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Calibration of Measurement Tools in the Experimental Test Rig for Hydropower Performance Evaluation

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ABSTRACT

The demonstration of a typical hydropower plant requires the development of a test rig with the installation of tools to measure the performance parameters. The measurement tools require a calibration process to improve the quality of recorded data. This study involved the calibration of traditional and automated measurement tools connected to the hydropower test rig through an Arduino microprocessor. The automated measurement tools included a pressure transducer, flow meter, digital tachometer, and torque transducer, while traditional measurement tools, including a pressure gauge, concrete water tank, contact tachometer, and force lever arm balance, were connected in the same test rig during the calibration process. Arduino microprocessor was employed with code to generate signals when connected to automated measurement tools. The results of automated tools varied linearly with traditional measurement tools, with R-squared closer to 1. Therefore, this study recommended that calibrating automated measurement tools during experimental testing is essential for accurately assessing the performance of the test rig development

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INTRODUCTION

Hydropower performance is primarily influenced by several key parameters, including flow rate, head, turbine rotational speed, and torque as the measured parameters during operation. The flow rate determines the amount of water that passes through the turbine, while the head represents the height difference that provides the water pressure. Rotational speed and torque relate to the mechanical power output of the turbine, as they directly affect the generated power (Kaunda, et al., 2012). These hydropower performance parameters must be optimized to achieve maximum efficiency and energy output (Karakoyun, 2024; Yildiz, et al., 2024). For instance, operating turbines outside their design flow range or seasonal flow fluctuations can significantly reduce energy output (Blume-Werry, & Everts, 2022). To ensure turbine efficient operation and energy output, hydropower plants rely on a range of measurement tools to monitor system performance (Majumder, et al., 2019).

Measurement tools play a vital role in recording the performance parameters of hydropower plants or a demonstrated test rig. These measurement tools fall into two main categories such as digital/automated and manual/handheld instruments. Digital measurement tools are typically integrated into modern hydropower systems for continuous, real-time monitoring with Supervisory Control and Data Acquisition (SCADA) systems or related tools, allowing for automated data logging, remote monitoring, and advanced diagnostics (Albița, & Selișteanu, 2023). Digital measurement tools enhance accuracy and efficiency by reducing human error and enabling constant system oversight for preventive maintenance and optimal performance (Alagöz, et al., 2021). In contrast, manual/handheld measurement tools are commonly used for field inspections and are simple to operate and do not require permanent installation, but their accuracy and consistency depend heavily on the operator's skill and environmental conditions. The integration of advanced digital tools offers enhanced accuracy, real-time monitoring, and predictive maintenance capabilities (Abba, 2025), while manual tools provide essential support for on-site inspections and immediate assessments (Mdee et al., 2018).

Combining hydropower test rig with an Arduino microprocessor allowed real-time monitoring of various key hydropower parameters using integrated sensors or transducers. Calibration of sensors and transducers is critical to ensure the accuracy and reliability of the collected data. Calibration measurements involved comparing the output of device such as sensor or instrument against known standard to ensure accuracy and reliability of measurements (Morris, & Langari, 2021). The calibration typically involved adjustments to the device to minimize any discrepancies between output and standard reference (Roody & Ginzberg, 1994). Different instruments or tools have different accuracy range as per provided from the specific manufacturer with the data sheet specifications (Rawal & Kshirsagar, 2007). Meaning while, using the microprocessors including Arduino microprocessor connected with sensors and transducers helped to read the data during experimental test rig. The sensors and transducers required the calibration before attached to the microprocessors (Monk, 2016).

Arduino microcontroller was often utilized in data collection and storage tasks in various research and practical applications including hydropower application. Researchers integrated sensors and transducers with Arduino boards to measure environmental parameters, such as temperature, humidity, and light intensity (Mobaraki, et al., 2020), aquaculture (Islam, et al., 2022), and so forth. The sensors and transducers converted physical parameters into electrical signals, which the Arduino then read and processed data. Data logging shields or computer with USB were commonly attached to the Arduino to facilitate the data storage

(Banzi & Shiloh, 2014). The common types of Arduino are shown in Figure 1. The collected data was then saved in CSV format, making it easy to analyze later using spreadsheet software or custom scripts in Python or MATLAB environment.

