MARDI Report No. 221

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MARDI Report No. 221 (2017)

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Development and calibration of a portable power measuring instrument for testing agricultural machines

(Pembangunan dan penentukuran instrumen pengukuran kuasa mudah alih bagi pengujian jentera pertanian)

Keywords: power measurement, torque, load transducers, calibration, agricultural machines

Abstract

The Engineering Research Centre in MARDI has developed a portable power measuring instrument for measuring power requirement, draft force and pull slip performance of agricultural machines. The methodology used to develop this instrument includes construction and testing of a portable power measuring instrument circuit, construction of a calibration stand and calibration of the power measuring instrument with commercial torque and force transducers. The construction and testing of the power measuring instrument involve the design and construction of a stable direct current power supply regulator and a suitable instrumentation amplifier circuit. The calibration of the instrument was then carried out with Honeywell torque and force transducers on the calibration stand. The correlation of the voltages output of the instrument and torque or force values from the transducers is very linear with an accuracy of 0.1% error margin. In short, a portable power measuring instrument which could be interfaced to any commercial torque or force transducers has been successfully developed. In addition, the calibration stand was found to be a convenient method to calibrate commercial torque or force transducers over a wide range of load capacity by subjecting the transducers to counter the variable weight moment of the cantilever beam pivoted at the calibration stand frame.

Introduction

Agricultural mechanisation is essential for enhancing production and productivity, as well as reducing the cost of crops production. It involves the application of available agricultural machines or the induction of improved or new technology which can work efficiently and is economically viable in the localised agricultural production system. It is necessary to have detailed information on the power and energy demands of any machinery utilised in the local area (Kheiralla et al. 2004). One of the reasons is because the measurement can determine the performance of an agricultural machine. For example, the efficiency of a rotor tiller can be determined by measuring the power it delivers and comparing it to the quality of soil tillage it produces.

The power being transmitted by Power Take-Off (PTO) shafts of tractors or agricultural machines can be obtained from the measured values of shaft torque and speed. The two common methods to obtain the shaft torque measurements are contact and non-contact. The contact method uses slip ring to transfer the strain gauge signals to stationary recording equipment (McLaughlin et al. 1993; Singh and Singh 2011). The slip ring applies power to and receives signal from strain gauges attached to the rotating shaft. It has the advantage of being lower cost, but on the other hand, needs to be properly maintained. The non-contact method uses radio telemetry to transmit the transducer signal to a nearby receiver (Yong et al. 2013; Honeywell 2015). Even though it eliminates the need for constant maintenance, it is relatively more expensive compared to the contact method.

Unlike the research by Snyder and Buck 1990; Kheiralla et al. 2003 who developed strain gauge torque transducers and was based on calibrated measurement of current sourcing due to the micro strain variation of the strain gauges embedded on the torque transducers, the research was not concerned in developing a new torque transducer, rather it was concentrated on utilising FUTEK CSG110 amplifier module to develop a portable power measuring instrument that can be used with any commercial contact-type torque or force transducers. This paper reports the research work on the design, testing and construction of the portable power measurement instrument and its calibration stand. The calibration processes of the instrument for torque and force transducers are also included.

Materials and methods

The methodology involved design, construction and testing of a portable power measuring instrument circuit, construction of a calibration stand and calibration of the power measuring instrument with the torque and force transducers.

