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Embedded digital drive wheel torque indicator for agricultural 2WD tractors

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ABSTRACT

A microcontroller based embedded system was developed to measure and display the dynamic wheel axle torque and drawbar power of agricultural tractor for tillage research. The device includes a special transducer to measure dynamic drive wheel torque of tractor, an embedded wireless digital system to receive process and display data digitally as well as record in SD card module near the dash board of the tractor. The embedded system mainly consists of an amplifier to amplify the transducer signal, a transmitter unit to process the amplifier data, and a receiver unit to receive and display the transmitter unit data. The developed system was rigorously tested under laboratory and actual field conditions. It was found that, a maximum variation of ±320 Nm torque between the theoretically calculated and experimentally observed values under field conditions. With the developed devices the real time power requirement of various agricultural operations could be known to help the tillage researchers. The developed device and systems are simple and accurate and can be used for any range of agricultural tractors.

1. Introduction

Agricultural tractor is a major power source on the farm. Utilization of the tractor power has not been at its maximum level with any given implement under any field conditions due to none matching implement size. A correct matching of tractor-implement system would result in decreased power losses, improved efficiency of operation, reduced operating costs and optimum utilization of capital on fixed costs (Taylor et al., 1991). Tractor designers need advanced instrumentation to improve field performance of tractor in terms of drawbar pull, power and fuel efficiency. Recent evolutions in electronics and computer technology have made measurements of field performance of tractors and implements easier.

Most of the field operations are conducted using a tractor implement combination; hence draft forces of the implements exerted on the tractor plays a major role in the prediction of tractor performance (Al-Janobi and Al-Suhaibani, 1998). The draft force data of implements is one of the major factor in selecting suitable implement for a various farming operation (Alimardani et al., 2008). Proper matching of tractor implement combination will maximize the fuel efficiency and reduce the operating cost of the tractor.

Measurements of wheel torque have received considerable attention in tractive performance studies. Several researchers (Mahmoud et al., 1972; Anderson et al., 1974; Tompkins and Wilhelm, 1982; Musunda et al., 1983; Palmer, 1985; Watts and Longstaff, 1989; Snyder and Buck, 1990; McLaughlin et al., 1993; Al-Janobi et al., 1997; Dong and Kyeong, 1997; Spath, 2001; Decker and Savaidis, 2002; Botta et al., 2002; Kheiralla et al., 2003; Gobbi et al., 2005; Nang et al., 2009) have developed various instrumentation systems to measure the dynamic drive wheel torque of tractor by mounting strain gauges directly on the axle and providing additional uniform extension shaft with strain gauges on to the axle and recorded the signals by slip rings and data acquisition system, but none of them have employed an embedded system, to read and report the data.

Measurement of field performance parameters of tractor implement combination with commercial data acquisition system is little bit cumbersome task due to its bulky construction and required well trained people and also comparatively more cost, but embed-

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Nomenclature

b	wheel width (in.)
B_n	mobility number
CI	cone index (kPa)
d	wheel diameter (m)
D	draft (kg)
d1	depth of operation (cm)
er	rear wheel eccentricity
ef	front wheel eccentricity
F	tractive effort
GTR	gross traction ratio
Hd	horizontal distance of tractor lower hitch point from the rear axle center (m)
h	tyre section height (m)
L	wheel base (m)
MRR	motion resistance ratio
MRR_r	motion resistance ratio of rear tyre
MRR_f	motion resistance ratio of front tyre
NTR	net traction ratio
P_y	vertical component of resultant soil force (kg)
RD	relative deviation (%)
R_r, R_f	dynamic reaction on tractor rear wheel and tractor front wheel (kg)
S	wheel slip (%)
SD	standard deviation
TF_f, TF_r	towed force of front and rear wheel
V_a	actual velocity (m/s)
V_t	theoretical velocity (m/s)
W	width of cut (m)
GTF	gross traction force
RWD	rear wheel dynamic weight
W_t	static weight of tractor (kg)
W_m	weight of implement (kg)
X_{cgt}	horizontal distance of CG of tractor from the rear axle center (m)
X_{cgi}	horizontal distance of CG of implement from tractor lower hitch point (m)
Y_d	distance of center of resistance from ground surface (m)
δ	tyre deflection
d1	depth of cut
r_r	rolling radius of rear wheel (m)
r_f	rolling radius of front wheel (m)
CG	center of gravity

ded system is a microcontroller based, software driven, reliable and real-time control system designed to perform a specific task. It can be easily customized, requires low power, comparatively less cost and helps in efficient data collection.

Moreover, there is little information available regarding on-the-go measurement of parameters such as dynamic wheel axle torque. In view of the above arguments, the main purpose of the present study was to develop a transducer for measurement of dynamic wheel torque experienced by tractor axle during different field operations and also to develop an embedded systems for on-the-go digital display of dynamic wheel axle torque of any given implement attached to the tractor with a high degree of accuracy. The developed device will be very much helpful for educational institutes and research needs on drawbar performance and tillage research.

2. Theoretical considerations

The following theoretical and empirical equations were used to develop visual basic software for predicting the dynamic torque values by using various empirical equations.

2.1. Implement draft (D_f)

The implement draft can be modeled as a function of speed, width of implement, soil texture, depth of operation and geometry of tools. According to ASAE standard 1997 D497.3, it can be calculated by

$$D_f = F_j(A + BV_a + CV_a^2) * W * d \quad (1)$$

where F_j is dimensionless soil texture adjustment parameter (j = 1 for fine, 2 for medium and 3 for course textured soils), and A, B and C are machine specific parameters, W is the width of operation and d is the depth of operation.

2.2. Wheel slip (S)

It is expressed as the ratio of the decrease in the actual speed (Va) to the theoretical speed (Vt) and is given by

$$S = \left(1 - \frac{Va}{Vt}\right) \quad (2)$$

2.3. Motion resistance ratio (MRR)

Coefficient of motion resistance or motion resistance ratio (MRR) is defined as the ratio of rolling resistance to the dynamic weight on a wheel.

2.4. Gross traction ratio (GTR)

The gross traction ratio is the ratio of the gross thrust developed by the tractor to the dynamic weight on the traction wheels (powered wheel). Brixius (1987) developed the following expressions for GTR and MRR as a function of mobility number (B_n) and wheel slip (S).

$$GTR = 0.88(1 - e^{-0.1B_n})(1 - e^{-7.5S}) + 0.04 \quad (3)$$

$$MRR_r = \frac{1}{B_n} + 0.04 + \frac{0.5 \times S}{\sqrt{B_n}} \quad (4)$$

$$MRR_f = \frac{1}{B_n} + 0.04 \quad (5)$$

$$B_n = \frac{CI \times b \times d}{R_r}\left(\frac{1 + 5\frac{\delta}{h}}{1 + 3\frac{b}{d}}\right) \quad (6)$$

2.5. Net traction ratio (NTR)

Net traction ratio is defined as the ratio of draft to the dynamic weight on the driving wheels.

$$NTR = D/R_r \quad (7)$$

$$\text{Also, } NTR = GTR - MRR \quad (8)$$

2.6. Dynamic front wheel reaction (R_f)

The dynamic weight on tractor axles is required to determine the gross traction force and drive wheel torque. Considering force and moments in Fig. 1 (Kumar and Pandey, 2012), the dynamic reaction on tractor rear wheel, R_r can be expressed as follows.

