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A PORTABLE TORQUE AND POWER MEASUREMENT SYSTEM FOR SMALL FARM EQUIPMENT BASED ON AN INSTRUMENTED PULLEY[1]

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ABSTRACT

A portable torque and power measurement system for small farm equipment based on an instrumented pulley was developed. The prototype pulley was machined from mild steel, with spokes serving as strain beams. Strain gages mounted to the spokes sense the bending strain due to the torque and convert this into millivolt output. Calibration results showed the torque-millivolt relationship was linear, while 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 that for ease of installation, no machine alterations needed and safety, this system had advantages over other methods for small farm equipment.

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INTRODUCTION

Methods of measuring power, directly or indirectly (through torque and speed) for small farm equipment testing are very limited, and are oftentimes invasive, inconvenient, or inappropriate. One such indirect method, mounting electric resistance strain gages on shaft requires enough space for the gages. Extending the shaft to accomodate the gages would often result in an imbalanced machine which could affect field performance. Off-the-shelf commercial torque cells are usually inappropriate for similar applications.

Another method, a direct power measurement type, used a calibrated motor and an AC power meter (Mazaredo, et al, 1990; *Fig. 1*). The method involved calibration of a motor (with equivalent hp as the original engine primemover) to establish the input power-output power relationship. The motor is later installed on the engine frame and an AC power meter is connected to its voltage supply wires. The components of the instrumentation based on the calibrated motor are shown in *Fig. 2*. The power meter measures the input power (kW) and through the calibration relationship, the output power (kW), the power required to drive the machine, was determined.

This method has merits in laboratory measurements. But it has problems when used in the field such as: weight addition due to the motor (5 to 10 kgs depending on the motor) which could affect field performance of the machine especially flotation, tests can only be done where electric power is accessible, inconvenience and safety risks.

An alternative portable method of torque and power measurement was developed for small farm equipment, based on an instrumented pulley. It offers the following advantages:

1) Ease of attachment, without any alteration to the machine;

2) Negligible change in weight relative to the original prime mover; no modification of its original effects, such as, vibration or noise level;

3) Compact, safe and convenient to use.

4) Can be easily made in the workshop with available materials and manufacturing equipment.

In this study an instrumented pulley for field measurement of torque for small farm equipment testing was designed. It was evaluated to determine linearity, accuracy, sensitivity and field performance.

DESIGN OF THE INSTRUMENTED PULLEY

Principle of Operation

When transmitting load, the spokes of the pulley are subjected to bending stress hence to resist this, the flat side of the cross-section is normally parallel to the bending force. In an instrumented pulley, the spokes serve as strain beams. By designing the flat side of the spoke cross-section to be perpendicular to the bending force, the spoke was made sensitive to bending strain. Also, an elastic material must be used instead of the original brittle material (cast iron). The bending strain in the spokes is related to the torque acting on the pulley.

Design of the Spoke Cross-Section

The bending force, *F* per spoke can be expressed as

$$F = \frac{P}{vdn}$$

where P is power in Watts, v 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 (3.73 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 179.48 N. Hence, the section modulus is

$$Z = \frac{1.5(179.48\ \text{N})(105\ \text{mm})}{(250\ \text{N/mm}^2)} = 113.07\ \text{mm}^3$$

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 (*Fig. 3*).

Basic Principle of the Strain Spoke

The total bending force acting on the pulley should be 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 four-strain gage bridge output a change in voltage proportional to the bending force F. The relationship between the output voltage E_o with bending force **F** at the gage location **x** can be derived and expressed as

$$E_o = \frac{6 F x G E_i}{bh^2 E} = k F \quad (1)$$

where:

$$k = \frac{6 x G E_i}{bh^2 E}$$

and:
- G = gage factor
- E_i = input voltage
- E = modulus of elasticity
- b = width of spoke cross-section
- h = height or thickness of spoke cross-section

Equation 1 indicates that the output voltage is linearly proportional to the bending force **F** by the calibration constant **k**. Sensitivity is the ratio of output (millivolt) to the input (torque), or E_o/Fx. From equation 1, it can be expressed as

$$\frac{E_o}{Fx} = \frac{6 G E_i}{b h^2 E} \quad (2)$$

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 dead-weights were hung. The strain gage (four 120 ohms) circuit was excited by a constant 5 Vdc 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 into the Polycorder which then stores this value, then reads and stores the corresponding millivolt output of the strain gage circuit. Four replications were done. 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 (*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 milivolt output of the pulley and the output of the torque meter were recorded for each load setting by a 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 (*Figs. 5 and 6*).

