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Technical Note

AN INSTRUMENTED PULLEY FOR FIELD MEASUREMENTS OF TORQUE AND POWER

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ABSTRACT

An instrumented pulley was developed to overcome field problems associated with the conventional method of torque and power measurement. The prototype pulley was machined from mild steel, with spokes serving as strain beams. Strain gages in bridge arrangement attached to the spokes sense the bending stress due to the torque and convert this into millivolt output. Calibration results showed the torque-millivolt relationship was linear, hysterisis and error were less than 1% fs.

For power measurements, an additional tachometer with dc voltage output is necessary. With the tachometer, error in power measurement was +-1.03 W or 0.2% fs. Field tests showed its advantages over the calibrated motor method such as, ease of installation, no weight addition relative to the original primeover, portability and safety.

INTRODUCTION

The measurement of actual power requirement of prototype machines is a common procedure in agricultural machinery development. This is done to optimally match the machine with the prime mover, thus preventing overloading of the power source on one extreme, or excessive power wastage on the other.

One method of measuring power is indirectly, through torque and speed. Torque measurement utilizes the elastic property of materials. Whenever a force is applied to an object - tensile, bending or twisting force, within less than its elastic limit, there will be a change in dimension proportional to the force applied. Such principle is used by torque wrenches, spring balances, and strain gages. Most torque cells consist of mechanical element, usually a shaft with a circular cross section and a sensor, usually electrical resistance strain gages (Dally et al., 1984). Commercial torque cells are usually attached to existing shafts by couplings, while "homemade" torque cells are made by attaching strain gages directly onto the shaft of a machine. This method works provided there is enough space to attach the strain gages, or the shaft can be extended (without affecting the machine performance) to accommodate the strain gages and the corresponding slip ring, if telemetry is not used. Otherwise, invasive design alterations are needed to accommodate the strain gages and slip ring.

Another method measures power directly through a calibrated motor and an AC power meter. This method was used in the measurement of the actual power requirement of the IRRI Hydro Tiller, a floating-type power tiller (Mazaredo et al., 1990). See Figure 1. The method involves, first, calibration of a motor (with equivalent hp as the original engine) to establish the input power-output power (or input power-torque) relationship. Second, the motor is installed on the engine frame and an AC power meter is connected to the motor's voltage supply wires. The power meter measures the input power (kW) and through the calibration relationship, the output power (kW) of the motor is determined. This output power of the motor is the power required to drive the machine. Figure 2 shows the components of the instrumentation based on the calibrated motor.

This method finds numerous applications in laboratory measurements, but it has several setbacks when used in the field. First, there is weight addition due to the heavier motor. In the case of the Hydro Tiller tests, the equivalent motor was 10 kg heavier than the original engine. In field machines for paddy fields, any weight addition affects its performance, and of course the power requirement. Second, the tests can only be done where electric power is accessible. Field machines are tested on different sites, and frequently on such sites electrical power is not readily available. Third, the method utilized long electrical cables carrying 220 V ac, portions of which are held by an assistant to allow the machine to move and turn, which is very inconvenient. On wet fields, even with protective clothing, safety risks are associated with this method. Fourth, testing requires 3 persons that must work in unison, and therefore requires several trials before actual testing is done. Because of these pre-trials, test area needs to be large.

Devises for field measurement of torque or power, therefore, must satisfy the following criteria:

1) Can be easily installed to the machine for testing;

2) Minimal alteration to the machine and its prime mover to retain its characteristic performance such as, vibration, speed, or noise level;

3) Portable, e.g. battery-powered, and compact to minimize weight interference and manpower requirement; and

4) Safe and convenient to use, with overload protection against shocks or abuse.

For Philippine conditions two additional criteria for any measuring devices are: availability of materials, and manufacturing skills and equipment.

The objectives of this were:

1) to design a torque and power measurement system based on the criteria listed above,

2) to evaluate the system response in terms of linearity, accuracy and sensitivity; and

3) to compare the system with the calibrated motor method of torque and power measurements.

