Design and Development of a three-point hitch dynamometer

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Tractor is used as a main source of power in developing countries. In order to reduce the cost of production, knowledge of today's complicated tools is essential. In this research, a three-point hitch dynamometer system was fabricated for the category 0 & I tractors with the weight of 49 kg and the chassis is in a reversed U-shaped frame which allows the use of PTO at the same time. With the strain gages installed on the three sensing pins and developed five Wheatstone bridges in such a manner that, the draft forces in each link in addition to vertical forces on the lower links are measured. The dynamometer system consists of three parts including: the chassis, sensing components, and recording system. The recording system consisted of a Campbell data logger (CR10X) with a notebook computer. The dynamometer system was calibrated and several field tests were conducted to measure the force required to pull the different mounted plows. The field tests showed that the dynamometer worked well without malfunction and the system was able to provide on-line graph and save the data in the memory.

Key words: Dynamometer, Draft force, Data logger, Three-point hitch, Wheatstone bridge

Introduction

The availability of draft requirement data for tillage implements is an important factor in selecting suitable tillage implement for a particular farming situation. Farm managers and consultants use draft and power requirement data of tillage implements in specific soil types to determine the proper size of tractor required. Also ownership and operating costs of both tractors and implements can only be minimized by using accurate draft data. Farmers mostly depend upon past experience for selecting tractors and implements for various farming operations. The previous experience may have little effect in selecting newly available implements. Therefore, prediction of implement draft

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requirement is important for tractor selection and implements matching (Al-Janobi & Al-Suhaibani, 1998). To evaluate a tillage operation in terms of energy utilization, the actual tillage energy input per unit volume is calculated from the measured draft, width of cut and depth of plow. The equivalent energy input determined by measuring draft force, is divided by the actual tillage energy input to obtain a dimensionless ratio that might be called the energy utilization factor (Kepner *et al*., 1979). Draft measurements are required for many studies including energy input for field equipment, matching tractor to an implement size, and tractive performance of a tractor. Vertical force affects weight transfer from implement to the tractor, and consequently, affects the tractive performance and dynamic stability of the tractor (Chen *et al*., 2007). Sever side load can affect tractor's steering ability. However, side force is generally negligible during field operation (Godwin, 1975; Leonard, 1980).

Measuring the drawbar power of tillage tools is accomplished by apparatuses such as hydraulic, mechanical dynamometers. Drawbar dynamometer is used for pull-type implements while the three-point hitch type is employed for mounted implements. The first attempts to measure the forces between tractor and mounted implement were made by measuring the forces in links themselves (Khan *et al*., 2006). This required simultaneous recording of at least three forces which involved very complicated instrumentation. Reece (1961) developed strain gauged pins for measuring the draft of a three-point-link implement. These pines could only measure longitudinal component of force in each link and were only suitable for free linkage systems. Scholtz (1964) improved the system proposed by R. Lal in 1959. Lal'system used instrumented ball joints. These ball joints system had friction induced cross-sensitivity problems. Scholtz reduced this effect by using self-aligning ball bearings and longer beam length. This caused the equipment heavier, displaced the implement backwards and thus increased the bending moment. Moving the implement back from its nominal position affects the tractor-implement geometry and hence it's operating characteristics. The instrument could not fit on many tractors. Modification to the tractor was required to fit the system. The use of P.T.O. was also obstructed.