Resolving forces in horizontal and vertical directions, yields

$$F - D - TF_r - TF_f = 0 \quad (9)$$

$$R_f + R_r - W_t - W_m - P_y = 0 \quad (10)$$

Taking moment of forces at point 'B', the dynamic weight on tractor rear and front axles was calculated as follows:

$$R_r(L - e_r + e_f) - W_t(L + e_f - X_{cgt}) - (W_m + P_y)(X_{cgi} + H_d + L + e_f) + DY_d = 0$$

$$\text{or, } R_r = \frac{W_t(L + e_f - X_{cgt}) + (W_m + P_y)(X_{cgi} + H_d + L + e_f) - DY_d}{L - e_r + e_f} \quad (11)$$

$$\text{and, } R_f = (W_t + W_m + P_y) - R_r \quad (12)$$

The rear and front wheel eccentricities were calculated by

$$e_r = MRR_r \times r_r \quad (13)$$

$$e_f = MRR_f \times r_f \quad (14)$$

$$GTF = GTR * R_r \quad (15)$$

$$T_a = GTF * r_r \quad (16)$$

2.7. Software development

A software was developed in visual basic© to calculate the theoretical dynamic front wheel reaction for a given soil type, implement and tractor parameters. Eq. (1) was used to calculate the draft of the implement, and (Eqs. (3)–(6)), were used for predicting GTR and MRR. The motion resistance ratio was calculated by iteration process by initially fixing the motion resistance ratio equal to 0.04 and comparing it with that derived from Brixius (1987) equation (Eq. (4)). The slip was also calculated by iteration process (assuming initial value equal to 2 percent) by comparing the net traction ratio from Eq. (7) with that derived from Brixius equation (Eq. (8)), otherwise it may be measured directly in the field. In the present study the slip was measured directly with specially developed system (Ashok Kumar et al., 2016). The dynamic rear wheel reaction of the tractor was calculated by using Eq. (11) and the gross traction force was calculated by using Eq. (15), and finally the theoretical torque was calculated by multiplying the gross traction force and rolling radius (Eq. (16)).

3. Materials and methods

Measurement of drive wheel torque plays an important role in drawbar performance of tractor implement. Most of the wheel torque transducers developed by the several researchers is designed to work in specific tractors for the required precision and usually are quite expensive. Hence, there is need for a general precision wheel torque transducer suitable for the most common agricultural tractors. The detailed description of the systems is as follows.

3.1. Design considerations

A transducer that could be fitted between the driven wheel mounting, which is usually the brake drum and the wheel itself, would meet the stated requirements. The transducer had to be as thin as possible so as to interfere as little as possible with the original range of wheel track positions. The signals from the revolving torque transducer were transmitted to a stationary receiver by using radio frequency modules due to simple construction and prolonged life.

3.2. Conceptualization of axle torque measurement

To measure the dynamic drive wheel torque of tractor, a design was selected to develop special transducers to be fitted to both the

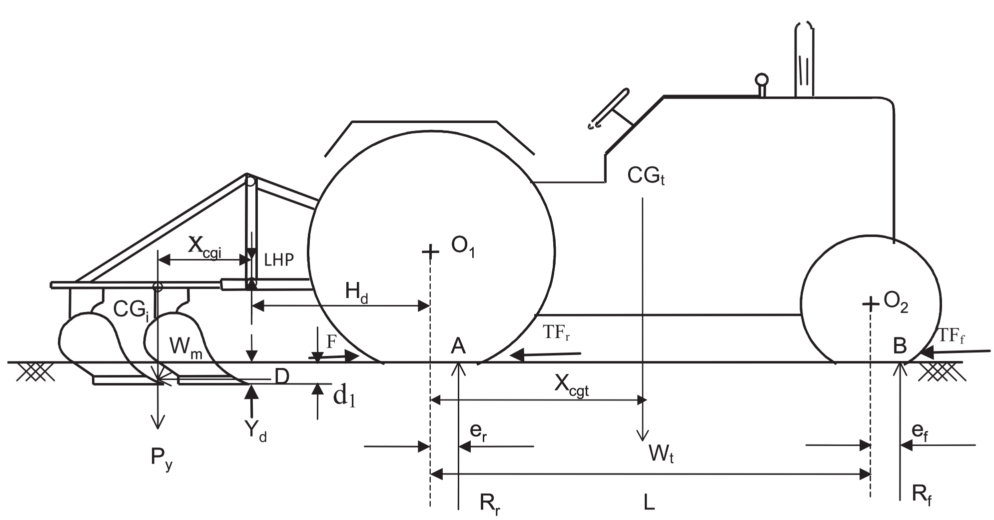

Fig. 1. Forces acting on tractor-mould board plough combination.

half axles (left wheel and right wheel) of tractor. The developed sensor has two flanges on both the ends with extension shaft at the center, one to fit to the axle flange of tractor and other to fit to wheel rim. The rotary motion caused by the wheel can develop torque on the axle and developed transducer. For sensing the axle torque, rosettes type strain gauges were bonded on the center of developed extension shaft. Since the wheel is in continuous rotary motion, it's not possible to measure the signals by direct communication with wires, hence a microcontroller based embedded digital wireless telemetry system was developed to read, process and display the sensing data of developed torque transducer. The conceptual layout of axle torque measurement system is shown in Fig. 2a and the developed extension shaft with mounted strain gauge type rosettes is shown in Fig. 2b.

3.3. Development of torque transducer

A universal drive wheel torque transducer was designed and developed for suitability of most common agricultural tractors. Developed transducer is a rosettes based unit which is mounted between axle flange and wheel rim of the tractor. The wheel torque sensing element design has 2 sets of rosette strain gauges installed on opposite sides of the extension axle shaft and positioned at 45° to axle axis to give the maximum sensitivity to torsional strains. The selected gauges have a gauge resistance of 120 Ohms, a gauge factor of 2.1, and one-meter length lead wires were bonded at 45° shear planes on opposite sides of the extension shaft. The available 4 gauges are wired to a constant current full Wheatstone bridge configuration. A full bridge 5 V constant current supply from the 12 V battery was used to excite the strain gauges bridge on the wheel torque transducer. The gauge installation was carried out after smoothing the extension shaft surface by fine silicon carbide abrasive paper. Accurate markings were done with the help of a Digimatic Height gauge for mounting of strain gauge rosettes. The strain gauges were positioned at 45° apart on the predetermined surface of the shaft and glued permanently using an epoxy adhesive. Finally, SG280 protective coating was applied to the installed gauges to provide protection against water, humidity and mechanical abrasion. In prior to the design of transducer, the axle flange construction of various agricultural tractors were studied and developed a transducer to be fitted for most common agricultural tractors. It mainly consists of two flanges; one as inner flange to be fitted to the half axel flange and other as outer flange to be fitted to the wheel rim of tractor. Special types of bolts were developed along with transducer system to fit for other tractors. Filleting was made on the outer flange periphery of transducer for proper mating with the disk curvature of wheel rim. An internal groove was made on the inner flange side for supporting and proper mating with half axle flange. A pair of transducers was mounted on both the half axles of tractor and the exceeded track width was reduced by changing the disk position of wheel rim.