RESULTS AND DISCUSSION

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

MV = 0.465508 * KG M - 0.83351 ($r^2 = 0.99$), and

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

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 slightly low sensitivity could be attributed to the material and strain gages used. Heat treatment plus the use of eight strain gages on four spokes, instead of the present four could improve sensitivity as proven in other dynamometer designs. For torque measurement, hysteresis was negligible at 0.71% and error was 0.75%. Error in power measurement was +-1.03 W or 0.02% fs.

Field tests showed the advantages of the instrumented pulley over the calibrated motor and other methods, namely: ease of installation, convenience of use, safety, and absence of machine alterations and weight addition relative to the engine primemover. It also required less number of persons to test a field machine.

Farm equipment researchers would find the instrumented pulley very useful in field measurements of torque and power. The cost of the pulley is about $123 as compared to $420 or more for commercial torque sensors. Clearly, it is a less expensive but a more application-specific alternative to commercial torque meters.

CONCLUSIONS

An instrumented pulley was developed as the transducer of a portable torque and power measurement system for small farm equipment. Considering that this was 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 heat treatment and the use of eight strain gages on four spokes, instead of the present four strain gages on two spokes.

Field tests showed its advantages over other methods, such as: ease of installation, convenience of use, safety, absence of machine alterations and weight addition relative to the original engine primemover. It is also a less expensive but more application-specific alternative to commercial torque meters.

RECOMMENDATIONS

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

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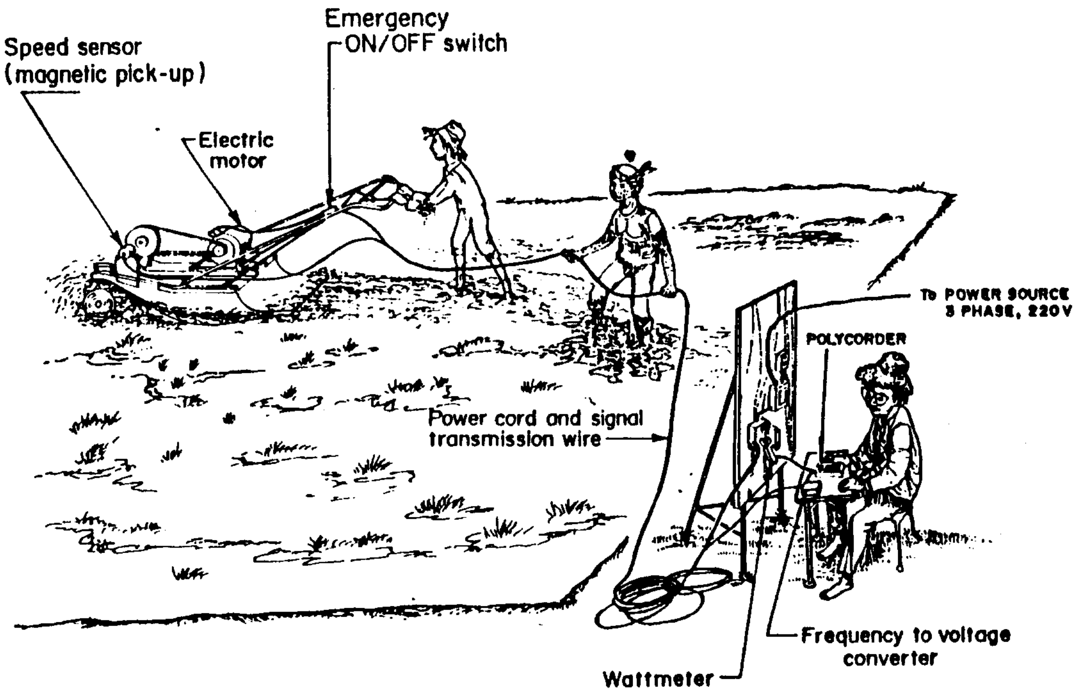


Fig. 1 . Instrumentation set-up for the measurement of actual power requirement of IRRI hydro tiller.