DESIGN OF THE INSTRUMENTED PULLEY

Conceptualization of the Instrumented Pulley

To satisfy the second criteria, the specified engine must be used in the instrumented tests to preserve its effects on the overall performance of the machine. By inspecting carefully the recipient field machine - the Mini Hydrotiller, the possibility of extending the drive shaft for attaching the sensor was eliminated, because it would be cumbersome to open the transmission case to replace the shaft. Moreover, extending the shaft would cause the engine to shift to the left, thus causing imbalance. By preserving the engine and retaining the drive shaft, only two options remained to be examined: the belt or the pulley as the primary sensors. Belt was eliminated because of inconvenience associated with its handling as a sensor. That left the pulley as the only possible primary sensor. With the pulley itself as the primary sensor, and strain gages as the secondary sensor, the other criteria were simultaneously satisfied.

Design of the Pulley Cross-Section

Power transmission involves transfer of torque and speed from primemover to the working parts of the machine. When loaded, the spokes of the pulley are subjected to bending stress. Hence to resist this, the wide side of the cross-section is normally parallel to the bending force. The spoke cross section can be made sensitive to bending strain and at the same time strong enough to carry the load without failure by proper design, and by orienting the narrow side of the spoke cross-section to be parallel to the bending force. Also, this requires the use of a ductile material in place of the original brittle material (pulley is typically made of cast iron).

The bending force, F per spoke can be expressed as

$$F = P/w\ d\ n$$

where P is power in Watts, w is angular velocity in rad/sec, d is the distance from the point of application of bending force to the center of the sensor location (treating one spoke as a cantilever beam), and n is the number of spokes. For example, a Mini Hydro Tiller with a 5 hp (3.7 kW) engine has a recommended 630 rpm rotation at the input axle. For a 304.8 mm (12 in.) driven pulley with three spokes, the distance from the point of application of bending force to the sensor is 105 mm. The bending force per spoke is 179.5 N. For a safety factor of 1.5, the section modulus is

$$Z = 1.5(179.5\ N)(105\ mm)/(250\ N/mm^2) = 113.1\ mm^3$$

This is satisfied by a 15 x 7 mm rectangular cross-section for each spoke. The groove of the pulley was designed to accommodate a B section V-belt. A threaded extension was added to accommodate a slip ring and a tachometer (See Figure 3).

Basic Principle of the Strain Beam

The pulley spokes serve as strain beams. The total bending force is divided equally among the spokes. A strain results in each spoke due to this bending force, the top surface is in tension while the bottom surface is in compression. With uniaxial strain gages bonded to the spokes, parallel to the length of the spokes and directly opposite each other, the gages output a change in resistance ($\Delta R/R$) proportional to the strain, e

$$\Delta R/R = Ge \qquad (1)$$

G is the gage factor or calibration constant of the strain gage. With a constant voltage wheatstone bridge arrangement, $\Delta R/R$ is converted to a change in output voltage, ΔEo expressed as

$$\Delta Eo = [R_1R_2/(R_1 + R_2)^2][\Delta R_1/R_1 - R_2/R_2 + R_3/R_3 - R_4/R_4]\ E_i \qquad (2)$$

where E_i is the constant input voltage. The design uses the typical arrangement where R_1 and R_3, R_2 and R_4 are on opposite arms of the bridge. The variation is R1 senses positive strain and R_2 senses negative strain in one spoke, R_3 and R_4 sense positive and negative strain, respectively in another spoke. In other words, two spokes each with two strain gages complete the sensing arrangement.

The bending force per spoke produces a moment M = Fx at the gage location x. This produces the following strains:

$$e_1 = -e_2 = e_3 = -e_4 = M/ZE = 6Fx/bh^2E \qquad (3)$$

where: Z = section modulus
E = modulus of elasticity
b = width of spoke cross-section
h = height or thickness of spoke cross-section

The response of the strain gages is obtained from equations (1) and (3)

$$\Delta R_1/R_1 = -\Delta R_2/R_2 = \Delta R_3/R_3 = -\Delta R_4/R_4 = 6\ F\ x\ G/bh^2E \qquad (4)$$

Substituting (4) into (2) and noting that $R_1 = R_2 = R_3 = R_4$, an equation relating Eo with F is obtained.

