x1+x2....+x6
 }
 unsigned long k = s / 6;   //x mean, e.g (x1+x2...x6)/6)
 unsigned long t = 0;
 for(int i = 0; i <6; i++) {
   t = t + torqueValues[i];      //total sum input torque value (y1+y2...y6)
 }
 unsigned long l = t/6;     //y mean e.g(y1+y2...y3)/6


 unsigned long E=0;
  for(int i = 0; i <6; i++) {
   E = E+strainValues[i]-k;      //sum(x-x mean)  eg((x1-xmean)+....+(x6-xmean)
 }
 unsigned long F=0;
  for(int i = 0; i <6; i++) {
   F = F+torqueValues[i]-l;       //(sum (y-y mean) eg((y1-ymean)+....+(y6-ymean)
 }
 unsigned long G = 0;
 for(int i = 0; i <6; i++) {
   G = G+(strainValues[i]-k)*(strainValues[i]-k);
//(sum (x-x mean) squar eg((x1-xmean)sqrt +.....+(x6-xmean)sqrt)
 }
 unsigned long H = 0;
 for(int i = 0; i <6; i++) {
   H = G + (strainValues[i]-k)*(torqueValues[i]-l);
 //(sum (x-x mean)*(y-y mean) eg (x1-xmean)*(y1-ymean)+....)
 }
 m = H/G;    //y= mx +c   m(slope)= (sum (x-x mean)*(y-y mean)/(sum (x-x mean) squar
 c = l-m*k ;
 // intercept(c) calculate in mean value of y and x (the regression line is passed through mean
value of data)
 Serial.print("M: ");
 Serial.println(m);
```

```
  EEPROM.put(m_address, m);        //x EEPROM_writelong(0,m);
  Serial.print("C: ");
  Serial.println(c);
  EEPROM.put(c_address, c);        //x EEPROM_writelong(8,c);
}

}

void loop() {
  EEPROM.get(m_address, m);
  EEPROM.get(c_address, c);
  Serial.println("Saved Values");
  Serial.println(m);
  Serial.println(c);
  // put your main code here, to run repeatedly:
    sum = 0;

 for (int i = 0; i < 100; i++)
 //Take 1000 readings and average.  This loop takes about 100ms
 {
  Response = (hx711.read());
  sum = sum + Response;            //Sum for averaging during measurement
  }

  X= (sum/100);
  Y= m*X + c;
 // regression equation for torque Measurement m and c is data store
  Serial.print(" Torque \t");
  Serial.print(Y);
  Serial.print( " \t N-mm");
  Serial.print("\t Average response \t");
  Serial.println(X);
  delay(500);         // Delay 500 millisecond


}
```