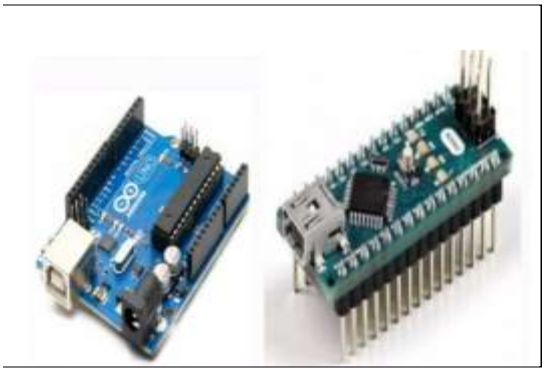

Figure 1: Types of Arduino, including Arduino Uno and Nano (Monk, 2016).

METHODS AND MATERIALS

The codes for running Arduino microprocessor is presented in Appendix 1 and work flow sheet for experimental setting is presented in Figure 2. Two pressure transducers (2.5 and 10 bar) were connected to the pressure gauge during calibration. The pressure transducer was connected one-side to the compressor gas tank valve and another to the Arduino processor. The flowmeter was calibrated using the concrete calibrated water tank of 30 m^3 capacity. The water filled in the calibrated tank and stopped after 1 minute by closing the ball valve. The calibrated tank consists of a manometer tube as used to indicate the water height inside the tank. The measured volume of water is equal to the cross-sectional area of the tank times measured water height. The flow rate was calculated as the ratio of measured volume and specific time taken. The data from the calibrated concrete water tank was recorded simultaneously with the reading data from the digital flow meter.

The contact and digital tachometers were applied together during measuring the rotational speed of the shaft. The contact tachometer is attached to the center of a shaft for recording shaft speed. At the same time, digital tachometer was pointed short distance from the rotating shaft for recording shaft speed. The rotating shaft was portion coated with the reflector materials as working together with the digital tachometer.

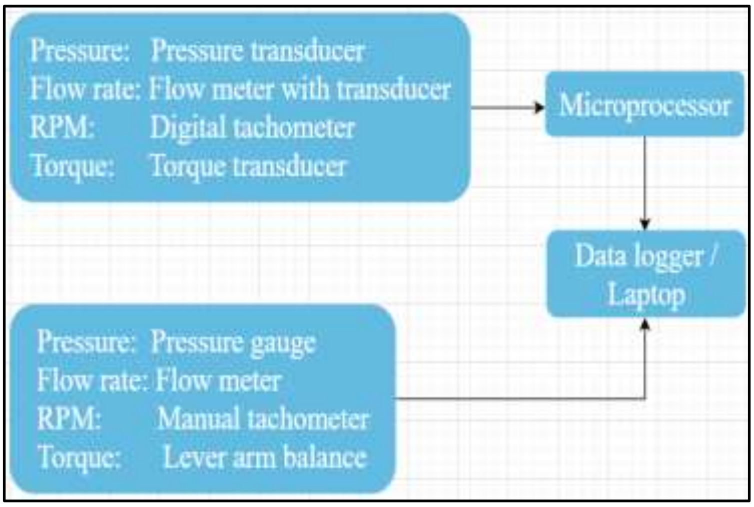

Figure 2: Calibration flow sheet for hydropower parameters measurement.

The torque meter built with transducer for detecting any torque between the two sides. The torque measurement involved preparation of an iron-angle bar, U-bolt with threads, and weight balance as described in Mdee, et al. (2019). The list of tools used during experimental works is presented in Table 1.

Table 1: List of tools with their specifications used during experimental works

Instrument	**Trade name**	**Specification**	**Measured uncertainty**
Flow meter	Optiflux 2000C	DN 50mm and 60 bar 0 to 21.2 m^3/h	±0.231%
Pressure transducer	GE UNIK 500	0-5 bar	±0.495%
	GE Drunk PTX 1400	0-4 bar	±1.154%
Torque transducer	HBM T22	200 Nm	PAT ±1.777% Pump ±0.563%
Speed Sensor	-	-	±0.025%

Data Analysis

Both traditional and digital tools were used to measure the same parameters. As data values recorded increase, the estimated mean value tends to approach the true standard value (EN ISO 5198, 1999). The fitness of data recorded using traditional and digital tools were compared using the R-squared coefficient. The R-squared is the coefficient of one minus the ratio of the sum of squares of residuals and total sum of squares. The coefficient of R-squared ranged between 0 and 1; away from 1 indicates a weak degree of fitness (Campbell & Campbell, 2008).

RESULTS AND DISCUSSIONS

Calibration of Pressure Transducers

The data of two pressure transducers (2.5 bar and 10 bar) were compared with the data from the pressure gauge. Figure 3 shows the linear relationship of pressure transducers (PT) and pressure gauge (PG) with the R-squared of 0.999.

