Comparison of Experimental Shaft Power of a Centrifugal Pump: Wireless Strain Gauges, Load Cell Sensor, and Electrical Approaches

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Keywords: Centrifugal Pump, Shaft Power, Efficiency, Stress, Strain, Wireless Strain Gauges, Load Cell Sensor.

Abstract: This study involves an experimental investigation of a centrifugal pump driven by an electric motor to determine the pump shaft power using three different approaches for power quality control. The centrifugal pump is operated at a constant rotational speed while varying the flow rate. To evaluate the relevance and accuracy of the shaft power calculation, experimental tests are conducted using an existing centrifugal pump test bench. First, the pump shaft power is measured based on the electric power supplied to the pump motor. This shaft power depends on the efficiency of the electric motor, which can introduce uncertainty in the performance results when motors with different efficiencies are used. Second, wireless strain gauges are applied to the pump shaft to measure its strains, which are converted into torque, ultimately providing the measurement of power at the pump inlet. Third, a load cell sensor is used. The results indicate that wireless strain gauges can accurately measure the shaft torque and allow for the measurement of shaft power with a very small relative error compared to the shaft power obtained from electric power and motor efficiency.

1 INTRODUCTION

Centrifugal pumps are extensively used, particularly in the industrial sector. They are designed, manufactured, and experimentally characterized to generate characteristic curves for head, shaft power, efficiency, and cavitation, represented by the Net Positive Suction Head (NPSH) based on flow rate (Gülich, 2010). Accurately determining the mechanical power of a centrifugal pump directly coupled to the shaft of an electric motor is crucial for ensuring energy efficiency, performance, durability, reliability, and safety, thereby enabling efficient, economical, and sustainable pump operation. Mechanical power varies with the pump flow rate. In most cases, the mechanical power of a pump is determined using the input electric power and the efficiency of a fixed or variable speed electric motor. Given that the efficiency of the electric motor can vary from one motor to another, it would be beneficial to know the power directly at the pump's input to more accurately determine its performance. This is especially important when pump manufacturers deliver pumps separately to be connected to the user's electric motor, which is not tested on the test bench for pump characterization.

Several research studies have evaluated the mechanical power of a pump based on the electric power input to the electric motor (Hydraulic Institute, 2011). In (Pambudi et al., 2024; Ahonen et al., 2012), the mechanical power of a centrifugal pump is calculated using the electric power of a three-phase alternating current motor, taking into account the motor's efficiency. (Pambudi et al., 2024) describes the parameters that significantly affect the electric motor's efficiency, as well as its electrical and mechanical losses. (Ahonen et al., 2012) illustrates the pump characteristics as a function of the electric current.

Moreover, (Sezer and Şahin, 2023) presents an experimental investigation of centrifugal pump characteristics, where the electric power is calculated using the measured electric current and voltage. The overall efficiency of the pump is determined using the pump head and electric power. However, the mechanical power is not calculated, and the variation of electric power with flow rate is illustrated.

Additionally, the mechanical power of a pump can be determined using load cell technology, which calculates torque from the force and lever arm. The shaft power is then obtained by multiplying the torque by the angular speed of the electric motor, with its rotational speed measured using a speed sensor. Wireless strain gauges are also employed to calculate the me-

St-Louis, P., El Assaf, B., Ngoma, G. D. and Erchiqui, F.
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DOI: 10.5220/0013557800003970
In *Proceedings of the 15th International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH 2025)*, pages 305-311
ISBN: 978-989-758-759-7; ISSN: 2184-2841

chanical power of a pump. Specifically, shear stress is derived from the shear strain of the pump shaft, which is obtained from the normal strains indicated by the strain gauges. The torque is then calculated from the shear stress and the shear modulus of the shaft material, considering the shaft geometry.