3.4. Dynamic simulation of developed transducer

A dynamic simulation was carried out in simulation software by applying twisting moment up to 30 kN to find the location of strain concentration also the maximum load bearing capacity of transducer. Initially the developed torque transducer with uniform extension shaft was analyzed in simulation software. It was observed that, the minimum stress development and the maximum stress development was 1.9529×10^{-6} and 1.5591×10^{3} Pa respectively and also observed that a very less and uniform stress distribution throughout the length of the extension shaft (Fig. 3a). Hence to get more stress concentration at the middle of the extension shaft for mounting of strain gauges, a narrow tapered section was made on the extension shaft from both sides of the flanges from opposite to each other to reduce the diameter of the extension shaft at the center. Again the similar procedure was followed by applying various twisting moments for dynamic simulation and it was observed that, the minimum stress development and the maximum stress development was 6.097×10^{-8} and 1.0628×10^{8} Pa respectively and also observed maximum stress concentration at the targeted portion for mounting of strain gauges as shown in Fig. 3b. Hence the tapered extension shaft was

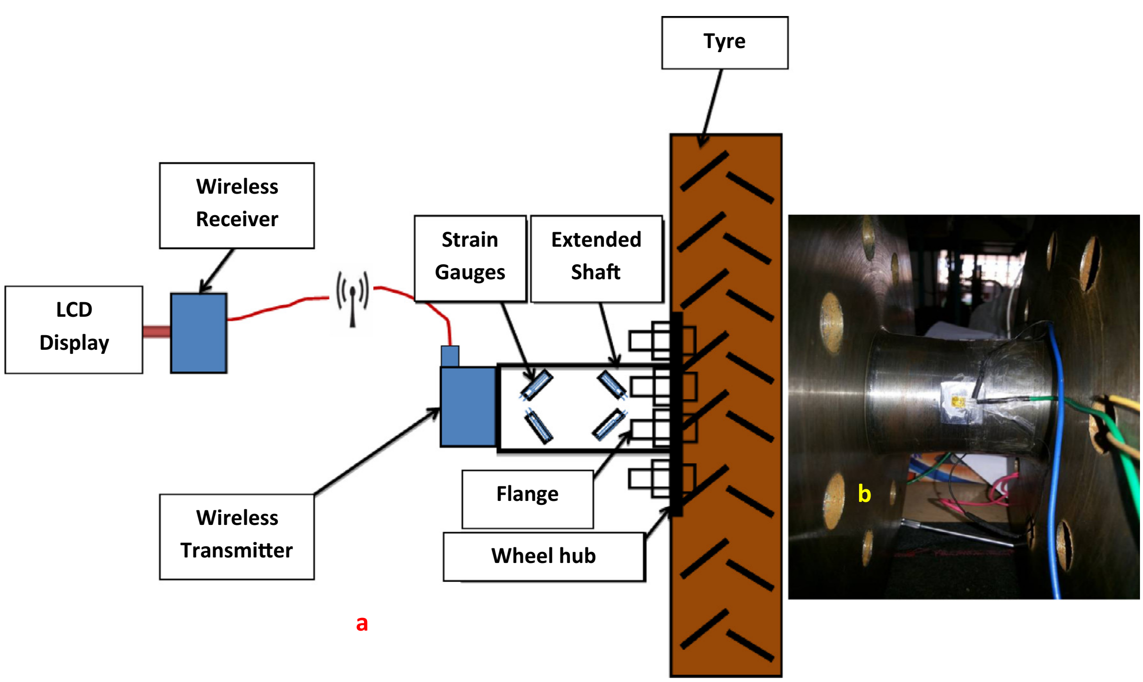

Fig. 2. (a) Conceptual layout of axle torque measurement, (b) extended shaft with strain gauges.

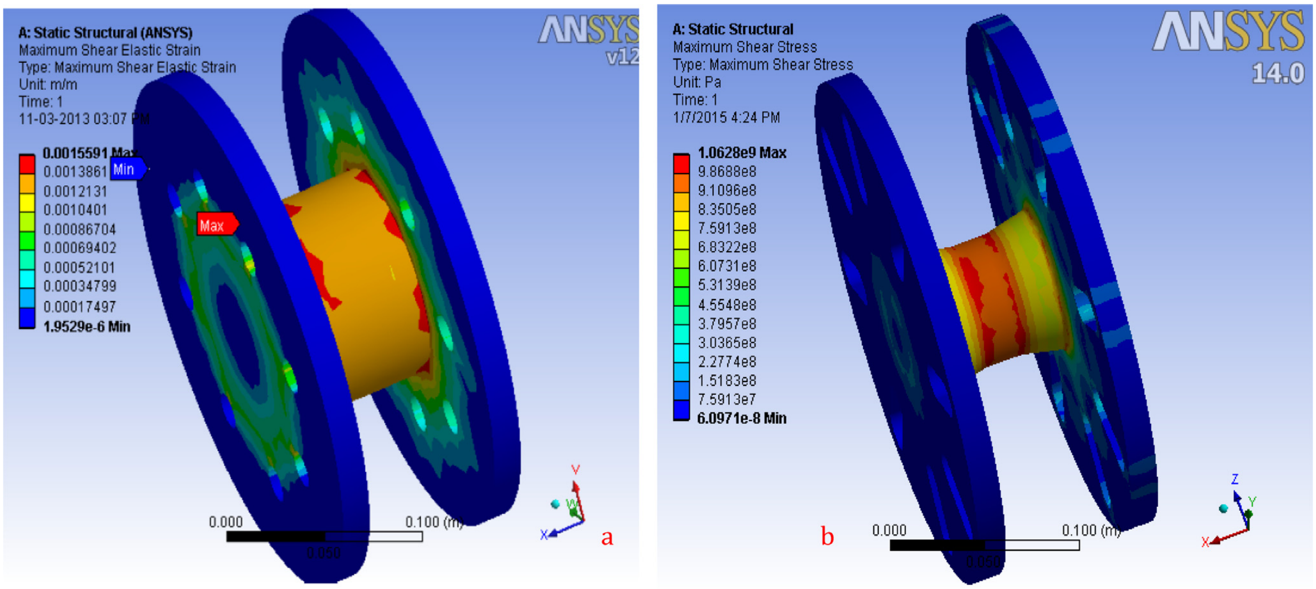

Fig. 3. Dynamic simulation of axle torque transducer: a. With uniform circular shaft, b. With tapered section shaft.

developed and mounted strain gauge type rosettes at the stress concentrated portion. The reason to get maximum stress concentration at the middle of the extension shaft may be the twisting force are transferred from both sides of the flanges and the diametric difference of the extension shaft at the starting point of each flange and middle of the extension shaft since the small diameter shafts are subjected to more stress and corresponding strain as compared to bigger diameter shaft with same load application.

After fitting of developed transducer to the axle and mounting of wheels, the transducer could bear bending moments due to overall weight of the tractor and extra weight caused by the undulations of the field during field operation apart with twisting moment. Hence to know the effect of bending moment due to weight of the tractor and twisting moment simultaneously, a simulation was carried out on developed transducer with half axle construction along with tyre in simulation software by applying combined bending moment and twisting moment simultaneously. The twisting moments were considered up to 20 kN-m with the bending load of 15 kN on each of the rear wheel. It was observed that, due to application of combined torque and bending force, there was no effect on the strength of half axle and fitted transducer.