Scholtz (1966) later developed a three-point hitch dynamometer which could be used with hydraulic linkage providing position and draft control, unlike his previous design which was for un-restrained linkages. The shape was such that to permit P.T.O. use accordingly. Friction was minimized by use of self-aligning ball bearings. Cross-sensitivity was 2% on horizontal draft force and 0.5% on vertical forces. Modifications were needed if the instrument was to be used with mounted implement and was not fit to category I implements. The construction was bulky which weighted 120 kg. The implement was shifted back by 23 cm from its nominal position. Backer *et al.* (1981) used six load cells mounted at different points within an A shaped frame to measure horizontal, vertical and lateral forces. The measurements were made with little error. The implement moved back by 19 cm. Chung (1983) developed a quick attachment coupler using pins mounted as strain gauged cantilever beams. It eliminated the need for modification in either tractor or implement since it could be used with category II and III hitch dimensions. This dynamometer gave minimum sensing errors but the implement was pushed back by 21 cm. Palmer (1992) designed and developed a three-point hitch dynamometer for measurement of loads imposed on agricultural tractors by implement mounted on a standard three-point linkage conforming to category I, II or III. He reported that the 350 kg mass of the dynamometer limits its use with small tractors to lightweight implements. This mass and the rearward displacement of the implement by 17.35 cm is slightly more than allowed by ASAE Standards S278.6. He also reported that the developed dynamometer has a force capacity of approximately 50 kN which provides adequate sensitivity at the low end of the designed tractor power range with sufficient strength for the high power range.

Another three-point hitch dynamometer was designed and manufactured by Al-jalil *et al.* (2001). The dynamometer was capable of measuring tractor - implement forces in three dimensions, which could help in the design of tillage tools and evaluating tractor performance. They reported that the dynamometer consists of three arms, which slide in an inverted hollow T-shaped section. The sliding arrangement also facilitates attaching the dynamometer to implement without the need for quick coupler. The end of each sliding arm has inverted U-shaped cantilever beam. To measure the draft, two strain gages were attached on each cantilever beam, and six strain gages together with two other dummy gages were arranged in a Wheatstone bridge so that only the draft force is measured. The dimensions of the dynamometer components were selected to match the Category I and II hitching systems with a capacity of 35 kN draft force.

Many other designs were developed. Some measured all the forces acting between the implement and tractor by using a six point dynamometer suspension system using load cells (Baker *et al.*, 1981; Chaplin *et al.*, 1987). Other systems measured longitudinal and vertical forces only, assuming lateral forces as zero. Kirisci *et al.* (1993) mounted strain gauges directly on the lower links of the tractor. He mounted these gauges on the linked arms to get tension and differential cantilever bridge. This system was calibrated for horizontal and vertical forces while applying load only up to 100 kg. The test results showed a cross-sensitivity of 2% in the differential cantilever (vertical force) bridge while 12.5% in the tension (horizontal force) bridge. A bi-axial direct mounted strain gauged lower-links system for measurement of tractor-implement forces was designed by Khan *et al.* (2006). They developed and calibrated it for coincident and perpendicular loads up to 10 kN. The results revealed a high degree of linearity between bridge output voltage and force applied. They reported that the hystersis effect between the calibration curves for increasing and decreasing applied coincident and perpendicular force was very small (<1.2%). They suggested that this system is the best suited where medium type equipment is used with a tractor. The use of a frame or frames in order to measure the forces between tractor and implement has the advantages of permitting easy resolution of the forces into horizontal draught, vertical force, and sideways force components and their respective moments, as well as being able to easily fit to any standard tractor and implement combination. Against this was the disadvantages of substantially changing the tractor and implement geometry by moving the implement backwards and vertically relative to the tractor and adding additional mass and resilience to the system (Palmer, 1992). Apart from three-point hitch dynamometer, several researchers have made effort to study over drawbar dynamometer such as: Hoag and Yoerger (1975), Zoerb *et al*. (1983), Leonard (1980), Tessier *et al*. (1992), Kirisci *et al*. (1993), Tessier and Ravonison (1997), McLaughlin (1996), McLaughlin *et al*. (2005) and Chen *et al*. (2007).

The objective of this study was to design and develop a three-point hitch dynamometer which adapted with tractor categories of 0 and I. Some special design parameters were considered such as quick-attachment coupler, using P.T.O. shaft simultaneously, light frame for more convenient attachment, and measuring both vertical and horizontal components of exerted forces.

Materials and methods

Three hitch-point dynamometers with chassis (frame type dynamometer) are more flexible in application, i.e. application is not limited to a special type of tractor. Therefore, in this study a dynamometer equipped with chassis was designed and developed. The dynamometer consists of main frame (chassis), force transducers, connecting members, and a data acquisition system including a notebook computer (Toshiba Sattelite 45 Notebook), data logger (CR10X), power supply (PS 12E), and leading cable (Fig. 1).