In (Gujarati et al., 2020), a multi-axis force torque sensor is developed, incorporating a strain measuring sensor, a signal processing circuit, and a data processing solution. The study compares force sensing solutions using strain gauges, piezoelectric sensors, and force-sensitive resistors. In (Malonda and Dituba Ngoma, 2023), a test bench is created to determine the strains and stresses on a pump shaft with an impeller using wireless strain gauge technology. Additionally, (Iriarte et al., 2021) estimates mechanical loads in shafts using strain gauges, identifying the optimal gauge locations on the shaft. In (Billur and Kerem, 2024), strain gauges are used to experimentally measure strain values of steel material during tensile, bending, and torsion tests within the material's linear region. Numerical analysis using the finite element method and theoretical approaches are also employed to compare strain value results. (Sabah Al-Dahiree et al., 2022) details the design and analysis of a strain gauge load cell, covering everything from initial conceptual design to shape optimization and calibration. This approach ensures ample load capacity using low-cost materials while achieving highly accurate force measurements. The load cell's structured shape is optimized through stress-strain analysis using the finite element method, enhancing its characteristics by reducing weight and increasing sensitivity within the allowable load range. Furthermore, (Bleho et al., 2023) conducts an experimental study to measure the force load on a single blade as the pump rotates, using a strain gauge and a data acquisition system.

From the foregoing, the error made when reading the torque on the pump shaft from the motor electric current is not precisely known. Therefore, to ensure better quality control in centrifugal pump systems, this research aims to compare different approaches for determining mechanical power on the pump shaft and to validate the relevance of measuring the torque at the pump.

2 CENTRIFUGAL PUMP PARAMETERS, ELECTRICAL VOLTAGE AND STRAIN FROM THE TRAIN GAUGE

2.1 Centrifugal Pump Parameters

2.1.1 Pump Shaft Power from Electric Motor Current

The electric power input to the electric motor can be expressed as (Ahonen et al., 2012):

$$P_e = \sqrt{3}\, E\, I\, P_f \tag{1}$$

where: E is the electrical voltage in a branch; I is the electric current in a branch; and P_f is the power factor of the electric motor ($\cos\phi$).

When the measured shaft power on a centrifugal pump test bench is derived from the current entering the electric motor, it can be written as:

$$P_s = P_e\, \eta_e \tag{2}$$

where η_e is the electric motor efficiency.

Furthermore, the shear stress on the pump shaft is given by:

$$\tau = G\,\gamma \tag{3}$$

where G is the shear modulus, it is expressed as $G = \frac{E}{2(1+\nu)}$; E is the Young's modulus; ν is the Poisson's ratio and γ is the shear strain.

The shaft torque is given by:

$$T = \frac{J\tau}{r} \tag{4}$$

where r is the pump shaft radius and J is the the polar moment of inertia of the shaft ($J = \frac{\pi r^4}{2}$).

Additionally, the mechanical power can be formulated as:

$$P_s = T\omega \tag{5}$$

where ω is the angular velocity of the electric motor.

2.1.2 Pump Head

The pump head can be written as follows:

$$H = \frac{p_{in} - p_{out}}{\rho\, g} \tag{6}$$

where p_{in} is the pump pressure inlet; p_{out} is the pump pressure outlet; ρ is the liquid density; and g is the gravitational acceleration ($9,81\ m/s^2$).

2.1.3 Pump Hydraulic Power

The hydraulic power provided by a pump can be expressed by:

$$P_h = \rho\, g\, Q\, H \tag{7}$$

where Q is the flow rate.

2.1.4 Pump Efficiency

The overall efficiency of a pump is the ratio of the hydraulic power to the shaft power:

$$\eta = \frac{P_h}{P_s} \tag{8}$$

2.2 Relationship Between Electrical Voltage and Strain from the Strain Gauge

Strain gauge technology utilizes a Wheatstone bridge circuit to accurately measure small changes in resistance caused by strain. The simple Wheatstone bridge circuit (Hewlett-Packard Co., 1981) can be characterized by an arrangement of four resistances on two parallel branches, as indicated in Figure 1. There are two resistances (R_1 and R_2) in series in the first branch and two other resistances (R_g and R_3) in series in the second branch. The circuit is powered with a given voltage V_{in}. The strain gauge is represented by the resistance R_g, and when the material deforms, its resistance changes, resulting in a different voltage reading between the resistances of the two branches, V_{out}.

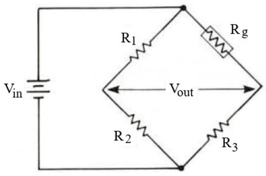

Figure 1: Simple Wheatstone Bridge Circuit.