Design, construction and testing of a portable power instrument circuit

The diagram of portable power measuring instrument is shown in *Plate 1* while its physical setup is shown in *Plate 2*. It consists of an instrumentation amplifier (IA), a DC power and regulator circuit, a torque or force transducer, a magnetic pick up speed measuring instrument, battery and a data logger. The first component is a FUTEK CSG110 instrumentation amplifier module. Its schematic diagram is shown in *Plate 3*. It is a general purpose DIN rail DC powered amplifier module inclusive of universal strain gauge signal conditioner. It has been chosen because it simplifies the wiring and construction of the transducers' amplifying circuit. It is also able to excite and amplify most of the commercial torque or force transducers of different capacities for torque or load measurements. This is made possible by the amplifier's capability to provide multiple output variations which are ±5 VDC, ±10 VDC, 0 – 20 mA, 4 – 20 mA, 0 – 16 mA and 5 – 25 mA (FUTEK 2013). The 10 V excitation is mostly applicable to the torque or force transducers made of 350 W strain gauge bridge, while 5 V excitation is applicable to transducers of 240 W strain gauges bridge. The recommendations must be followed to avoid overloading excitation current specified by the amplifier. In addition, the amplifier has a wide range of gain and span voltages setting which can be set to the particular bridge sensitivity of the commercial torque or force transducer. It also has a shunt resistor calibration connector to install shunt resistor provided by the transducer manufacturer for periodic checking of the gain without exposing the particular strain gauge transducer to known physical traceable load. The second component is a DC power regulator circuit which converts the DC battery voltage sources of 12 V and 24 V into stable 5 V and 18 V. The 5 V and 18 V voltage sources are applied to power a magnetic pick up speed sensor and an instrumentation amplifier respectively.

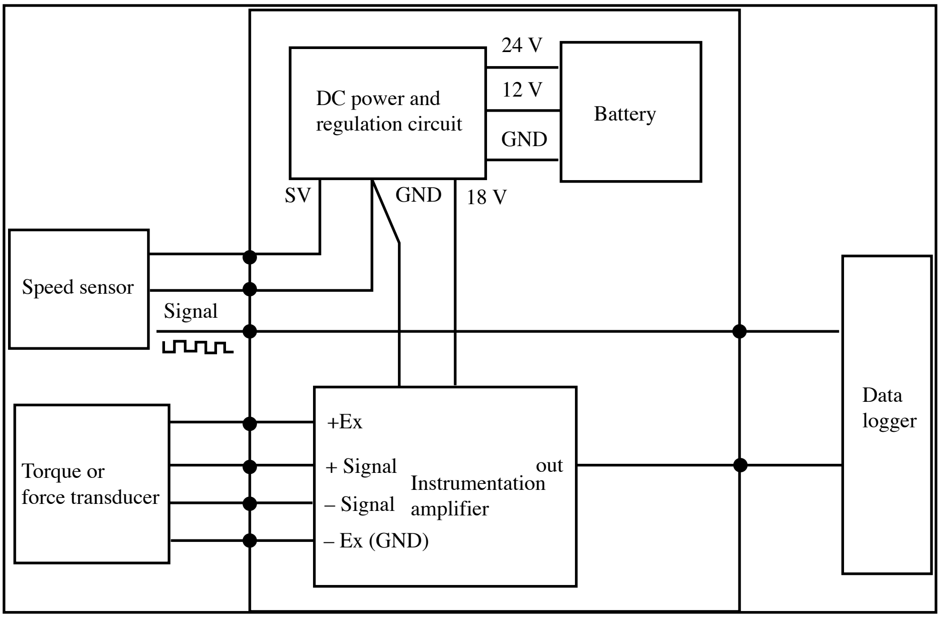
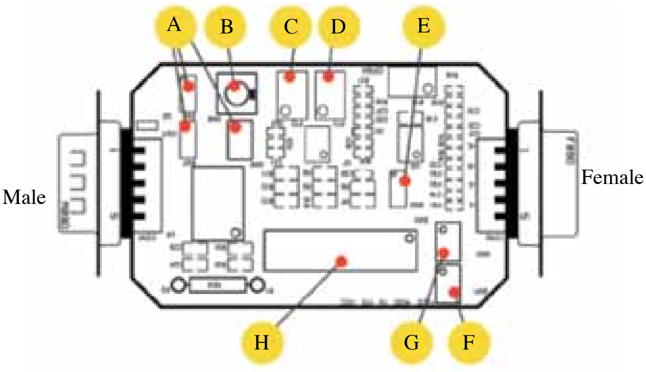


Plate 1. Diagram of portable power measuring instrument

Plate 2. Physical setup of the portable power measuring instrument



A = Current switches
B = Shunt button
C = Span potentiometer
D = Zero potentiometer
E = Bandwidth switch
F = Excitation switches
G = Polarity switch
H = Gain switch

(Source: FUTEK, Advanced Sensor Technology, Inc.)