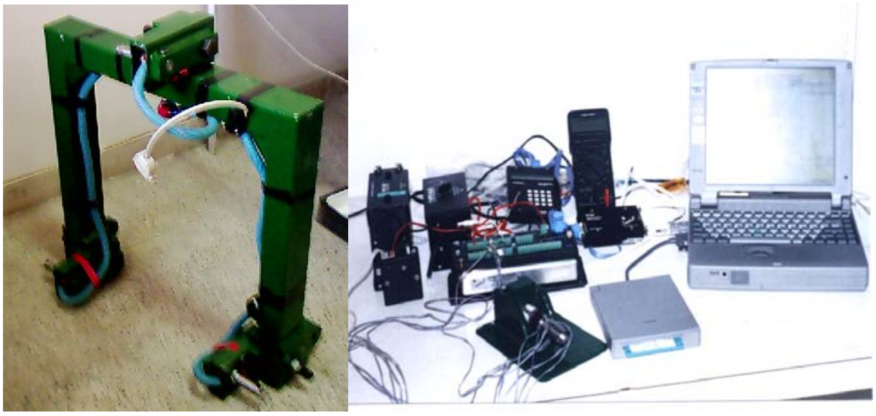

Fig. 1. Dynamometer and Data acquisition system.

Fabrication of dynamometer

The designed dynamometer was fabricated to be used for measuring the resistance pull of the soil engaged implement. The dynamometer is considered to be used with a 2WD Mitsubishi tractor (MT-250D) which has a weight of 1200 kg and provides power of 25 kW. This tractor has selected since it was instrumented to measure parameters affecting the tractor performance in another research projects. To satisfy the latter goal, the dynamometer was installed on the fore-mentioned tractor. Note the purpose of this dynamometer was to measure the draft of either single or multi bottom tillage tools. Computations related to the dynamometer chassis was accomplished based on the design parameters of the tractor and maximum horizontal force.

The resultant force P, exerted by tractor is resolved into horizontal (F_X), vertical (F_Y) and side (F_S) components over lower link arms and accordingly, F_X and F_Y over upper link arms of the three-point hitches. Among components of draft force, side force F_S is less important, therefore measurement of this component was ignored and horizontal force merely was measured in upper link arm (Fig. 2).

Care should be taken into consideration that, eliminating any force components mentioned above has not adverse effect on measuring the other force components. It is because of installation of force transducers on the dynamometer frame in such a manner that force components were measured only in predetermined direction. If the draft force is to be determined, then eliminating each of the components would not result in achieving the draft force magnitude.

Chassis

The chassis of the dynamometer was built as an inverted U-shaped frame which allows the use of PTO at the same time. Since the designed dynamometer has been devoted to small weight tractors, chassis was built as light as possible. To measure the impact and dynamic forces, the conventional mast design is used to instead of quick attaching coupler. Note that the designed chassis is also appropriated enough to use in soil bins. Considering the distance of attaching points on the link arms, chassis selected dimensions (height and width) were 62 and 64 cm, respectively. Chassis is attached to the tractor from on side through the force transducer's sensing pins while on the other side by mast members.

By considering the resolution of the exerted forces, chassis cross section is subjected to both torsional and bending forces and associated moments. Based on the calculations, A ST37-2 rectangular hollow section of 8×4 cm with thickness of 4 mm was used for building the chassis. The chassis was reinforced with 8 mm brace in thickness to protect it from transfiguration during overloading. In order to ensure the reinforcement, they were attached to the inter sections and corners of the chassis. At last, the weight of chassis reached to 37 kg.

Force transducer

Transducer is a device that converts the mechanical quantities into electrical signals. In this study, three force transducers were used. Two of them were employed to measure the forces on the lower links whereas the other one was used for measurement of the force exerted on the upper link.