4. Laboratory validation of developed transducer

4.1. Test rig for dynamic calibration

For calibration of developed transducer in laboratory a set up was made in which the transducer was attached to the left rear axle flange of test tractor to measure dynamic drive torque as shown in Fig. 4a. The left wheel of test tractor was replaced by a wheel rim and tractor was supported with help of fabricated base frame. The developed transducer was connected to the axle flange of test tractor. A canvas belt was mounted on the wheel rim to oppose the motion of the rim with help of loading crane to get braking torque on the half axle. Two load cells were connected at the two ends of belt to measure the forces and tractor was operated at different gears for rotary motion of the axle and output was measured with the help of developed display system and it was observed a very good linearity (Fig. 4b) of output values with load application. Each test was replicated three times for more accuracy. The loads were varied from 0 to 40 kg in all the speeds of rear wheels.

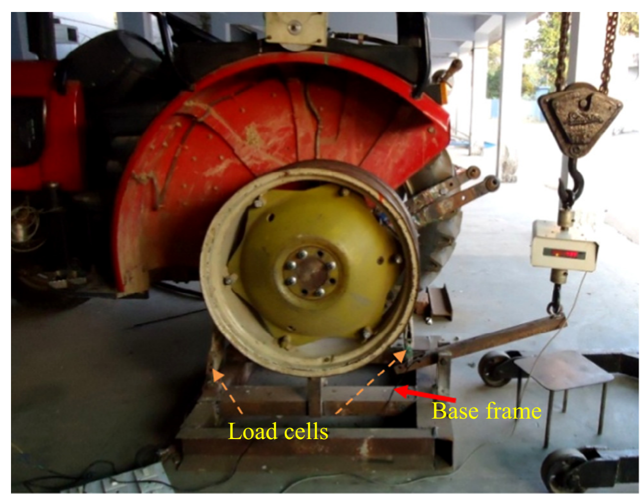

Fig. 4a. Test rig for dynamic calibration of developed transducer.

4.2. Development of digital drive wheel torque and drawbar power indicator

It is relatively easy to design a transducer to measure the drive wheel torque then drawbar power of tractor. The main problem is in transmitting the torque signals from the revolving wheel to the stationary onboard data logging system. This problem can be solved by using telemetry system with radio-frequency transmitters mounted on shaft and picking up the signal by means of a receiver placed nearby. To read and process the sensor data, an embedded digital display unit was developed. It includes an amplifier to amplify the transducer signal, a transmitter unit to process and send the amplifier data, and a receiver unit to receive the transmitter unit signal data for recording as well as displaying digitally.

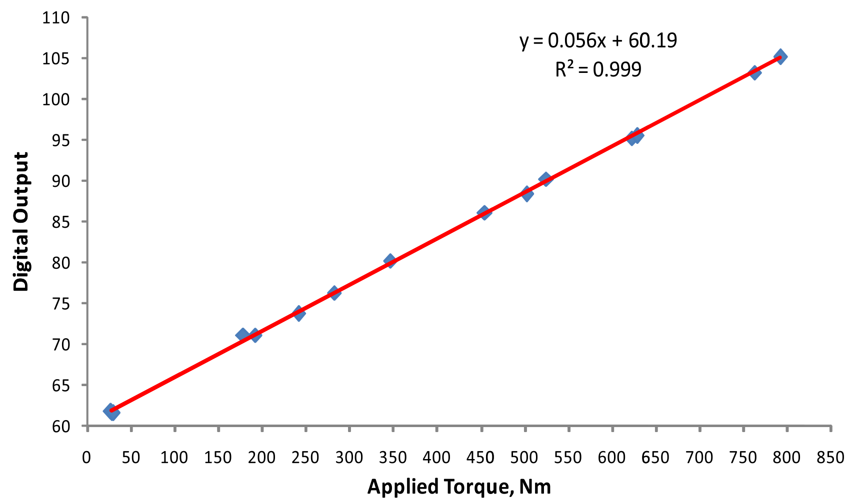

Fig. 4b. Dynamic calibration curve of developed sensor at different speed and loads.

4.2.1. Development of amplifier

During laboratory calibrations of the developed transducer, it was observed less output values, hence to avoid the errors at the signal processing system; the output signal was amplified using an operational amplifier, which was then fed to the analog to digital converter (ADC) port of the microcontroller. Developed transducer along with amplifier was calibrated at different resistance and found best output at 423 Ohms and fixed the same. The overall circuit diagram of the developed differential amplifier is shown in Fig. 5.

4.2.2. Development of data processing and transmitter unit

Since the drive wheel of tractor is in continuous rotary motion, hence it's not possible to track and send the data for storing and display unit with wires; hence a wireless display system was developed with simple materials. It includes amplifier circuit, microcontroller, xbee shield and RF transmitter module. The output of amplifier was connected to the ADC of microcontroller to convert the analog values into digital values. The microcontroller program was written in C language to process the sensor data. A xbee shield was connected to the microcontroller to pick up processed data and RF module was used to get the data from xbee shield as non possibility to get data directly from microcontroller. A 12 V battery was used as a power supply and a voltage emulator was connected to convert 5 V and fed the same as power supply. The system can work continuously for a period of 5 h at full charged condition. The frequency of data can be changed by adjusting the delay period in burned program. In present study 50 ms delay period was used, hence for every 50 ms, it reads and sends the data. Two transmitter units were developed for both wheels. The overall circuit diagram of the developed signal processing and transmitter unit is shown in Fig. 6

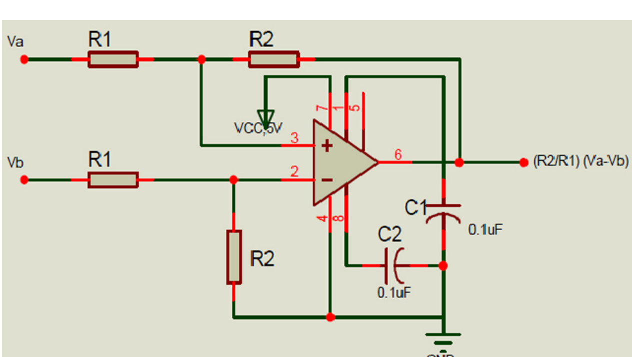

Fig. 5. Circuit diagram of the developed difference amplifier.

4.2.3. Development of data receiver and digital display unit

To receive transmitted data from the transmitter unit, a receiver unit was developed to receive data and display digitally. It mainly consists of RF receiver modules to receive the transmitted data from both the transmitter unit, xbee explorer to read the data from RF receiver module which is connected to the microcontroller for storing and displaying digitally on LCD screen and also record the received data in a SD card module. The program flowchart of digital drive torque indicator is shown in Fig. 7 and overall circuit diagram of the signal receiver and display unit is shown in Fig. 8. It is convenient, simple, and reliable in operation. It is able to communicate the signals through radio frequency modules (RF) up to 100 m distance without any interruption, however with the same circuit, the signals may be communicated up to 750 m with new version of Xbee RF modules.