$$E_o = 6F \times GE_i \ / \ bh^2E = kF \qquad (5)$$

where : $k = 6 \times GE_i / bh^2E$

Equation 5 indicates that the output voltage is linearly proportional to the bending force F by the calibration constant k. Sensitivity S, is the ratio of output (millivolt) to the input (torque), or E_o/Fx. From equation 5, it can be expressed as

$$S = E_o/Fx = 6 \ GE_i \ /bh^2E \qquad (6)$$

CALIBRATION AND FIELD TESTS

Calibration Set-up and Procedure

The static calibration rig consisted of a fixed horizontal shaft, a 1m loading beam, calibrated deadweights, and a Polycorder, a portable, high speed, data logger (OMNIDATA, 1985). The pulley was keyed to a horizontal fixed shaft. One end of the loading beam was attached to one spoke of the pulley, while on the other end deadweights were hung. The strain gage (four 120 ohms) circuit was excited by a constant 5 V source from the Polycorder which was programmed to store the keyed torque values, scan 10 voltage output values, and store the average voltage.

Loads were incremented by adding deadweights until the maximum design torque (8.163 kg-m or 80 Nm) was reached. Load was then decreased by the same magnitudes until zero was reached. For each load, a corresponding torque value was keyed to the Polycorder which then stores this value, then reads and stores the corresponding millivolt output of the strain gage circuit. There were four replications. The torque (kg-m) - millivolt relationship was established through a regression analysis. Hysteresis and error for torque measurement were determined from the calibration results. Error for power (product of torque and speed) measurement was quantified by uncertainty analysis (Holman & Gajada 1978).

The dynamic calibration set-up was one typically used in motor calibration. It consisted of a driving motor, a torque meter, a generator and resistive elements such as lamps or heaters (See Fig. 4). The motor was connected to the torque meter through a coupling; the torque meter was connected to a shaft through another coupling. At the end of this shaft the instrumented pulley was keyed. This instrumented pulley drives the generator pulley through a belt. The output of the generator was connected to a number of heaters and lamps in parallel connection. To vary the load, the voltage of the variac was varied, or one or more of the resistive elements were switched on. The millivolt output of the pulley and the output of the torque meter were recorded for each load setting by the Polycorder.

Field Tests

For field tests, the instrumented pulley was attached to the corresponding input shaft of the Mini Hydrotiller (Pasikatan, 1993). A detachable shaft extension was provided for the slip ring. A dc-tachometer with 0 to 2 V output (for a range of 0 to 2000 rpm) was attached to the end of the slip ring. The output of the two devices were wired to the Polycorder which read, converted and stored each torque and speed (rpm) value. See Figures. 5 and 6.

RESULTS AND DISCUSSION

The calibration results of the instrumented pulley confirmed the linear torque-millivolt relationship, previously derived. For static and dynamic calibration, the relationships were:

$$MV = 0.465508 * KG\ M - 0.83351 \quad (r^2 = 0.99), \text{ and}$$

$$MV = 0.440345 * KG\ M - 0.83817 \quad (r^2 = 0.99).$$

The small difference in calibration, 7% at most, showed that static calibration, if properly done can be used in the absence of a dynamic calibration set-up.

The sensitivity of the instrumented pulley was 0.468 mV/kg-m or 0.763 mV/V of excitation which was slightly low but comparable to some commercial torque transducers which have sensitivities of 0.6, 0.75, 1 and 1.5 mV/V, depending on application (KYOWA, 1990). The main reason for this slightly low sensitivity could be the spoke cross-section was larger than the optimum for sensitivity (the yield strength value used in calculation was not confirmed by actual hardness tests). A reduced cross-section calculated from strength values derived from actual hardness tests could further improve sensitivity. The use of eight strain gages (on four spokes) instead of the present four could also improve sensitivity as proven in other dynamometer designs. For torque measurement, hysterisis was negligible at 0.71% and error was 0.75%. Error in power measurements was +-1.03 W or 0.02% fs.