Transducers comprises of two parts: elastic member (sensing pin) and Wheatstone bridge configured with four active stain gages (full bridge). This composition increases transducer sensitivity as well as compensation of temperature. It should be noted that the strain caused by exerting the force on the elastic member must not be exceeded the allowable strain of strain gauge. Equation related to the calculation of elastic member strain is as follows:- (Fazel niari, 2002):

$$\varepsilon_{total} = \varepsilon_s + \varepsilon_p = \frac{F_s}{AE} + \frac{MC}{IE} \qquad (1)$$

where, ε_s and ε_p are side and vertical strains, respectively. F_s is the side force, A is the cross section of elastic member, M is bending moment caused by vertical force, C and I are radius and inertia moment of the elastic member cross section and ε_{total} is maximum strain caused by both vertical and side forces which is considered as design criterion of the elastic element.

Note the strain yielded by combination of the vertical and side forces is significantly less than ε_{total}. To determine the allowable strain of all strain gauges installed on the elastic member, the following equation was used.

$$\varepsilon_{SG} = (\frac{\Delta R}{R})S_g \quad (2)$$

where ε_{SG} is the allowable strain caused by resistance changes of strain gauge, S_g is the gauge factor and R is the strain gauge resistance.

In this stage, a computer program was written using Visual Basic software and then predetermined magnitudes related to designing the elastic member including exerted force, length, diameter, and material type were entered to the program as input data. Subsequently ε_{total} is calculated and by using the equation (2), ε_{SG} was calculated for optimum strain gauge. If the magnitude of ε_{total} is to be less than allowable strain ε_{SG}, it indicates that magnitudes of effective length and elastic member diameter have been selected properly. The computer program is run as trial and error until two elastic members with diameter of 24 mm for lower links and another one with diameter of 20 mm for top link were determined. Referring to the strain gauge catalogue (from TML company), strain gauges were selected from Series FLA-3-11-IL (Anonymous, 2003). The strain gauge resistance and their changes were 120 and 0.3, respectively. To ensure strain gauge accuracy, ε_{SG} was calculated using equation (2). Subsequently, it was found that the strain gauges have been selected properly, because ε_{SG} was obtained higher than ε_{total}.

After preparing the strain gauges and fabricating the elastic members, based on instructions guide for strain gauge installation, the force transducers were built. The four strain gauges are wired into a Wheatstone bridge and bonded on the elastic member of the upper link arm while the other two Wheatstone bridges were located each on the lower link arms. As a whole, 20 strain gauges were bonded on three sensing pins of transducers to complete the development of the three-point hitch dynamometer (Fig. 2).

Interface member

The interface member consists of three parts: base support, frame (made of rectangular hollow section of 40×80 mm with thickness of 8.3 mm) and a stand (Fig. 2). At first, transducers were installed on interfacing members, and then they were bolted to the main frame of the dynamometer. Three interfacing members were built in such a way that one is used for upper link arm and other two members were considered for lower link arms. Members relate the transducers to the link arms of tractor; furthermore strain gauges are located into the interior part of member frame to immune from being damaged. Ultimately, the weight of dynamometer including chassis, transducers, and interfacing members becomes 49 kg.

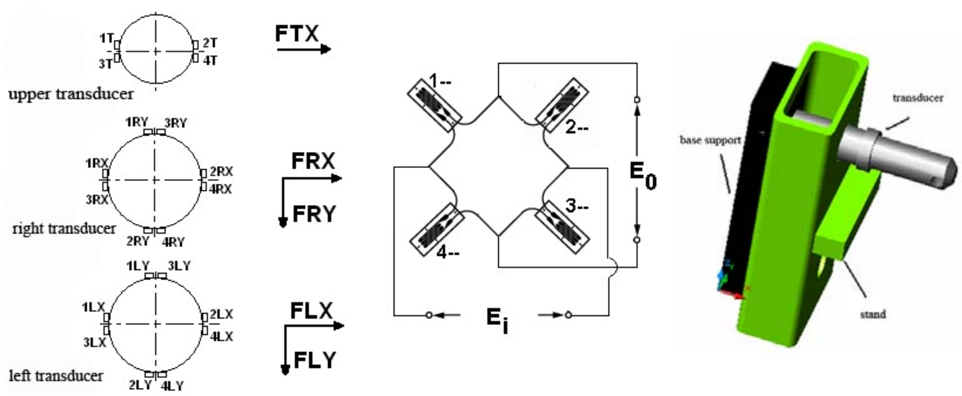

Fig. 2. Interface member along with transducer and arrangement of the applied strain gages.