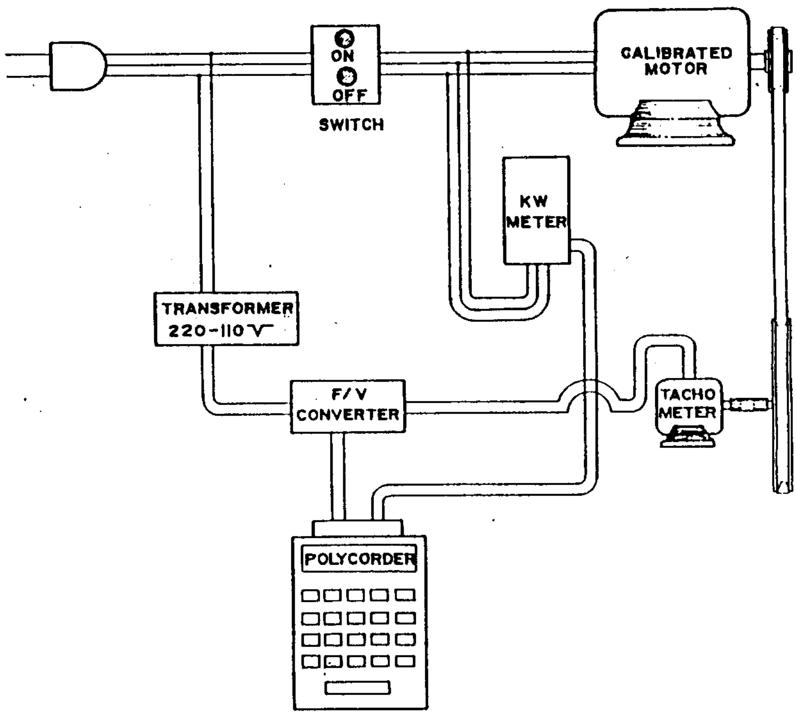
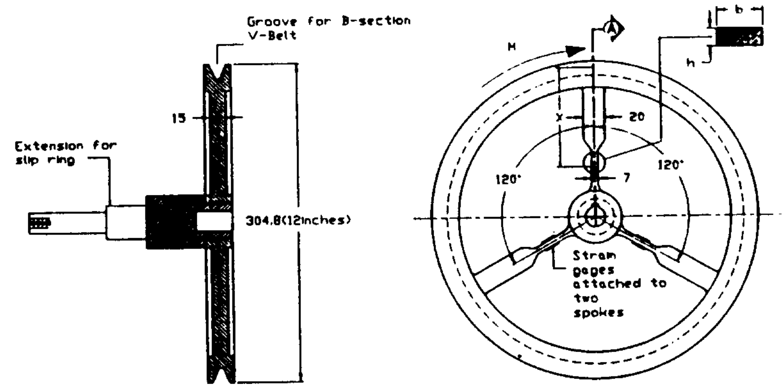


Fig. 2. Schematic Diagram of the Instrumentation System



PARTIAL SECTION THRU A-A

Fig. 3. The instrumented pulley showing basic dimensions and parts

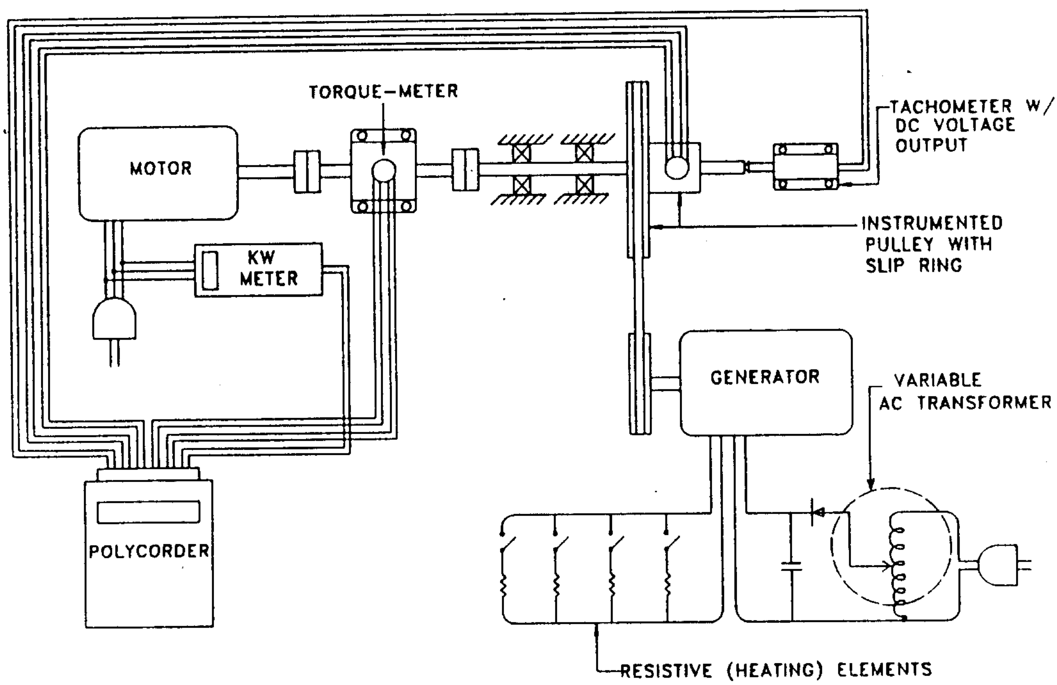


FIG. 4 . SCHEMATIC OF DYNAMIC CALIBRATION SET-UP FOR INSTRUMENTED PULLEY.