5. Testing of the developed devices

5.1. Validation of the transducer in laboratory

For dynamic calibration of the developed torque transducer, a test rig was developed with the TAFE 4410 tractor (test tractor in the present study) available at Agricultural and Food Engineering Department, IIT Kharagpur. The torque data obtained from the sensor was compared with the theoretical calculated values based on the results obtained from the load cells. It was observed that, the data obtained from both the methods are directly proportional. It was also observed that, a maximum variation in between applied torque with loading crane and observed torque from the developed sensor was about 6.468 Nm to 30.39 Nm. The comparison of observed torque and applied torque at different speeds and varying loads are shown in Figs. 9a and 9b. It was also observed more toque values from sensor than the applied torque in all the cases may be due to vibrations, hysterisious and internal stresses and strains.

The data obtained from sensor and theoretical calculations were analyzed statistically by using a Duncan Multiple Range Tests (DMRT) and observed that, there is no significant

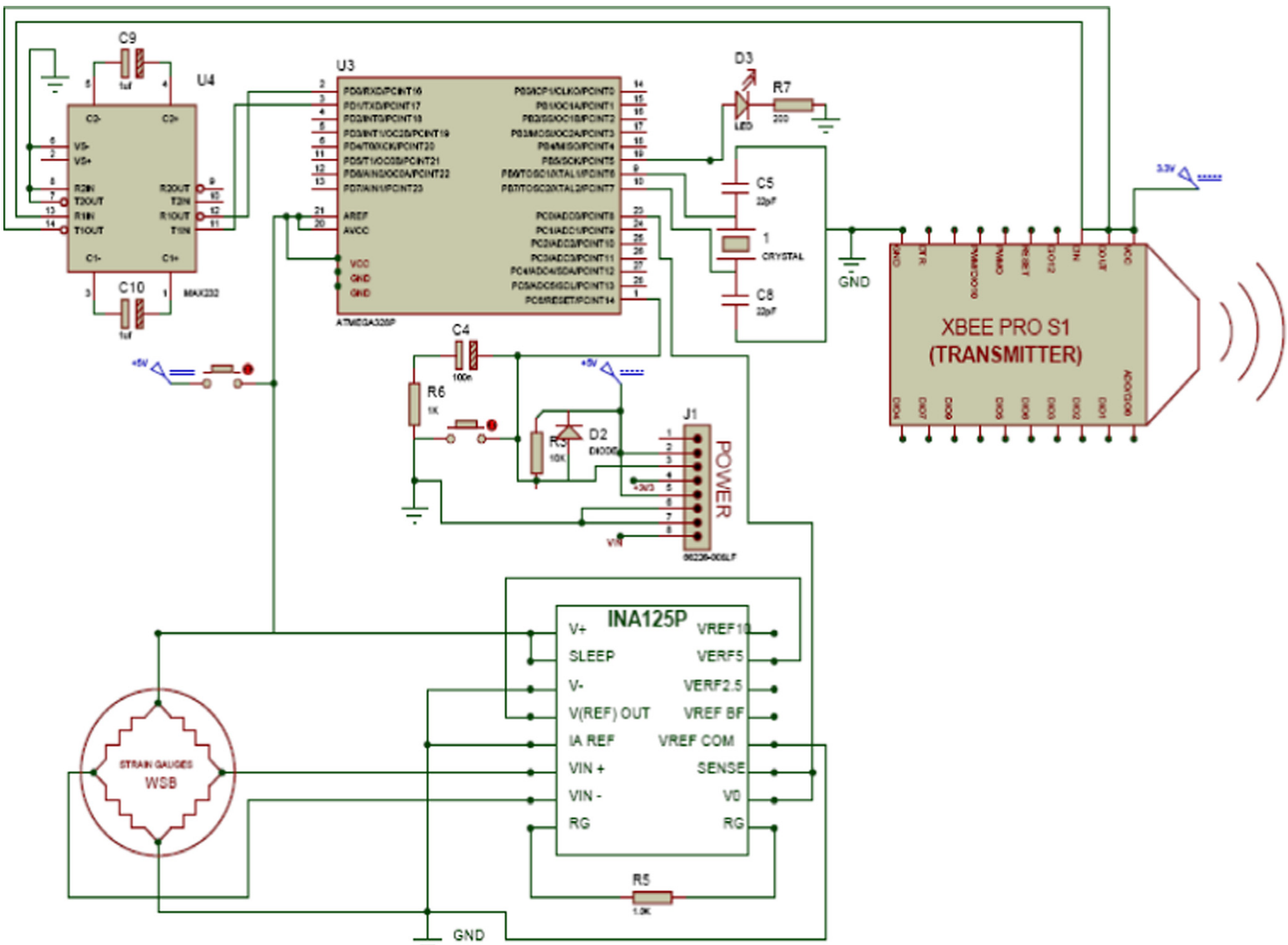

Fig. 6. Circuit diagram of the developed signal processing and transmitter unit.

difference between applied torque and observed torque at 5% significant level. The statistical analysis of the results obtained from the sensor and the theoretical calculated values are given in Table 1.

5.2. Testing of developed system on tar macadam surface

To validate the developed axle torque indicator under real dynamic condition, number of trails was conducted on tar macadam surface with help of towed tractor. Both the developed sensors were mounted to the half axles of test tractor. The test tractor was connected with the dummy tractor as a towed tractor to exert load on test tractor. The draft force requirement of the test tractor to pull dummy tractor was measured with help of load cells and the test tractor was operated at different gears. The dynamic torque of test tractor was measured with help of developed sensors and also compared with the theoretical results and found a maximum variation of ±256 Nm. The dynamic torque of test tractor at L_2 gear is shown in Fig. 10. It was clearly indicated that, the observed torque values on both the half axles are changing simultaneously as change of draw bar pull. As the drawbar pull increases, the dynamic wheel torque was also increases. The observed sensor values at various pulls were compared with the theoretical calculated values by using empirical equation. It was observed that, a maximum variation of ±4–8%, this may be due to ground undulations, bending moment and vibration of the sensor.

5.3. Testing of developed device on actual field condition

The test tractor (TAFE 4410, 38.5 kW) with the developed digital drive torque and drawbar power indicator with different implements of MB plough, disk harrow and spring tine cultivator was tested under actual field conditions. A three point hitch dynamometer was used to measure the draft force of the implement and a Hall Effect sensor based magnetic pins mounted discs were used to measure the actual speed, theoretical speed of operation there by wheel slip in percentage simultaneously (Ashok Kumar et al., 2016). A rotary potentiometer was used to measure the depth of operation. The drive torque of the test tractor on both the axles during operation was measured and logged into the developed embedded digital drive torque indicator. The out puts of dynamometer, Hall Effect sensor based wheel slip measurement system and rotary potentiometer were measured with separate developed microcontroller based embedded system with same frequency of torque and drawbar power indicator (Ashok Kumar et al., 2016). A field of one acre fallow land was selected for testing of the developed devices. The field was divided into equal parts for validation with different tractor implement combination. Cone index (CI) of the soil was measured at different places with digital cone penetrometer. Measured average depth of operation of test tractor with the mb plough was ranged from 15.7 to 24.8 cm where as 9.7–15.8 cm for cultivator and harrow. It was observed that, as the draft force increase drive torque of the tractor increases. The experimental results of drive torque values at specific draft at