Data acquisition system

Date acquisition system consists of a programmable data logger with 8 differential voltage and 4 pulse channels, an interface (SC 32A) and serial cable (RS-232) from Campbell company (Anonymous, 2000). A notebook computer is also used for monitoring and processing of data in the system. The system hardware is showed in Fig. 4.

Connection between outputs of transducers and data logger are established through a soft ware (PC 208-W 3.3) which has been represented along with the data logger. Applying the latter software, the data logger program was written by means of a program, which is connected the transducers to data logger and processing the written data based on exclusive cods of the company of manufacturing the data logger (CSI). After running the program, data logger is able to receive the signal transmitted by transducers and then output is noticeable as a text or a graphic on the computer screen and is recorded on the both data logger and computer simultaneously.

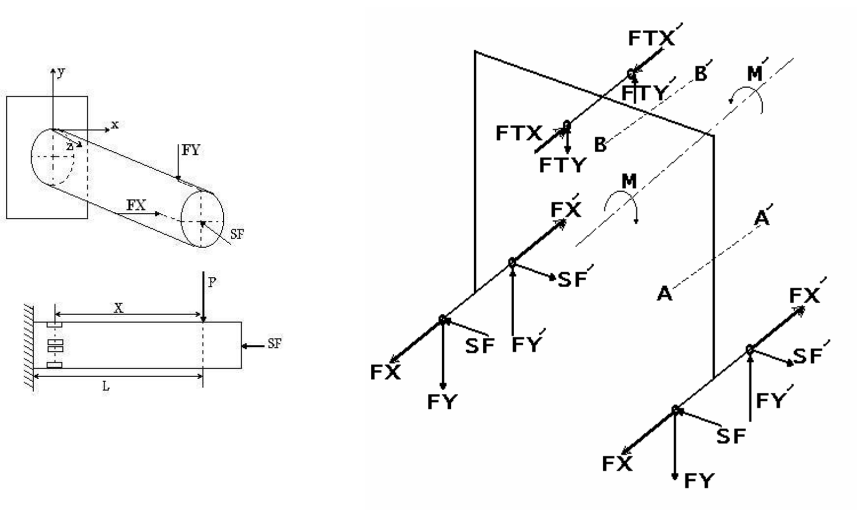

Fig. 3. Force diagram (A) and Force components on the elastic element (B).

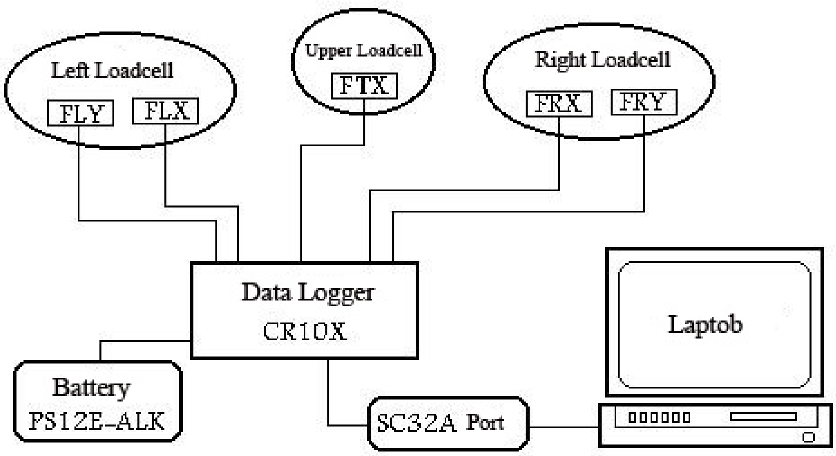

Fig. 4. Schematic illustration of all system.