The ratio of V_{out} to V_{in} is expressed by:

$$\frac{V_{out}}{V_{in}} = \left(\frac{R_3}{R_3 + R_g} - \frac{R_2}{R_1 + R_2}\right) \tag{9}$$

For an unbalanced Wheatstone bridge circuit, the measured strain is formulated as follows:

$$\varepsilon = \frac{-4V_r}{GF(1 + 2V_r)} \tag{10}$$

where

$$V_r = \left(\frac{V_{out}}{V_{in}}\right)_{strained} - \left(\frac{V_{out}}{V_{in}}\right)_{unstrained}, \tag{11}$$

GF is the gauge factor based on the gauge material. It is given by:

$$GF = \frac{\frac{\Delta R_g}{R_g}}{\varepsilon}, \tag{12}$$

ΔR_g is the change in resistance of the gauge when strained ($\Delta R_g = R_{g,strained} - R_g$).

Furthermore, for a full Wheatstone bridge circuit as depicted in Figure 2 (Hottinger Brüel and Kjær, 2025), the strain can be determined using Equation 13.

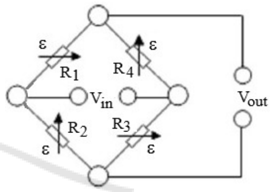

Figure 2: Wheatstone Bridge Circuit for Gauges Measuring Torsion.

$$\varepsilon = \varepsilon_d = \frac{V_{out}}{GF\ V_{in}} \tag{13}$$

where ε_d is the shear strain measured by each gauge.

3 EXPERIMENTAL TESTS

Figure 3 shows the existing centrifugal pump test bench (School of Engineering, 2025) used for characterizing the pump under variable operating conditions in terms of flow rates at a fixed rotational speed of the electric motor. The tests conducted in this study allow for a comparison between the mechanical power from the electric current and an estimate electric motor efficiency, and the mechanical power from the torque (load cell sensor and wireless strain gauges) and the rotational speed. This is to determine the accuracy of the torque measurement technology.

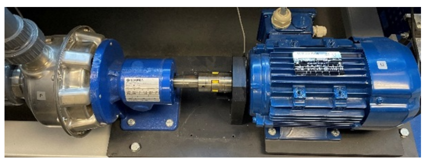

Figure 3: Centrifugal Pump Test Bench.

In addition, the characteristics of the electric motor driving the test bench pump are summarized in Table 1.

Table 1: Electric Motor Characteristics.

Voltage V	$\Delta 230/Y400$	$\Delta 265/Y460$
Frequency Hz	50	60
Power kW	2.2	2.64
Power Factor -	0.85	0.85
Rotational speed rpm	2890	3465
Current	7.81/4.49	8.13/4.69
Efficiency	83.2	83.2

The used test bench provides a torque measurement by means of the load cell sensor "Flintec ZLB-20kg-C3" (Flintec, 2025), making it possible to directly validate the torque from strain gauges. The flow rate of the centrifugal pump is regulated by a throttle valve when the centrifugal pump operates at a fixed rotational speed. The mechanical power is calculated from Equation (5). Moreover, the wireless strain gauges are installed on the pump shaft to obtain a torque value and verify that the result is consistent using the test bench's speed sensor to complete the mechanical power measurement. Hydraulic power can also be determined from the pump's flow rate and discharge pressure accounting for the suction pressure using Equation (7). To measure the electric power input to the electric motor driven the centrifugal pump, the two-wattmeter method (Matlakala et al., 2019) is used on the three-phase circuit supplying the electric motor. Thus, two identical wattmeters are used as indicated in Figure 4 to get the electric power for each flow rate at a fixed rotational speed.

Moreover, the voltage data from the wireless strain gauges are transmitted by a transmitter connected to the gauges and received by a receiver, which is connected to an oscilloscope (TPS 2024 oscilloscope Tektronix: Figure 5) to read the measurement. The transmitter system used is the TECAT WISER 4000 as depicted in Figures 5 and 6 (Malonda and Dituba Ngoma, 2023).

Furthermore, to install the strain gauges on the pump shaft, each gauge is attached at a 45° on the shaft as shown in Figures 7 and 8. They are connected to the transmitter's electronic board. Then, the electronic board and the transmitter's battery are secured to the shaft using adhesive tape. They are well-fixed since they are needed to withstand a shaft rotation of 2900 rpm. The receiver part of the transmitter is connected to the oscilloscope to read the voltage differences caused by the gauge strain.

To measure the strain on the gauges placed on the shaft from the voltage read by the data acquisition

Figure 4: Lutron DW-6060 Watt Meter (School of Engineering, 2025).