Plate 3. Schematic diagram of FUTEK CSG110

The third component is a Honeywell model 1228 flange drive torque transducer. It has a 226 Nm torque capacity (Honeywell 2008) and is connected to the coaxial socket input of the instrumentation amplifier. The basic construction of a typical torque transducer is shown in *Plate 4*. It has four 350 Ω strain gauges of bridge circuit configuration bonded on the torsion zone of the shaft. The slip rings and brushes provide the link between the rotor and the housing. The 10 V excitation voltage from instrumentation amplifier was carried by two slip rings to strain gauges on the rotating shaft. The two other slip rings serve to transfer the measured signal from carry strained the gauges bridge to the instrumentation amplifier. Both ends of the torque transducer shaft consist of mounting flanges to connect the PTO drive and driven shafts to the agricultural machines.

The excitation current of the strain gauge bridge, I_e is defined as

$$I_e = V_e/R_s \qquad (1)$$

where,

V_e = Excitation voltage

R_s = Strain gauges resistance

The excitation current supplied to energise the torque transducer was estimated using equation 1 to be 28 mA which is within the typical value specified by the instrumentation amplifier. The output voltage of torque transducer V_o made of four arm strain gauges bridge is expressed as $V_o = V_e \Delta R_s / R_s$, while the voltage output of the instrumentation amplifier V_a to the data logger is expressed as

$$V_a = G_{span} V_e \Delta R_s / R_s = G_{span} V_o \qquad (2)$$

where,

G_{span} = Gain or span of the instrumentation amplifier

ΔR_s = Changes of strain gauges resistance due to torque or draft

Equation 2 indicates that to obtain high accuracy of measured output voltage V_o from this power measuring instrument, the excitation voltage V_e must be stable and a span adjustment G_{span} of

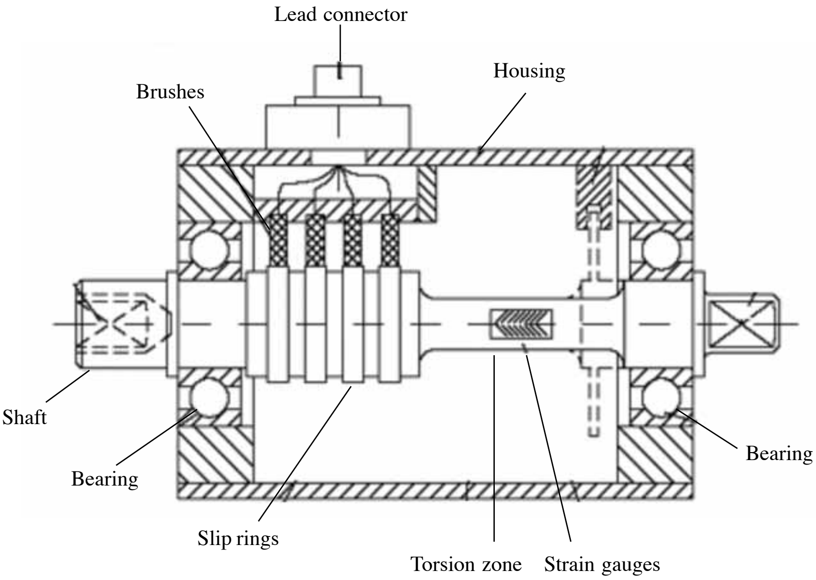


Plate 4. Basic construction of a torque transducer

the instrumentation amplifier must be maximised over the range of torque or load to be measured by the torque or force transducer. The excitation current of the bridge supplied by the amplifier, $I_e=V_e/R_s$ should not be overloaded. Thus, the DC power regulator circuit was designed to provide stable input voltage to the instrumentation amplifier. Another parameter which needs to be considered is bridge sensitivity, $S_b = V_o/V_e = \Delta R/R$, which refers to the highest output voltage V_o at the rated torque or force capacity of the particular transducer over the excitation voltage V_e.

This typical torque transducer is convenient to install into a PTO drive line of a tractor or agriculture machine which generates only pure torque. This is done by a simple bracket to support the housing of the torque transducer to the machine. It should be noted that, the torque transducer shaft must not be subjected to bending stress when it is coupled between the power drive shaft and load driven shaft, which is necessary for proper functioning and to avoid mechanical damage of the torque transducer. In order to perform power measurement of heavy rotating member of agricultural machines such as threshing drum, the torque transducer shaft ends should be mounted between power drive and load driven shafts that are firmly supported by bearings.

