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Faculty of Engineering & Tech., University of Ilorin, Nigeria

DESIGN AND CONSTRUCTION OF AN INSTRUMENTATION SYSTEM FOR MEASURING FORCES ON MODEL TILLAGE TOOLS

E. MAMMAN [+], K. C. ONI [++] & A. T. AJIBOYE [+++]
[+] Department of Agricultural Engineering, University of Maiduguri. P. M. B. 1069, Maiduguri
[++] Director, National Centre for Agricultural Mechanization, P. M. B. 1525, Ilorin.
[+++] Research Engineer, National Centre for Agricultural Mechanization, P. M. B. 1525, Ilorin.

ABSTRACT

This paper describes the design and construction of an instrumentation system for measuring tool forces on model tillage tools. The instrumentation system was incorporated into a carriage mounted on a laboratory soil bin. The instrumentation system was used to measure draught on model chisel furrowers drawn through soil in the laboratory soil bin. Results obtained were similar to those reported by other researchers who conducted their investigations under similar conditions.

Keywords: Instrumentation, strain gage, voltage, soil bin, carriage

1.0 INTRODUCTION

In modern agricultural production, soils that are adjudged to be suitable for crop production are usually manipulated to cause some desired effect such as cutting, breaking or inversion. The manipulation is accomplished with a tillage tool by moving the tool through the soil. There are five design factors that define soil manipulation, namely, initial soil condition, shape of tillage tool, manner of moving the tool, forces required to move the tillage tool through the soil and the results of the soil manipulation which is usually referred to as the final soil condition (Gill and Vanden Berg)[1]. Two parameters that are commonly used to assess the performance of a tillage tool are the degree of soil manipulation and the magnitude of forces required to cause the manipulation (Gill and Vanden Berg)[1]. Tillage tool forces are, however, more difficult to measure than the degree of soil manipulation. This is because tillage forces relate directly to soil conditions, deformation resistance, tool geometry and working depth.

Several authors used different methods for measuring the forces on tillage tools and implements. Majewski [2] measured the draught of model chisel ploughs in a laboratory soil bin. The model tools tested had vertical supports. Each of the chisel plough model tools was clamped on a frame of the carriage. Electric resistance wire strain gages were bonded to the vertical support of each model to measure the horizontal component of working resistance in the direction of motion. Strain gage multi-channel bridges and ultraviolet loop oscillograph were used to record the measurements on tape. Reid et al. [3] designed a dynamometer for measuring draught. The dynamometer used strain gages mounted on a vertically cantilevered aluminium beams to sense the implement loads including side draught. Owen [4] conducted an experiment to determine under field conditions, in two compact soils, the effect of tool speed on the vertical, horizontal and total forces on a subsoiler tine. The effect of tool speed was also determined on the moment applied to the tine, soil areas heaved and disturbed, total soil area, specific resistance, and to compare the vertical, horizontal and total forces to values predicted by a three dimensional model of soil wedge failure. A vertical rigid tillage tool mounted on a trailed tool bar system was used. An instrumentation system was installed on the trailed tool bar system and was used to record several operating parameters of the tillage tool. The instrumentation system recorded the vertical force, horizontal force in the direction of travel and the moment in the plane of these forces as applied to the tine. These values were measured using an octagonal ring transducer rigidly mounted on the tool bar. Oni et al.[5] determined the effects of design on the draught of undercutter-sweep tillage tools in a laboratory soil bin. The instrumentation system used for draught measurement included a rectangular tubing frame, a dynamometer and a tool holder. The tubing frame permitted lateral and vertical movements of the dynamometer in the soil bin through arrangements of stainless steel shafts, bearing blocks and mechanical actuators. There were six load cells on the dynamometer frame. Two in the vertical plane, three oriented in the horizontal plane and one in the side plane to monitor side draught. Shirin et al.[6] evaluated the effects of disc and working parameters on the performance of a disc plough in a clay soil. A three-point linkage dynamometer was used to sense the draught on disc plough. Each lower link transducer of the dynamometer had two bridge circuits to detect the draught and the vertical force. A linear variable differential transducer (LVDT) mounted on a three-point linkage of the tractor was used for the measurement of ploughing depth. A Massey Ferguson 4-cylinder diesel engine tractor with a rated power of 46 kW at 2000 rpm was used for testing. Shinners et al.[7] investigated the performance characteristics of a