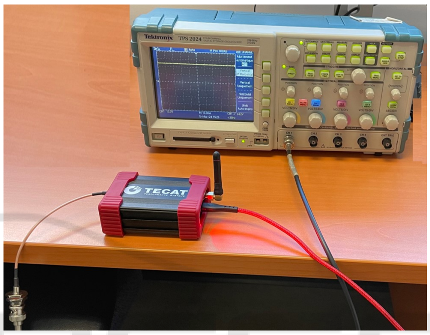

Figure 5: Connecting the Receiver and Oscilloscope for Laboratory Testing (School of Engineering, 2025).

Figure 6: TECAT WISER 4000 (TECAT Performance Systems, LLC, 2018).

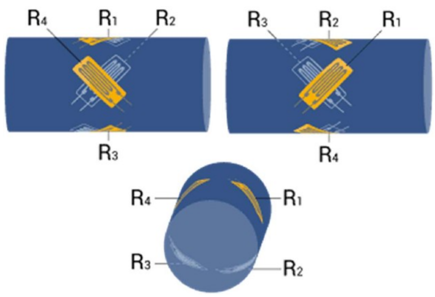

Figure 7: Arrangement of Strain Gauges on the Shaft (Hottinger Brüel and Kjær, 2025).

system, the Wheatstone bridge theory is used for the specific gauge arrangement in this test (Figure 2). The shear strain is calculated using a gauge factor of 2.06.

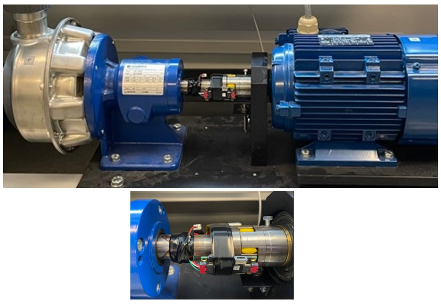

Figure 8: Strain Gauges on the Pump Shaft (School of Engineering, 2025).

4 RESULTS AND DISCUSSION

Experimental tests for centrifugal pump head, strain, stress, torque, mechanical power, and electric power are conducted using the reference data provided in Table 2.

Table 2: Reference data for the pump.

Shaft diameter [m]	0,0246
Young's modulus [Pa]	$196x10^9$
Shear modulus [Pa]	$75.3x10^9$
Rotational speed [rpm]	2900
Water density at 25° $[kg/m^3]$	997
Water kinematic viscosity $[m^2/s]$	$0.884x10^{-6}$
Flow rate range [m³/h]	0.5 – 31.9

4.1 Torques from Load Cell Sensor and Wireless Strain Gauges

Figure 9 shows the curves of shear strain and shear stress on the pump shaft as functions of the flow rate. The shear strains from the wireless strain gauges are determined using Equation 13, and the corresponding shear stresses on the pump shaft are calculated using Equation 3. From this figure, it can be seen that both shear strain and shear stress on the pump shaft increase with the rise in the flow rate of the centrifugal pump. This can be explained by the increase in shaft torque with rising flow rate.

The strain gauges and transmitter can then be positioned on the shaft to measure strains and calculate the transmitted torque. This, combined with the measurement from an accurate load cell sensor, allows for the verification of the measurement tool's accuracy.

Moreover, the torque curves from the load cell and wireless strain gauges are illustrated in Figure 10. The torque obtained with the load cell sensor is greater than that measured by the strain gauges.

Focusing on the torque values, significant discrepancies between the measurements provided by the wireless strain gauges and those provided by the load cell sensor are noted. The load cell sensor reads only very small strains, which can lead to some uncertainty in the measurement since very small variations in strain can have a large effect on the final measurement. Furthermore, the strain gauges may not be placed exactly at 45° as intended, since it is difficult to accurately measure the angle and precisely adhere them to such a small shaft, which undoubtedly affects the accuracy of their shear strain measurement.

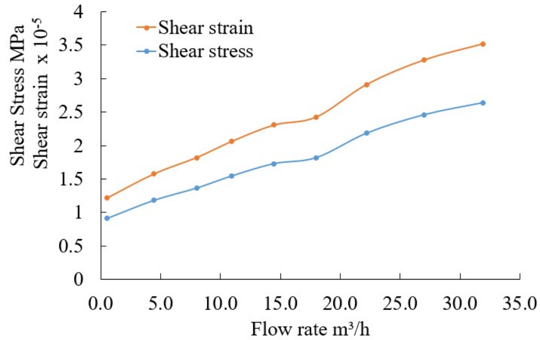

Figure 9: Shear Strain and Shear Stress versus Flow Rate.