The fourth component of our power measuring instrument is a speed sensor. The Honeywell model 1228 torque transducer comes together with a magnetic pick up speed sensor and tooth ring which are mounted on it housing and shaft member respectively. The magnetic speed up sensor generates 5 V voltage pulse rates in proportion to the tooth ring rotational speed.

The torque and speed measured by the transducers produce small voltage output signals which are amplified by the IA to a suitable voltage range input for the fifth component which is a data logger. Any commercial data logger can be interfaced to our portable power measuring instrument through its D connector output to record the torque and speed signal of the torque transducer and speed sensor respectively. In our project, a Squirrel SQ2010 Grant data logger has been selected.

The construction of torque and force transducers calibration stand

It is difficult to directly correlate an instrument's measurements to the torqueor force of a machine undergoing a field test. This is due to the unknown and fluctuating disturbances acting on the test machine. Therefore, the instrument must undertake static calibration through a proper calibration procedure to get an accurate relationship against known varying torque or load. Once it is calibrated, the torque or force measurement data of the test machine sensed by these transducers is reliable enough to be analysed.

A calibration stand to calibrate the portable power measuring instrument with a torque and a force transducer was constructed as shown in *Plate 5*. The calibration stand was made of cantilever beam with its pivot made of shaft supported by two bearings mounted on the top horizontal bar of the main frame. It utilised dead weight of steel bars hanged on hooks at different positions of the longer cantilever beam

Plate 5. Power measuring instrument, torque and force transducers at the calibration stand

to impose varying torque or load values at the torque or force transducer. A torque produced at the pivot shaft was applied to the torque transducer shaft. An opposite hook to pull a force transducer was made at the shorter cantilever beam, which is 100 mm apart from the pivot. The torque transducer was installed by connecting one side of its shaft to the cantilever pivot shaft, while the opposite shaft was fixed to main frame of the calibration stand to resist the respective torque. The pivot shaft bearings freed the hanged steel bars from the frictional force encountered at the cantilever pivot. The longer arm of the cantilever consisted of several hooks spaced 100 mm apart for hanging the steel bars. The steel bars could be hooked at a maximum distance of 1 m from the pivot.

The calibration stand was only used to calibrate either a torque or a force transducer atone occasion. It could be used to calibrate a wide range load capacity of commercial torque or force transducers. The required torque or load could be applied to the particular transducer by hanging multiple known capacity of steel bars at various positions of the cantilever beam. The torque and load values applied to the torque and force transducers by varying themoment of weights are described by

$$T_v = \Sigma W_d L_i \tag{3}$$

$$F_v = 1/L_s \Sigma W_d L_i \tag{4}$$

where

W_d = Dead weight in N
L_i = Distance of right arm's dead weight in mm
T_v = Torque applied to the torque transducer in Nm
L_s = Distance of left arm's load transducer in mm
F_v = Force in N

Calibration of the power measuring instrument, torque and force transducers

The Honeywell model 1228 torque transducer was mounted to the calibration stand by connecting one side of its shaft to the cantilever pivot shaft and fixing the opposite shaft to the main frame of the calibration stand. Initially, the cantilever beam was freely supported in a horizontal position to eliminate a torque at the pivot due to the self-weight of the cantilever beam. The IA's 'zero potentiometer' was adjusted to produce a zero voltage at the amplifier output terminal. The torque transducer was then subjected to the highest torque value by hanging several steel bars at further distances from the pivot of the cantilever beam. The IA's 'excitation switch' was then selected to excite the torque transducer with a voltage of 10 V, so were the 'gain switch' and 'span potentiometer'. Then the highest torque and voltage values were recorded. The maximum applied torque was not to exceed the maximum rated torque, which was 1,130 Nm. The torque value was then reduced gradually by changing the steel bars' hook position towards the pivot of the cantilever or by reducing their number. The IA's "Zero Potentiometer" was then readjusted to zero voltage output after the hanged steel bars were removed and the cantilever beam was freely supported. The decreasing torque and voltage output values of the IA were successively recorded. All the recorded torque values were calculated using equation 3.