Field tests showed the advantages of the instrumented pulley over the calibrated motor method, namely: ease of installation, portability, safety, and absence of machine alterations and weight addition relative to the engine primemover. Also, it required only two persons to test a field machine - the operator and the test engineer, compared to three or four for the other method. For comparison of the convenience and simplicity of the instrumented pulley-based measurement system over the calibrated motor method, compare Figures 5 and 6 to Figures 1 and 2.

Farm equipment researchers would find the instrumented pulley very useful in field measurements of torque and power. The cost of the pulley is about P4,500 (mainly due to machining cost) as compared to about P26,000 or more for imported torque meters. But any commercial torque meter could not be used without first altering the machine to be tested. Clearly, this proves that the instrumented pulley is a cheaper and more application-specific alternative to commercial torque meters.

CONCLUSIONS

An instrumented pulley was developed for field measurement of torque or power requirement of prototype machines. For a "homemade" torque cell it exhibited highly linear response, high accuracy, negligible hysterisis and fairly acceptable sensitivity. Improvements could still be made for increasing sensitivity by using a reduced cross-section computed from strength values derived from actual tests, or using eight strain gages on four spokes, instead of four strain gages on two spokes.

Field tests showed its advantages over the calibrated motor like ease of installation, portability, safety and absence of machine alterations and weight addition relative to the original engine primemover. Because of these advantages, it is an improvement over the calibrated motor as a device for field measurements of torque and power. It is also cheaper and more application-specific alternative to commercial torque meters.

RECOMMENDATIONS

The inclusion of an overload protection device, and the use of eight strain gages on four spokes for improved sensitivity of the instrumented pulley are recommended.

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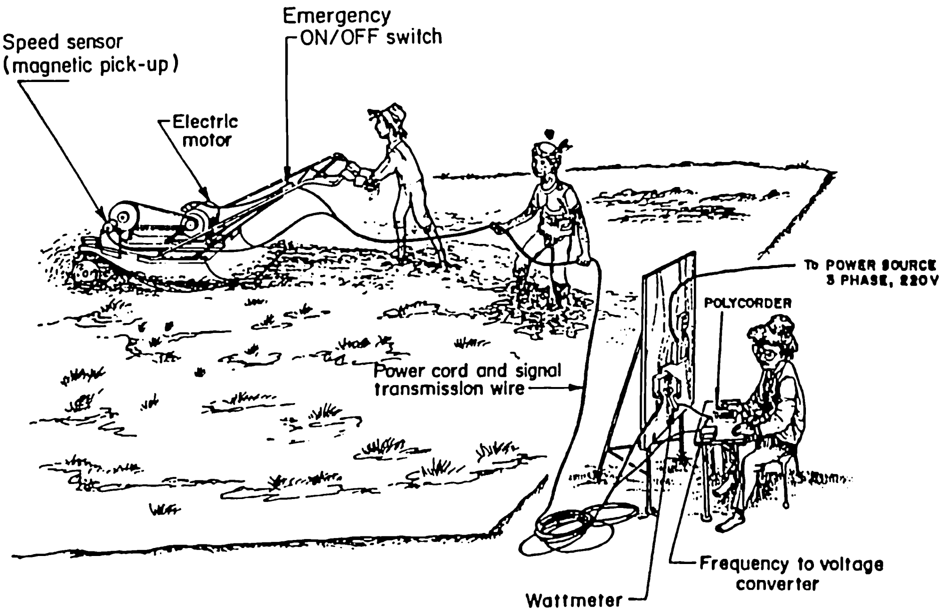


FIGURE 1
Instrumentation Set-up for the Measurement of Actual Power Requirement of IRRI Hydro Tiller