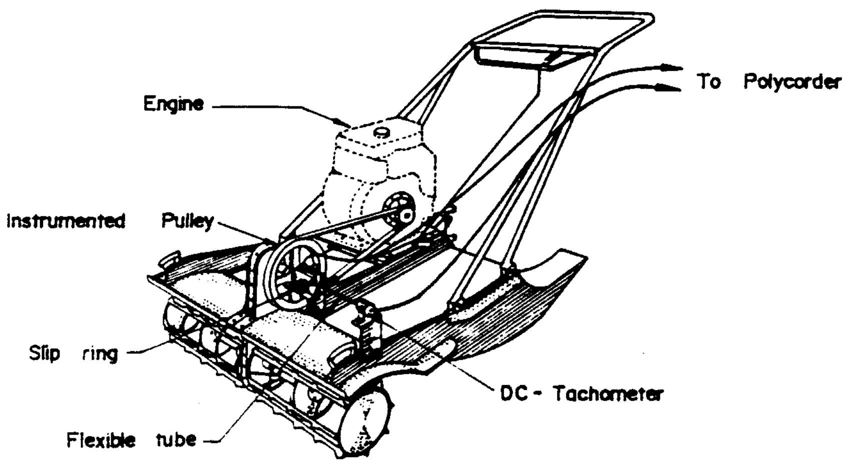


Fig. 5 . Instrumented pulley, slip ring and speed sensor (dc - tachometer) measuring system for mini hydrotiller.

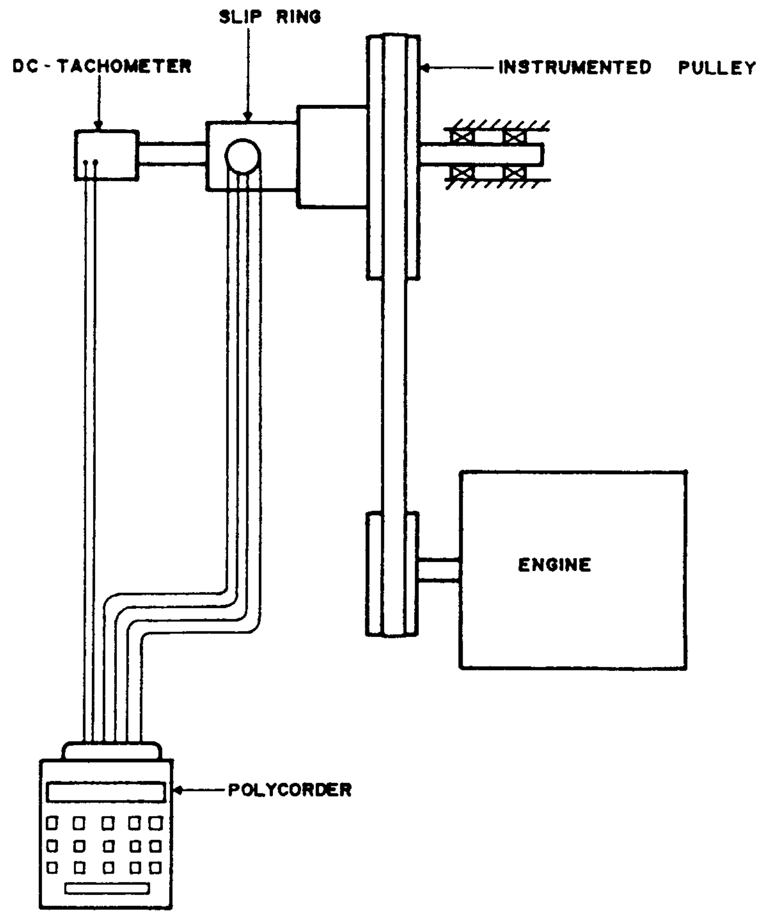


Fig. 6. Schematic Diagram of the Instrumentation System of the Mini Hydro Tiller (Based on the Instrumented Pulley)