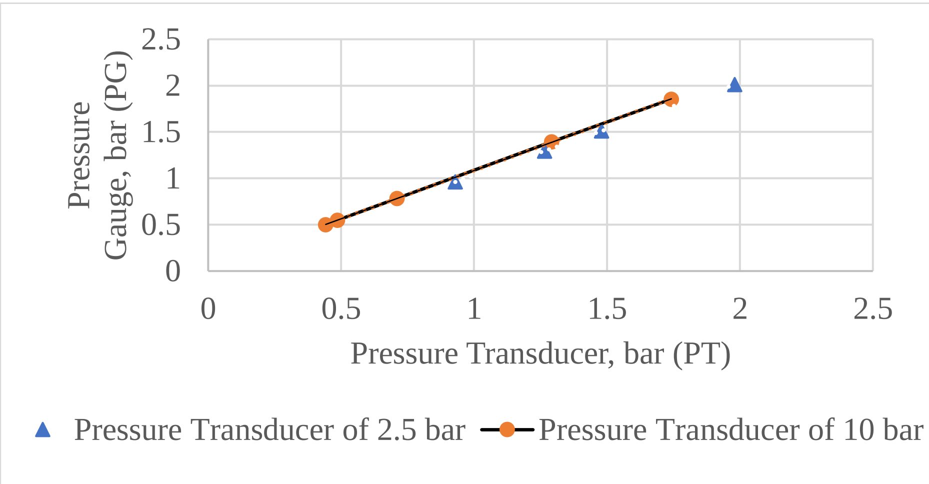

Figure 3: Comparison of measured data of two pressure transducers and pressure gauge

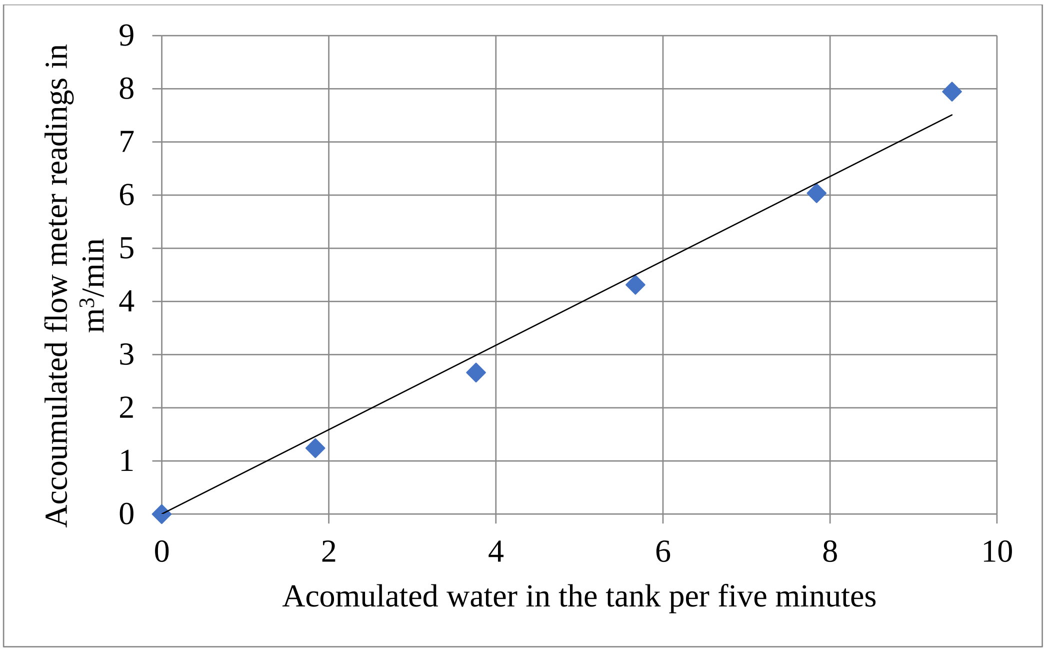

Figure 4: Comparison of measured data of the flow meter and calibrated water tank

Calibration of Flow meter

Lastly, every 1-minute the water passed through the flow meter was recorded, at same time, filled to the calibrated concrete water tank. Figure 4 shows the accumulated flow rate recorded in the flow-meter (FM) and accumulated water flow in the concrete water tank (CWT) with the R squared of 0.990.

Calibration of Tachometer

The measured data from both contact tachometer (CT) and digital tachometer (DT) are presented in Figure 5. The tachometers varied linearly with the R-squared of 0.995.