The calibration of a Honeywell model 6443 force transducer and the portable power measuring instrument was carried out in a similar procedure as the calibration of the torque transducer. The force transducer was installed using a specially made upper and lower hook type brackets. The force transducer's upper hook bracket was joined with the hook of the shorter arm cantilever beam, while the transducer bottom hook bracket was joined to the bottom frame of the calibration stand. The cantilever beam was set into horizontal position by adjusting the screw type bottom hook bracket of the force transducer. All the recorded force values were calculated using equation 4.

Results and discussion

The result relating the voltage measured by our power measuring instrument to the varied torque was plotted in *Figure 1*. The R^2 value of the regression line is 0.99 which shows a very high correlation of the output voltage and the measured torque. The straight line equation describing the voltage measured by the instrumentation amplifier, $\mathbf{V_a}$ in terms of torque values, T_r is given by

$$V_a = 0.041T_r - 0.042 \quad (5)$$

where

V_a = Voltage output of the instrumentation amplifier in V
T_r = Torque of the rotating shaft in Nm

The result shows that the power measuring instrument can measure torque from 1.00 to 242.40 Nm with a high voltage resolution of 41.43 mV/Nm. Based on equation 5, the torque measurement calibration curve for the instrument was deduced. The resulting calibration curve is

$$T_r = 24.14V_a + 1.002 \quad (6)$$

The result relating the voltage measured by our power measuring instrument to the varied force was plotted in *Figure 2*. The R^2 value of the regression line is 0.99 which shows a very high correlation of the output voltage and the measured force. The straight line equation describing the voltage measured by the instrumentation amplifier, V_a in terms of force, F_d is given by

$$V_a = 0.0045F_d + 1.15 \quad (7)$$

where

V_a = Voltage output of the instrumentation amplifier in V
F_d = Force in N

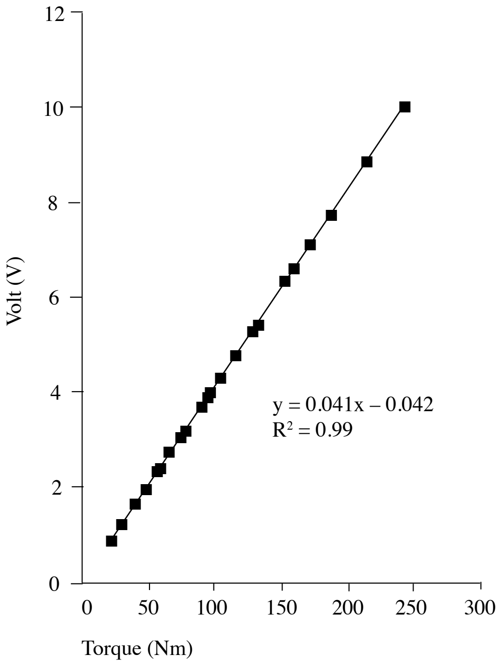


Figure 1. Result of the developed power measuring instrument with Honeywell model 1228 torque transducer calibration

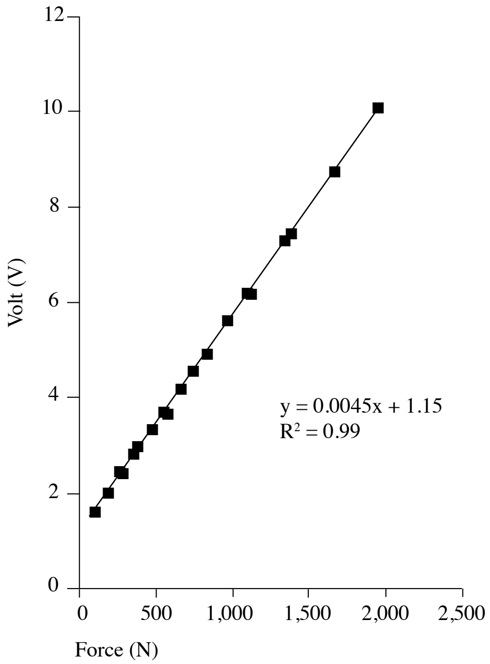


Figure 2. Result of the developed power measuring instrument with Honeywell model 6,443 force transducer calibration