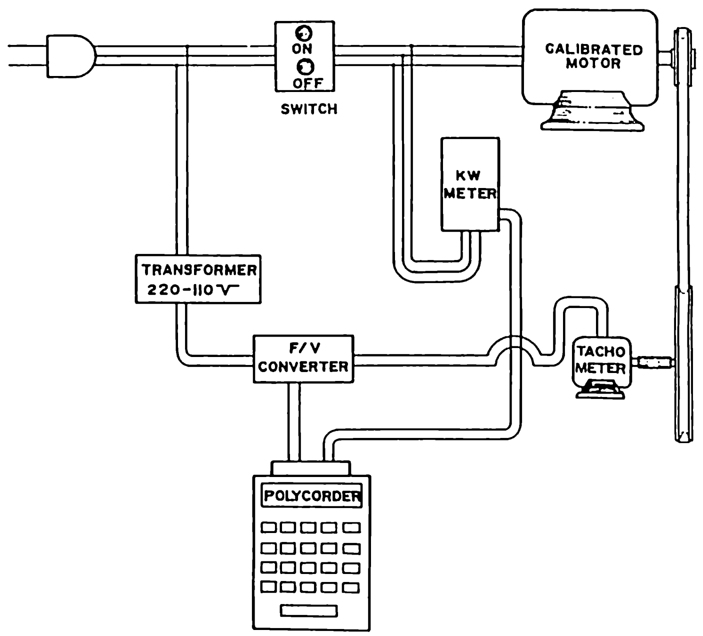
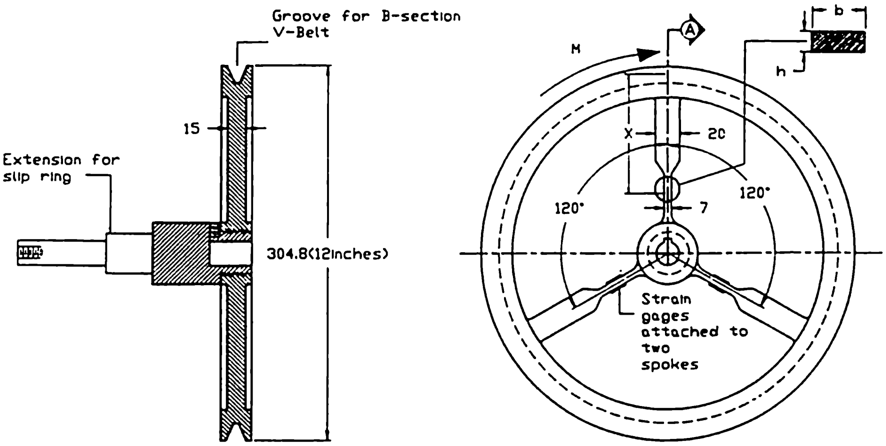