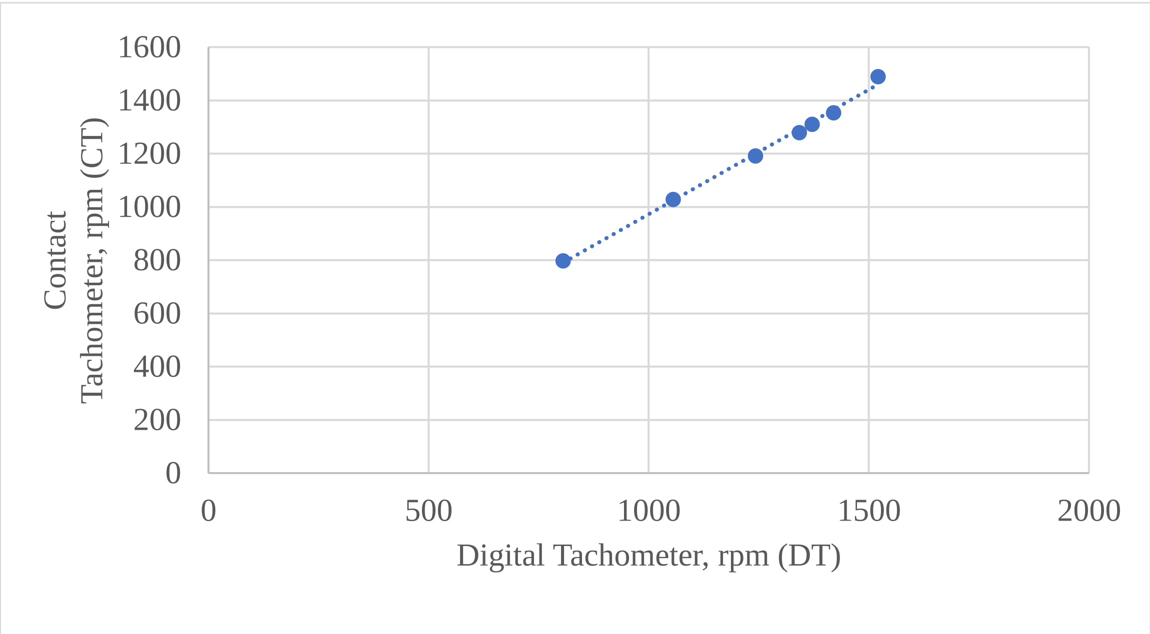

Figure 5: Comparison of measured data of contact tachometer and digital tachometer