The result shows that the power measuring instrument can measure pulling force from 255 to 1954 N with voltage resolution of 4.53 mV/N. Based on equation 7, the force measurement calibration curve for the instrument was deduced. The resulting calibration curve is

$F_d = 220.9V_a - 254.8$ (8)

The magnetic pickup speed sensor produces logic voltage pulse output directly connected to the counter input channel of the data logger. Its frequency F_{mp} is determined by the turning speed of the magnetic tooth ring through

$F_{mp} = 2\pi C_p/T_sN_t = 0.1047C_p/T_s$ in rad/sec

(9)

where

C_p = no of pulse recorded by the counter input of the data logger

N_t = no of teeth of the magnetic tooth ring

T_s = test duration in second

The value of N_t for our speed sensor is 60 equation 9 indicates that the usage of a magnetic pick up sensor does not really require any calibration work for speed measurement of a rotating shaft. The speed is computed by the pulses count, C_p during the test duration, T_s recorded by the data logger. The accuracy of the rotational shaft speed measurement is determined by the number of teeth of the magnetic tooth ring.

The drive shaft torque and speed measured by the torque transducer and magnetic pickup sensor were calculated from Equation 6 and 9 respectively. Hence the power of the rotating drive shaft P_t after simplification is given by

$P_t = T_rF_{mp} = 2.52V_aC_p/T_s$ in Watt

(10)

Therefore, by recording the average values of torque output voltage, V_a and speed pulse count, C_p of the shaft over specified test duration, T_s, the power requirement of tractor implements or agricultural machines can be computed.

A typical application of the portable power measuring instrument is to measure the power requirement of a rotor tiller in the land preparation as shown in *Plate 6*. The torque transducer shaft outputs are coupled between the tractor PTO shaft and the rotor tiller drive shaft. The torque and speed of the tractor PTO shaft measured by the instrument are recorded by data logger, and

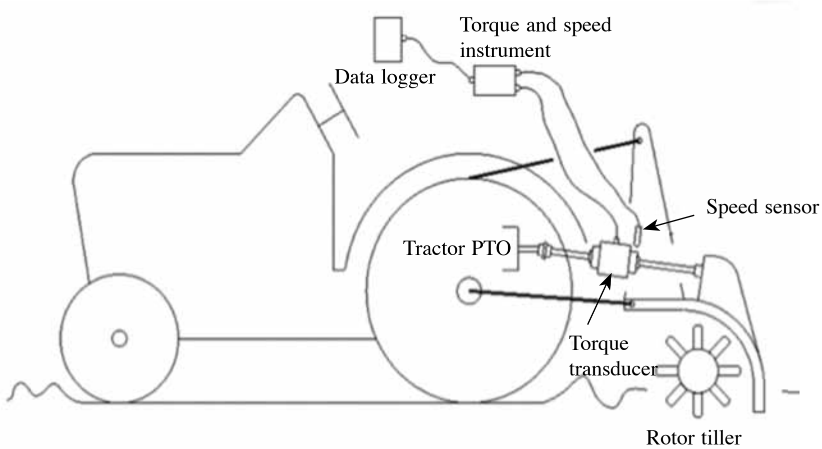


Plate 6. Measuring power requirement of a rotor tiller

these data could be transferred to the computer after completion of the test run for analysis. Both the instrument and data logger are light, small size and battery powered. Therefore, field handling and installation of the equipment onto a tractor implement are less troublesome.

The rated torque capacity of the Honeywell model 1228 torque transducer is 280 Nm which is about 80% of its maximum torque capacity. Based on this torque rating, it is estimated that a torque power of up to 25 hp or 40 hp of tractor PTO drive which rotates at 650 rpm or 1,000 rpm can be measured by our power measuring instrument. Therefore, it could be used to measure the power requirements of tractor PTO driven implements or threshing equipment with rated power of less than 40 hp at a torque of below than 280 Nm. However, to measure implements or agricultural machines of low power and torque rating, a low rated commercial torque transducer should be used in place of the Honeywell model 1228 to obtain better torque measurement sensitivity. This can be easily done by connecting the low rated torque transducer to the existing instrument and adjusting the IA sensitivity gain and span over its calibrated torque values.