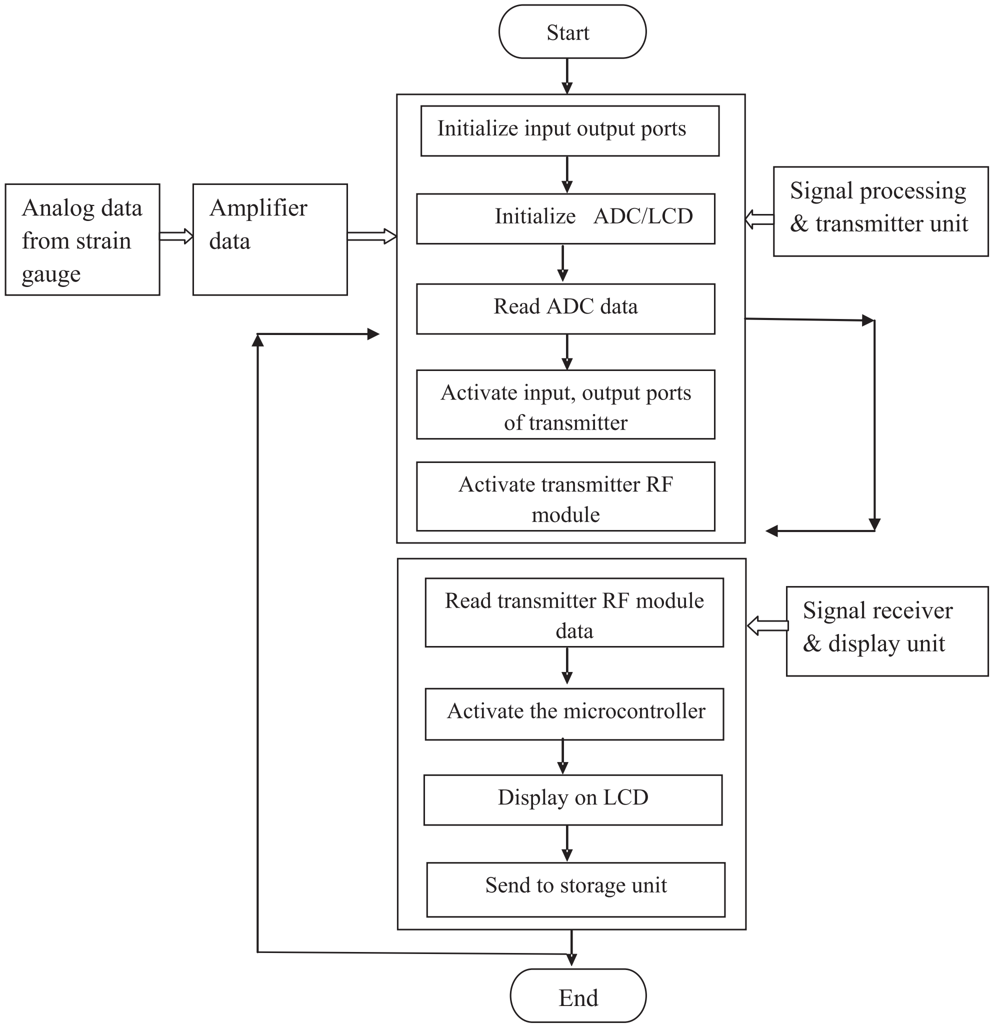

Fig. 7. Flow chart for working digital drive torque indicator.

different depths were then compared with the theoretical results and found a maximum variation ranging from ±260 Nm to 320 Nm with SD = 2.73 for tractor with MB plough where as ±190–273 Nm with SD = 2.13 for tractor with cultivator and harrow, this variation may be due to field undulations. A comparison of experimental values and that with the theoretical calculated values are shown in Fig. 11.

During field trails, it was observed that, the axle torque values on both the half axle are not uniform and axle torque was increased with increase of draft force of implement. While starting of the tractor, the wheel was demanded more torque at the axle and after starting, torque at the axle was slightly reduced. During field trails, the axle torque values were measured at different gears and throttle conditions. The axle torque was increased as changing throttle condition and depth of operation as shown in Fig. 12. It was also observed that, the torque values of both the wheels are not uniform and are independent for applied load due to field undulations. During ploughing operation in L2 gear of the test tractor, the draft force of the implement was varied from 800 kg to 1278 kg at depth ranges from 16.1 cm to 24.7 cm where as the axle torque of the test tractor varied from 4282 Nm to 7352 Nm with maximum variation of axle torque of both the wheels i.e. left and right was varied from ±81 Nm to 365 Nm, this may be due to vibrations and field undulations as well as the tractor self weight and side forces of the implement. Similarly during ploughing operation in L3 gear of the test tractor, the draft force of the implement was varied from 845 kg to 1386 kg at depth ranges from 16.1 cm to 24.7 cm where as the axle torque of the test tractor varied from 4610 Nm to 7825 Nm with maximum variation of axle torque of both the wheels i.e. left and right was varied from ±34 Nm to 364 Nm, this may be due to vibrations and field undulations as well as the tractor self weight and side forces of the implement. The observed experimental data were also compared with theoretical results using a statistical term, relative deviation (RD), which is defined as follows (Kumar and Pandey, 2012).

$$\mathrm{RD} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\mathrm{DT_e} - \mathrm{DT_t}}{\mathrm{DT_t}}\right)100 \tag{17}$$

where DT_e is the experimental drive torque values value measured by using developed device, DT_t is the theoretical drive torque values measured with empirical equations and N is the number of observations. The RD values for the entire test observations were found less than ±7.04 percent (Table 2). The analysis of the test results was done using the Duncan Multiple Range Test (DMRT) (DC Montgomery, 2008). The analysis showed that the difference in dynamic drive torque values measured using developed device and that with the theoretical calculated values was found to be significant at 1 percent level of significance. This shows the suitability of developed device to measure real time dynamic drive torque.