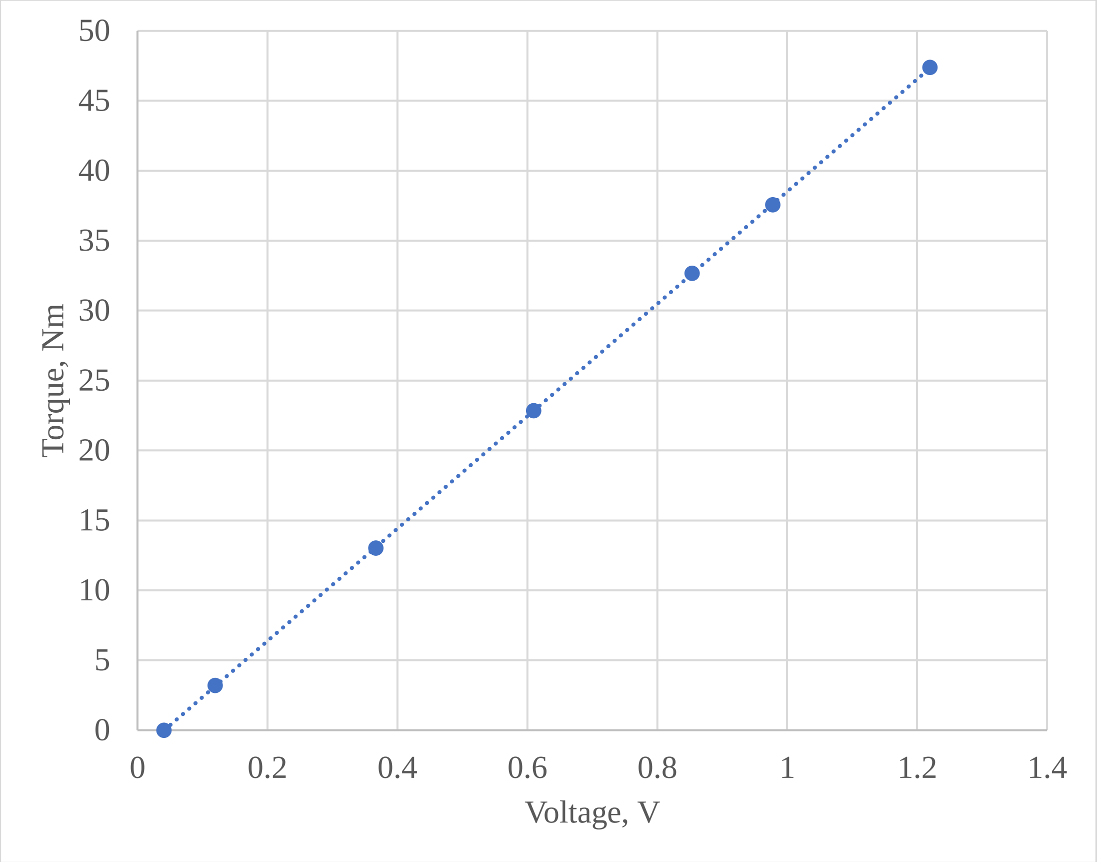

Figure 6: Comparison of measured data of voltage for in-built torque transducer and calculated torque

Calibration of Torque Transducer

The torque calculated as generated force times the perpendicular distance. But, the transducer built in the torque provided voltage signals in the Arduino processor that corresponded to the generated force. Figure 6 shows the variation of the calculated torque (TT) and generated voltage (V) with the R-squared of 0.999. The linear relationship of four calibrated instruments for measuring the hydropower parameters is expressed in Equation (1).

$$\left.\begin{array}{l} Speed: DT = 0.94CT + 36.68\,. \\ 10\ bars: PT = 1.04PG + 0.04 \\ 2.5\ bars: PT = 0.99PG + 0.03 \\ Torque: TT = 40.17V - 0.66 \\ Flow\ meter: FM = 0.793CWT \end{array}\right\} \quad (1)$$

CONCLUSIONS

This study calibrated the digital measurement tools such as pressure transducer, digital tachometer, torque transducer, and flow meter connected with the Arduino microprocessor concurrent with the manual/handheld measurement tools. The methods involved connecting parallel the digital tools with Arduino and handheld tools before starting recording data. Even for the same input values recorded in the digital tools shown different values from the either of handheld tools such as contact tachometer, pressure gauge, force lever arm balance, and calibrated concrete water tank. The calibrated pressure transducers and pressure gauge as used to measure inlet and outlet pressure, varied significant linearly with R-squared of 0.99; flow meter with sensor and calibrated concrete water tank as used to measure the water flow, varied linearly with R-squared of 0.99; digital tachometer and contact tachometer as used to measure the rotational speed, varied linearly with the R-squared of 0.99; lastly, torque transducer and force lever arm balance as used to measure the torque, varied linearly with R-squared of 0.99. This study provided insight information of calibrating the digital measurement tools before starting experimental works and would improve the quality of automated measurement data.

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Appendix 1. Arduino code for microprocessor to read with excel software

```
int reading0;   // Variable with numbers from 0 to 1024 (10-bit)
int reading1;
int reading2;
int reading3; // variable for flow rate from 0 to 1024
floatPinlet;   // Variable with value from Analog A0 to A5
floatPoutlet; // For A1
float Torque; // For A2
float Flowrate; // For A3
voidsetup(){
  // put your setup code here, to run once:
Serial.begin(9600);   // communication between computer and arduino
Serial.println("CLEARSHEET"); // to clear all data in the activesheet include active label
// to set the labels for the top most row of the Activesheet.
Serial.println("LABEL, DATE, TIME, TIMER, millis, Pinlet, Poutlet, Torque, Flowrate");
Serial.println("RESETTIMER"); // to reset timer to 0.}
voidloop() // Over and over to run the program{
reading0=analogRead(A0);
Pinlet=((float)reading0*4.72)/1024; //10 bar pressure as the maximum pressure of transducer
reading1=analogRead(A1);
Poutlet=((float)reading1*4.72)/1024; //2 bar pressure as the maximum pressure of transducer
reading2=analogRead(A2);
Torque=((float)reading2*4.72)/1024; // 500 NM torque as the maximum torque of torque transducer
reading3=analogRead(A3);
Flowrate=((float)reading3*4.72)/1024;   // 380 m3/hr as the maximum flow rate measured by the flow meter
//to send data from your Arduino to excel and printed to activesheet
Serial.print((String)"DATA, DATE, TIME, TIMER," + millis()+",AUTOSCROLL_20");
Serial.print(",");
Serial.print(Pinlet);   // Print takes in new line for pressure inlet at A0
Serial.print(",");
Serial.print(Poutlet); // Print takes in a new line for pressure outlet at A1
Serial.print(",");
Serial.print(Torque); // Print takes in a new line for torque at A2
Serial.print(",");
Serial.print(Flowrate); // Print takes in a new line for flow rate at A3
Serial.println();
delay(1000); //Wait for 100 mill second before next reading}
```