FIGURE 2
Schematic Diagram of the Instrumentation System



PARTIAL SECTION THRU A-A

FIGURE 3
The Instrumented Pulley Showing Basic Dimensions and Parts

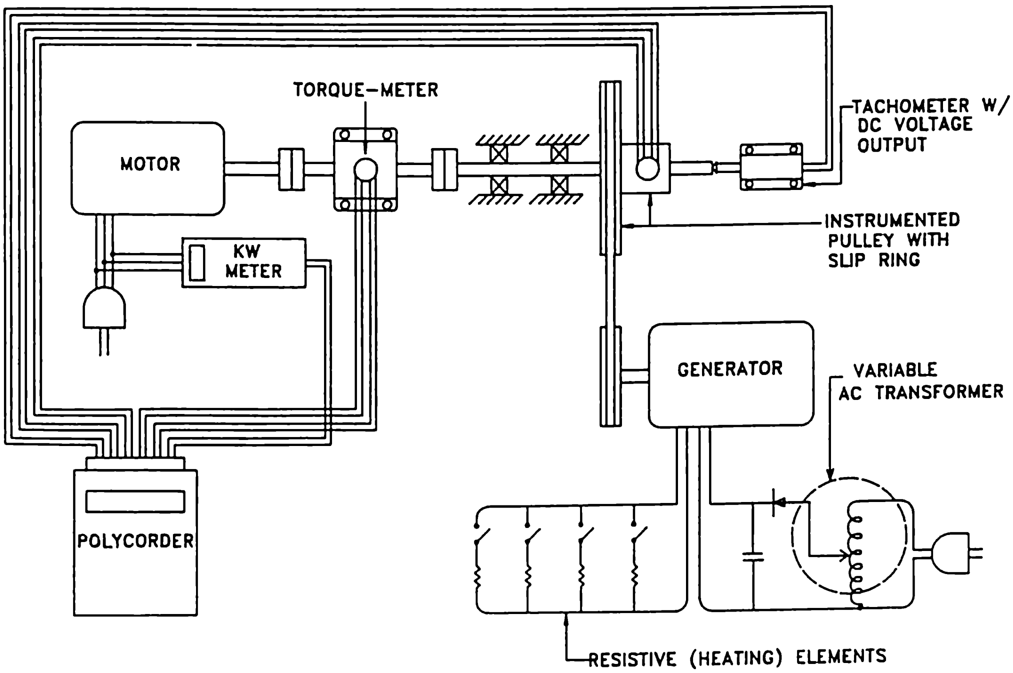


FIGURE 4
Schematic of Dynamic Calibration Set-up for Instrumented Pulley

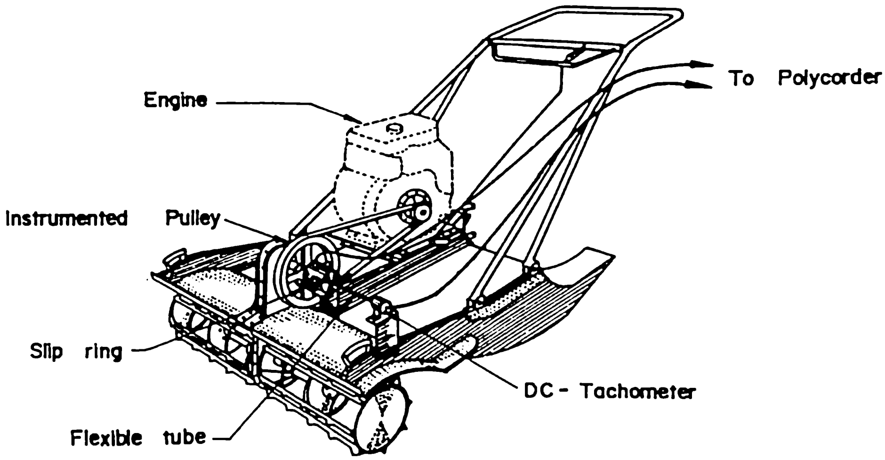


FIGURE 5
Instrumented Pulley, Slip Ring and Speed Sensor
(DC-Tachometer)
Measuring System for Mini Hydrotiller

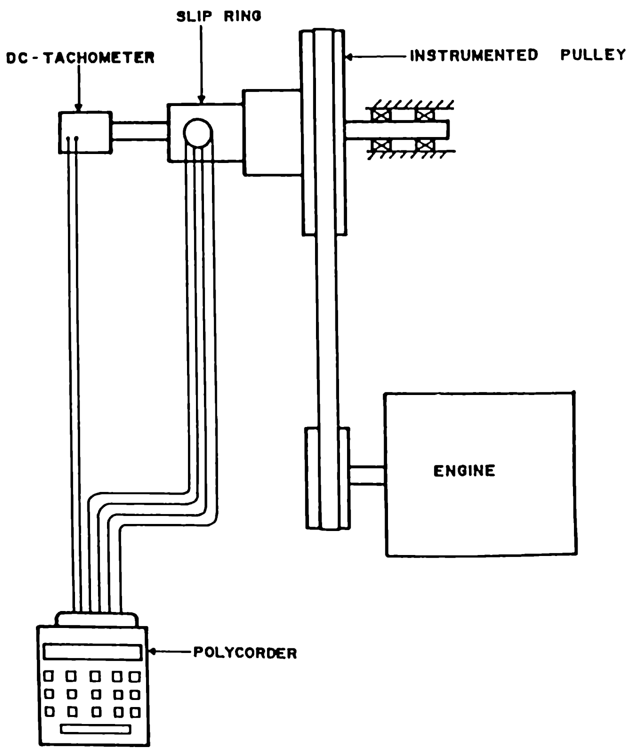


FIGURE 6
Schematic Diagram of the Instrumentation
System of the Mini Hydro Tiller
(Based on the Instrumented Pulley)