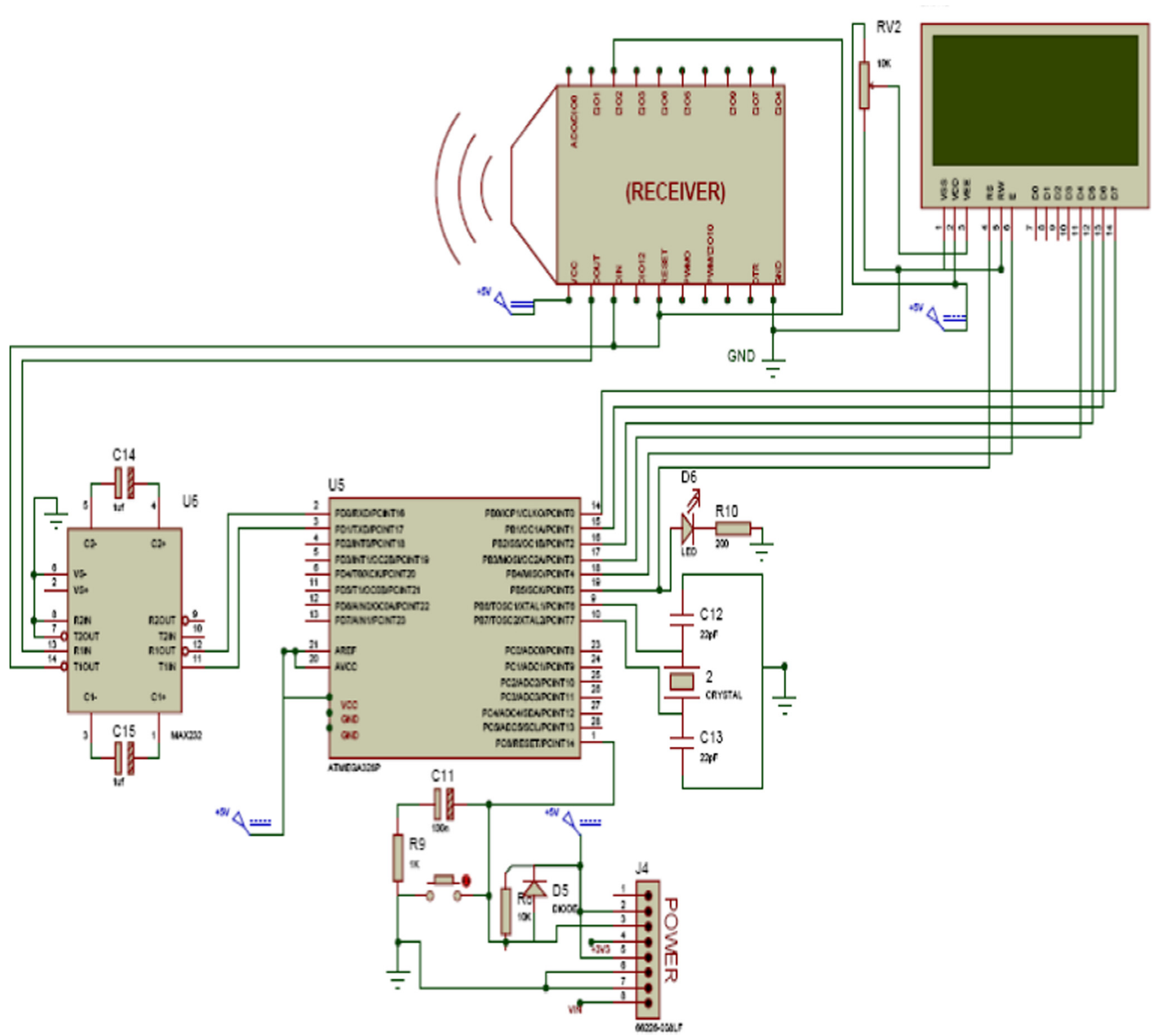

Fig. 8. Circuit diagram of the signal receiver and display unit.

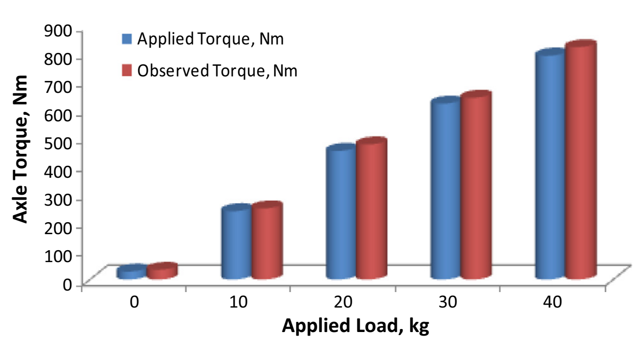

Fig. 9a. Comparison of applied and observed torque at a rear wheel speed of 2.61 kmph.

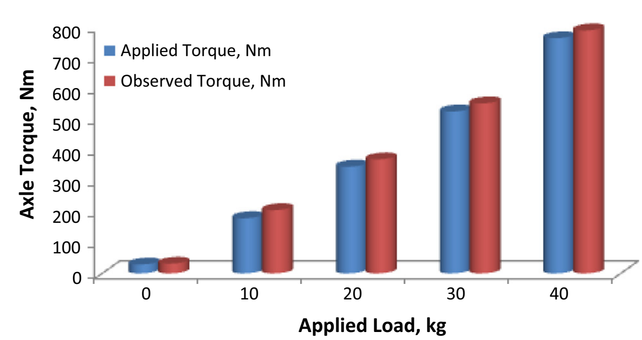

Fig. 9b. Comparison of applied and observed torque at a rear wheel speed of 4.11 kmph.

During tillering operation of the test tractor, the draft force of the implement was varied from 514 kg to 741 kg at depth ranges from 9.4 cm to 16.1 cm where as the axle torque of the test tractor varied from 3686 Nm to 6152 Nm with maximum variation of axle torque of both the wheels i.e. left and right was varied from +55 Nm to 486 Nm, this may be due to vibrations and field

Table 1
Statistical analysis of the results obtained from sensor and the theoretical values.

		Sum of Squares	df	Mean Square	F	Sig.
ANOVA (sub set for alpha = 0.05)						
Observed torque	Between groups	25572.089	2	12786.044	0.166	0.849
	Within groups	922435.214	12	76869.601		
	Total	948007.303	14			
Theoretical torque	Between groups	27854.035	2	13927.018	0.170	0.845
	Within groups	981255.112	12	81771.259		
	Total	1009109.147	14			

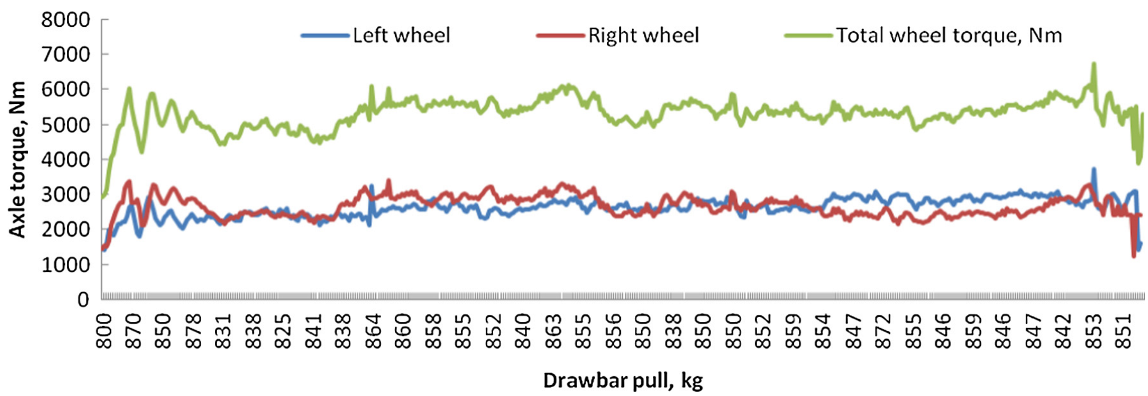

Fig. 10. Comparison of left and right wheel torque at L_1 gear of dummy tractor and L2 gear of test tractor.