Calibration of transducers

To determine the profound parameters such as sensitivity, hystersis, repeatability and calibration constant, transducers should be calibrated. For this purpose, transducers were individually calibrated by using the tension test machine (Amsler, Germany). To insert the transducer between the apparatus jaws, a stand was constructed in order to simulate the condition of exerting the forces on dynamometer attached to tractor. Depending upon the allowable force, calibration processes were performed for each transducer. However, each transducer was individually inserted between the apparatus jaws and then loading was applied in a step manner such that force was increased from zero to maximum allowable force with interval of 500 kN (For transducers of lower link arms, 650 kN while for upper link arm, 450 kN). Strain changes of transducers were recorded by a strain-meter. Using the equation (2), the recorded strain was multiplied by gauge factor of 2.1 in order to achieve the magnitude of resistance changes ($\Delta R / R$). Upon reaching to the maximum allowable force, to determine transducer hystersis, exerted force was reduced in the same manner with interval of 500 kN and strains were recorded at a same time. Using the following expression, the ratio of $(E_0 / E_i) \times 1000$ can be obtained (1,000 was incorporated for converting the unit of Volt into miliVolt).

$$\frac{E_o}{E_i} = \frac{r}{(1+r)^2} \Sigma \frac{\Delta R}{R} \qquad (3)$$

A typical calibration curve for the left lower link arm is illustrated in Fig. 5. The correlation Coefficients between the exerted force and the ratio of $(E_0 / E_i) \times 1000$ is represented in Table 1. The correlation coefficient of above 0.999 showed a high correlation between force and voltage ratio. After calibration process, hystersis magnitude was found to be inconsiderable because the average recorded hystersis was 10 micron for all the transducers.
An average sensitivity in magnitude of 3.75 mV/kN was found for all three transducers which was high in sensitivity. To assess the repeatability of transducers, tests were performed with three replications and then there was not significant difference among the obtained results.

Table. 1. Coefficients of determination of force and voltage ratio for three-point hitch link arms.

Link arm	Horizontal force	Vertical force
Upper link arm	0.9995	-
Right link arm	0.9991	0.999
Left link arm	0.9994	0.9997

Programming the data logger

The PC-208 W3.3 software was used for calibration constants and preparing the data logger for data collection. At first, output wires of transducers were connected to the input channels of data logger and then connection of data logger to computer was established through the cable SC 32A. Calibration constants were entered in PC-208 W3.3 for each transducer. Using mathematical operation, output voltage of Wheatstone bridge was divided by its input voltage and the obtained result was multiplied by 1000. By applying the following expression, calibration constant (S) and zero drift (C) were entered for each force component to record output as calculated force (F). To calculate F, magnitude of S and C were obtained from calibration curve.

$$F = C + S\left(\frac{E_o \times 1000}{E_t}\right) \quad (4)$$

Data logger software has the capability of displaying and recording the force diagrams against the time for data collected. It also performs summing and averaging the forces for selective time.

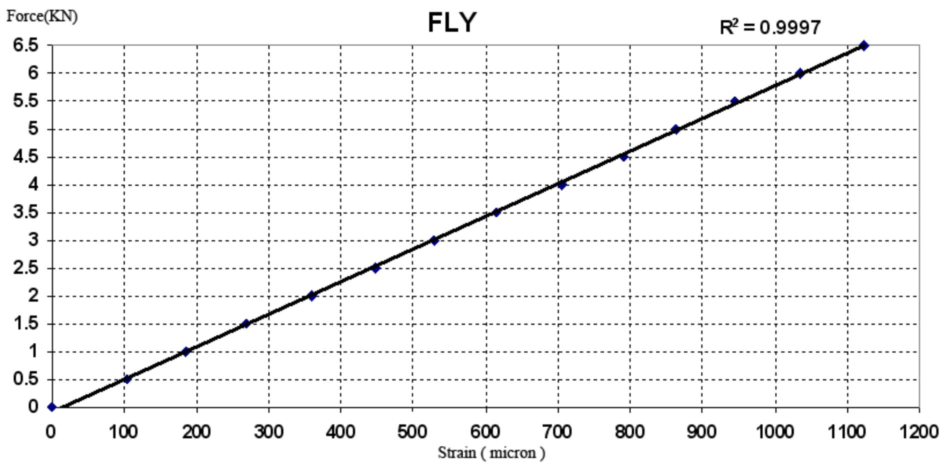

Fig. 5. Calibration curve of left arm.