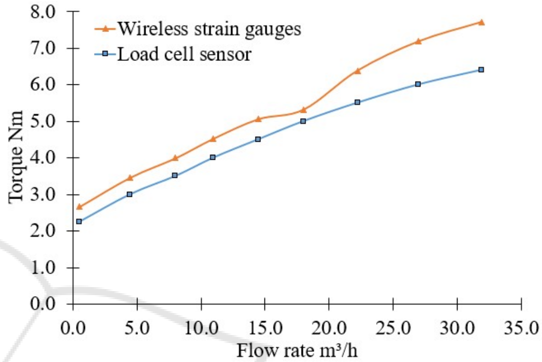

Figure 10: Shaft Torque versus Flow Rate.

4.2 Shaft Powers from Load Cell Sensor, Wireless Strain Gauge Sensor, and Electric Current

Figure 11 illustrates the mechanical powers on the pump shaft, calculated using wireless strain gauges, a load cell sensor, and electric current, as well as the electric power and hydraulic power of the centrifugal pump, all as functions of the flow rate at a rotational speed of 2900 rpm. The mechanical power from the electric current is determined using the motor efficiency and the input electric power. From this figure, considering the mechanical power from the load cell as a reference, it is observed that the mechanical power from the wireless strain gauges is almost equal to the mechanical power from the electric current. Moreover, there is a discrepancy between the mechanical power from the strain gauges and the mechanical power from the load cell. This can be explained by the uncertainty in the load cell sensor measurement or an error in the wattmeter measurement, which are connected to the input of the speed controller, potentially causing some power losses.

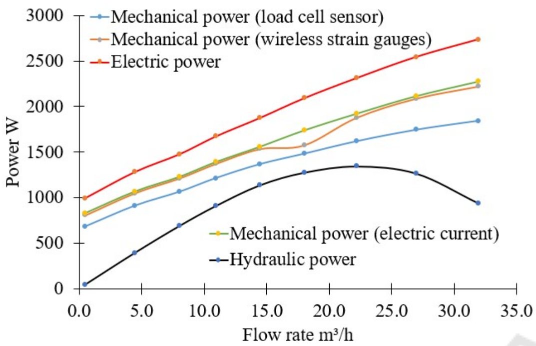

Figure 11: Power versus Flow Rate.

4.3 Efficiencies of the Motor-Pump and Pump

Figure 12 shows the efficiency curves for the motor-pump assembly, the pump with wireless strain gauges, and the pump with the load cell. The figure indicates that the efficiency of the pump measured with the load cell is higher than that measured with the wireless strain gauges. The motor-pump assembly has the lowest efficiency due to losses in both the electric motor and the centrifugal pump.

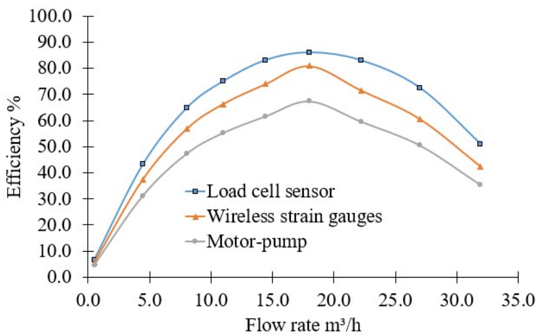

Figure 12: Efficiency versus Flow Rate.

5 CONCLUSIONS

In this study, the aim was to validate a torque measurement technology to obtain a more accurate representation of the mechanical power on the centrifugal pump shaft, thereby improving the quality control process. An existing centrifugal pump test bench was used to experimentally determine the mechanical power on the pump shaft using three approaches: a load cell, wireless strain gauges, and electric current. The mechanical power was measured by operating the centrifugal pump under different flow rate conditions while maintaining a constant rotational speed. The results indicate that the mechanical power determined from the wireless strain gauges closely matches the mechanical power calculated from the electric power, considering the efficiency of the electric motor. The mechanical power calculated using the load cell approach was the lowest. Future work will involve using wireless strain gauge technology to determine pump shaft power on a larger scale in the context of technology transfer.

ACKNOWLEDGEMENTS

The authors are grateful to *Technosub Inc.*, Industrial Pumps Manufacturing and Distribution (Rouyn-Noranda, Quebec, Canada) and the *Turbomachinery Laboratory of the Engineering School* (University of Quebec in Abitibi-Témiscamingue).

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