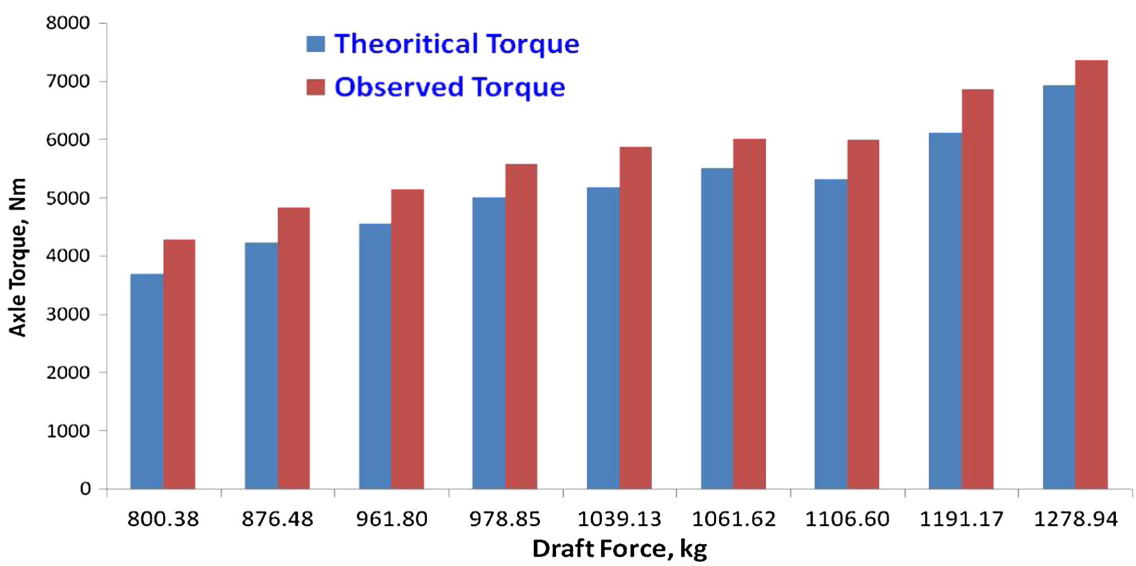

Fig. 11. Comparison of experimental values and theoretical calculated values.

undulations as well as the tractor self weight and side forces of the implement. Similarly during harrowing operation of the test tractor, the draft force of the implement was varied from 550 kg to 771 kg at depth ranges from 9.4 cm to 16.7 cm where as the axle torque of the test tractor varied from 4029 Nm to 6789 Nm with maximum variation of axle torque of both the wheels i.e. left and right was varied from ±41 Nm to 345 Nm, this may be due to vibrations and field undulations as well as the tractor self weight and side forces of the implement. The data obtained from both the sensors i.e. left and right sensors for left wheel torque and right wheel torque was analyzed statistically.

The data analyses further indicate the mean, percent accuracy, percentage deviation, percentage RMSE, and correlation between measured drive wheel torques by both the sensors under field use as presented in Table 3. The RMSE of the developed sensors under various field operations is 0.01, 1.44 and 1.85 during ploughing, tillering and harrowing operation respectively.

6. Conclusions

A mechatronic based embedded digital device was developed to measure and display the drive wheel torque of tractor. The developed sensor was able to withstand even for more than 30 kN twisting moment and 20 kN bending moment and can be fitted to tractor axle without disturbing the original track width. The

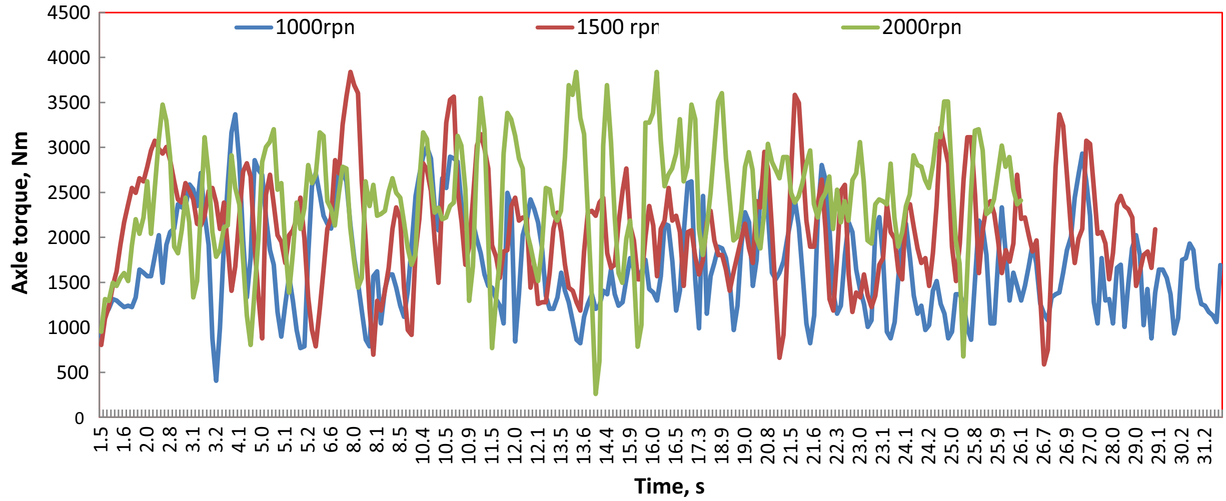

Fig. 12. Axle torque values of left wheel in different throttle condition at a depth of 16 cm during ploughing operation.

Table 2
Sample test results during ploughing operation at different operating depths.

Implement	Depth (mm)	Draft (N)	Drive torque values			
			Theoretical torque (DT_t), Nm	Experimental torque (DTe), Nm	$\left(\frac{DT_e-DT_t}{DT_t}\right)$ (%)	RD (%)
MB plough	152.4	930	7347.98	7112.43	3.21	2.95
		947	7453.67	7241.28	2.85	
		966	7632.39	7397.31	3.1	
		973	7755.15	7494.52	3.36	
		983	7817.07	7642.73	2.23	
	193.4	994	8279.41	8021.33	3.12	2.27
		1017	8375.38	8173.84	2.41	
		1044	8532.44	8224.51	3.61	
		1085	8652.21	8762.25	1.27	
		1112	8716.37	8634.37	0.94	
Cultivator	94.5	378.6	4205.35	3956.22	5.92	2.97
		395.56	4224.56	4105.98	2.81	
		407.76	4238.23	4178.43	1.41	
		431.91	4484.35	4589.72	2.35	
		422.55	4254.56	4356.12	2.39	
	13.56	509.47	4360.70	4531.27	3.91	3.47
		523.14	4426.24	4195.85	5.21	
		535.07	4489.81	4278.56	4.71	
		549.06	4525.72	4639.23	2.51	
		552.74	4542.91	4496.97	1.01	

Table 3
Performance parameters of developed systems under various field operations.

Implement	Mean drive torque, Nm		Accuracy, %	Min and Max deviation, %	RMSE, %	RD, %	CV
	Left wheel	Right wheel					
Ploughing	2961.58	2871.43	97.24	−9.13 to 9.07	0.01	2.37	0.16
Tillering	2359.963	2367.845	96.48	−8.9 to 10.4	1.44	3.51	0.14
Harrowing	2649.83	2637.31	96.10	−12.65 to 9.63	1.85	4.04	0.15

developed transducer was validated under laboratory and field condition and found satisfactory results. It was found that, a maximum variation of ±320 Nm and ±256 Nm torque between the theoretically calculated and experimentally observed values under field condition and haulage performance. An embedded system for on-the-go digital display of dynamic wheel axle torque of an agricultural tractor was developed. It is convenient, simple, and reliable in operation. It is able to communicate the signals through radio frequency modules (RF) up to 100 m distance without any interruption. With the developed embedded device, the data can be collected without any malfunctioning in either collecting or recording with minimum efforts. The developed device helps to know the real time power requirement of various agricultural operations. The developed device and systems are simply and accurate and can be used for any range of agricultural tractors.

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