Results and discussion

To measure the forces at three-point hitches of the tractor with the designed dynamometer, transducers were individually calibrated and then calibration constants were used to obtain the exerted forces directly. The assembled dynamometer system was tested in the actual field condition.

Fig. 6. Field test of dynamometer.

Field tests

The dynamometer and data acquisition system for the test and evaluation were transferred to the field. As shown in Fig. 6, a single bottom plow and a Mitsubishi tractor (MT-250D) were used. The tested dynamometer was placed between the plow frame and tractor while data logger and computer were located in a tray next to the operator. Tests were performed at average speed of 2.2 Km/h, in length of 36 m which average speed was based on the time required for travel distance of 36 m. Before experiments, the dynamometer was vertically adjusted relative to ground surface and then the angle between upper link arm and horizontal plane was measured and entered into the data logger for calculating the horizontal force component of upper link arm. This was not necessary for the lower link arms because they were parallel to ground surface. After adjusting the plow for the depth of 24 m, running the established program while the tractor was working, data collection was initiated. Results of measuring the sum of both vertical and horizontal forces have been individually illustrated in Fig. 7. Also, the magnitude of forces concerned with upper and lower link arms were recorded individually to determine the forces exerted on either link arm (Fig. 8).

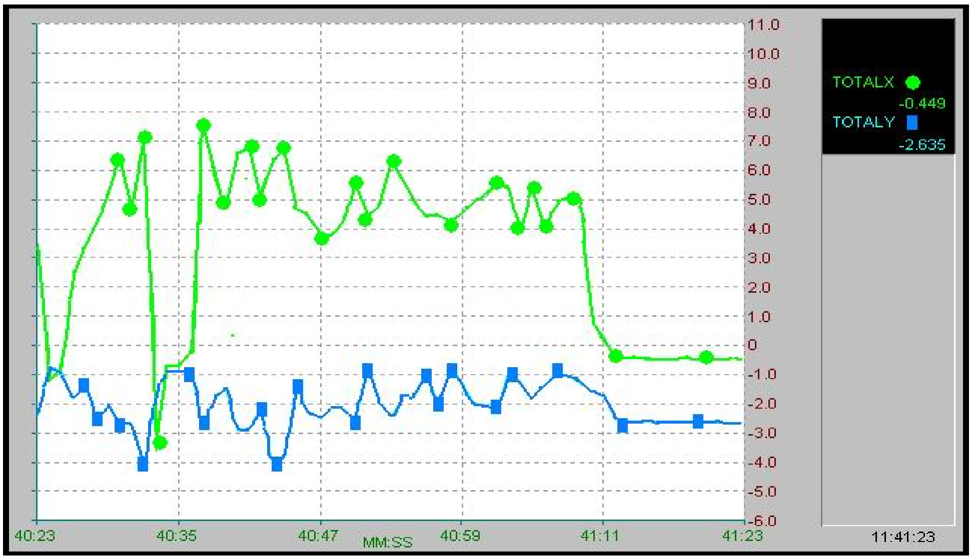

Fig. 7. Aggregate of horizontal force (upper curve) and vertical force (lower curve) of the tested dynamometer obtained in field test.

The forces for upper and lower link arms are negative and positive, as illustrated in Fig. 7 and Fig. 8. This finding was in agreement with the fact that during plowing, top-link arm is subjected to compression while the lower links undergoes to tensile forces. Forces may be divided unequally over lower link arms. It was due to the one side moldboard plowing. The reaction of soil on the bottom, a clockwise moment has been developed on the moldboard plow frame which causes an increase in exerted force to the right lower link arm. The fluctuation in the recorded data was due to data collection with a scan rate of 20 data point in one minute. Note that, the small changes in draft resistance are caused due to soil failure. Graphically recorded picture represent the data collection for an interval of one minute, but data acquisition system can represent graphical representation of averaged data in longer time interval to achieve less fluctuations between data obtained.