Since the power measuring instrument could be interfaced directly to most of commercial torque or force transducers made of either 240 or 350 ohm bridge strain gauges, it could also be used to measure draft force of pulling type soil engaging implements and test the traction pull slip performance of tractors. To perform these tests, a suitable rated tensional force transducer is interfaced to the portable power measuring instrument to measure the implement's draft force and a magnetic pick up speed sensor is mounted on the tractor wheel hub to measure the distance traveled by the tractor drive wheel. The force measured by the force transducer while pulling the implement, F_l is

$$F_l = KVa \text{ in N} \qquad (12)$$

where

K = Slope of force-voltage relationship of the particular transducer rated capacity in N/V

V_a = Voltage output of the force transducer in V

The percentage slip of the tractor, %S is given by

$$\%S = 100(1-L_t/L_a) \qquad (13)$$

where

L_a = Actual distance traveled by the tractor wheel measured by tape during the test duration

L_t = Theoretical distance traveled by the tractor drive wheel measured by the speed sensor

= $2\pi D_w C_p/N_t$ in meter

D_w = Tractor wheel diameter in meter

C_p = No of spike pulse count recorded by data logger

N_t = No of speed sensor spike

Besides that, the calibration stand was found to be a convenient method to apply increasing load onto the torque or force transducer since it only requires dead weight of light steel bars which could be hooked at the cantilever beam by a single person.

Conclusion

A portable power measuring instrument was successfully developed. It was based on a stable DC power supply regulator circuit and an amplifier circuit based on FUTEK CSG110 instrumentation implifier module. It has proven to be accurate in measuring torque and force values based on the experiments done with Honeywell model 1228 torque transducer and model 6443 force transducer with the regression lines' R^2 value of 0.99. It could also be interfaced to any commercial torque or force transducers by setting the excitation, zero and span voltage adjustment at the IA to produce a higher accuracy output voltage resolution for the particular transducer's rated load capacity. Some of the developed instrument's applications are measuring power requirement, draft force and pull slip performance of agricultural machines. Finally, the calibration stand was found to be a convenient method to calibrate commercial torque or force transducers over a wide range of load capacity by subjecting the transducers to counter the variable weight moment of the cantilever beam pivoted at the calibration stand frame.

Acknowledgement

This research project is classified under RM9 Development Project. The authors are very grateful to the Ministry of Agriculture and Agro-based Industry Malaysia for granting the fund.

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Abstrak

Pusat Penyelidikan Kejuruteraan MARDI telah membangunkan jentera pertanian baru dan juga penilaian ujian serta penyesuaian jentera pertanian komersial. Penyelidikan turut melibatkan pengujian jentera untuk menganalisis prestasinya dari segi fungsi, keperluan kuasa dan ketahanan. Sebuah instrumen pengukuran kuasa mudah alih untuk mengukur keperluan kuasa, daya draf dan slip tarik telah dibangunkan. Metodologi yang digunakan untuk membangunkan instrumen ini termasuklah membina dan menguji litar instrumen pengukuran kuasa, membina alat penentukuran dan melaksanakan penentukuran ke atas instrumen pengukuran kuasa menggunakan transduser tork dan daya komersial. Pembinaan dan pengujian litar instrumen pengukuran kuasa melibatkan reka bentuk dan pembinaan sebuah pengatur kuasa arus terus (DC) yang stabil dan sebuah litar penguat *amplifier* yang sesuai. Penentukuran instrumen tersebut kemudiannya dijalankan dengan transduser tork dan daya berjenama Honeywell menggunakan alat penentukuran. Korelasi bacaan voltan instrumen dengan nilai tork dan daya daripada kedua-dua tranduser berkenaan adalah lurus dengan margin kesilapan 0.1%. Secara ringkasnya, sebuah instrumen pengukuran kuasa mudah alih yang boleh disambungkan dengan transduser tork atau beban komersial telah berjaya dihasilkan. Di samping itu, alat penentukuran yang dibangunkan dapat memudahkan kerja-kerja penentukuran transduser komersial tork atau beban dengan mengaplikasikan daya yang bertentangan daripada momen beban di *cantilever beam* yang disangkutkan pada alat penentukuran tersebut.

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