To assess and confirm the measured forces by the dynamometer, the ASAE standard expression as shown in equation (5) was used. Parameters related to soil and tool were determined and applied (Anonymous, 1998).

$$D = F_i[A + B(S) + C(S)^2]WT \qquad (5)$$

where D is horizontal draft force, F_i is the parameter related to soil (soil texture was loom-clay and F_2=0.7), A, B, and C are specific amounts for tool (for moldboard plow A = 652, B = 0, C = 5.1). S is forward speed of tractor, T is width, W is working depth of tillage tool.

Magnitude of D was calculated to be 4 kN for forward speed of 2.2 Km/h, depth of 24 cm, and a bottom width of 34 cm. With regard to the changes around 40% closed by ASAE standard, calculated magnitude of D is a number within ranges of 2.6-5.6 kN. The average horizontal force measured in field test was 4.2 kN (average of 20 numbers drawn out from the recorded data file of Fig. 7) which is closed to the calculated draft force. The error of magnitude D between measurement and calculation were ± 5 %. By averaging the measured data in more time interval, error can be significantly reduced.

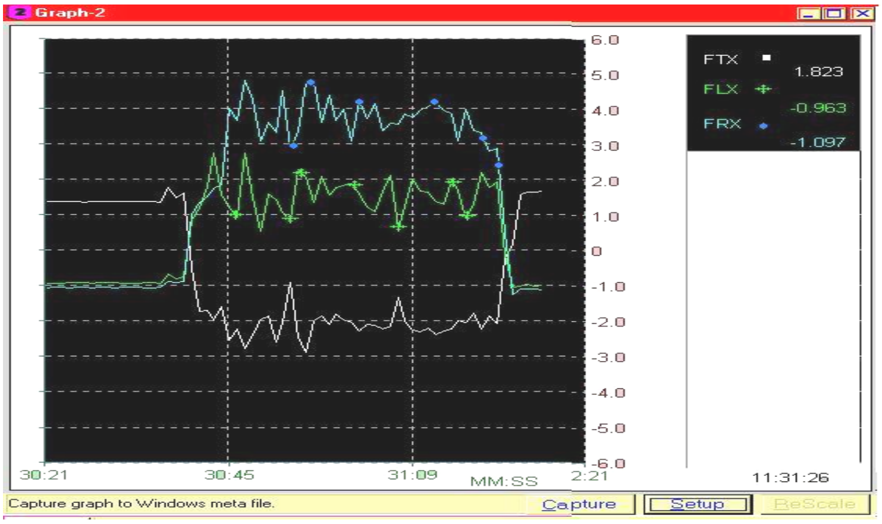

Fig. 8. Force diagrams of individual arms: right arm (upper curve), left arm (intermediate curve), and upper link arm (lower curve).

Conclusion

Drawbar or draft power of tillage implement is of concern since it is used for pull-type implements. The most implement now are attached to the three-point hitch of tractor which are categorized as mounted implements. The knowledge of the force between mounted implement and tractor is considered by designer which justifies the needs of a three-point hitch dynamometer. In this study, a three-point hitch dynamometer was designed and fabricated with a total weight of 49 kg, having high sensitivity and strength, measuring 5 force components simultaneously, compensating the temperature changes using the full Wheatstone bridge and adapted to the tractor categories of 0 & I. Before installing the transducers, chassis strength was verified for a single bottom type moldboard plow at the depth of 30 cm. Appropriate repeatability and inconsiderable hystersis are of desirable characteristics of this dynamometer. Field test showed that the dynamometer can measure the components of forces exerted on three-point hitch without malfunctions and data acquisition system also can record the data instantaneously. Furthermore, it can display the data as graph or record them in a table in computer's memory. Implements such as chisel plow, subsoiler and rotary tiller do not cause a moment on the lower link arms, therefore using them can be confirmed the equal forces on lower link arms. Field test with such implement is recommended.

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