tillage machine similar to a chisel plough that uses active-passive components. A portable three-point linkage dynamometer was used to measure draught. The dynamometer was attached to the three-point linkage of the tractor used. Load cells were located at each of three hitch points, which measured the vertical and horizontal reaction forces of the implement. The active-passive tillage machine was equipped with transducers to measure rotor speed. PTO torque and speed. Durairaj and Balasubramanian[8] developed a dynamometer and used it to measure soil reactions of a bent leg plough. The dynamometer included six force transducers and an L-shaped tool bar with a cross beam on it. Four of these six sensors were strain-gaged load cells. One of these four strain-gaged load cells measured the horizontal force, two measured the vertical forces and the remaining one measured the lateral force. Two of the four transducers measured the other two horizontal forces on the cross beam itself. Each of the six transducers had a separate instrumentation amplifier with necessary balancing circuits. The gain was made adjustable so that the output could be calibrated according to the capacity of the transducer. All the transducers were calibrated by applying the required load using a manually operated hydraulic press, with the load being monitored on its oil pressure gauge. The outputs of the instrumentation amplifiers were multiplexed by an analog multiplexer and led to a digital data logger for storing the information. Hann and Giessibl[9] measured forces on driven discs. A triaxial dynamometer employing two extended octagonal rings and a torque tube mounted between the carrier frame and carriage was used to measure draught, vertical and side forces on the disc implement. Voltage outputs of the dynamometer strain gage circuits were fed through d.c. differential amplifiers to a data logger. From the recorded parameters, disc performance variables such as draught, vertical and side forces, total power, specific total power and specific draught resistance were calculated. Al-Janobi and Al-Suhaibani[10] measured the draught of primary tillage implements in a sandy loam soil. The instrumentation system consisted of a data logger, a three-point linkage dynamometer, a rotary position transducer, and a fifth wheel ground-speed sensor mounted on the tractor. The three-point linkage dynamometer that was used to measure implement draught was calibrated prior to the experiments using a specially built calibration rig. The fifth wheel used to measure tractor speed was calibrated on the soil surface at the beginning of the experiment.

Many more instrumentation systems have been designed and constructed for tillage studies (Wegscheid and Myers [11]; Godwin [12]; Johnson and Voorhees [13]; Stafford [14]; Godwin et al.[15]; Clark and Adsit [16]; Green et al.[17]; Chaplin et al.[18]; Thomson and Shinners[19]; Onwualu and Watts [20]). The selection or construction of an instrumentation system by researchers depended on the soil-tool interaction parameters to be measured, level of accuracy of the measured parameters and convenience of measuring the parameters. Although several instrumentation systems have been designed and constructed for measuring forces on different tillage tools in different parts of the world, there is no known instrumentation system for measuring forces on model chisel furrowers.

The objective of this study was therefore to design and construct an instrumentation system for measuring forces on model chisel furrowers.

2. 0 THEORY

The measurement of strain is an increasingly important area of stress analysis. Strain is the amount of deformation of a body due to an applied force. Strain measurement involves three main stages. These are sensing, transducer and signal conditioning stages. In practice, strain measurements rarely exceed quantities larger than a few millistrain. If an electrical strain gage is used as a sensor, a quantity measured in millistrain will give rise to a very small change in strain gage resistance. To detect such a small change in resistance and compensate for temperature sensitivity, electrical resistance strain gages are usually used in a Wheatstone bridge configuration to form a transducer. In order to obtain a reasonable output to drive the indicating instrument, the output of the bridge circuit is conditioned by using an amplifier. Figure 1 shows a complete strain measuring system.

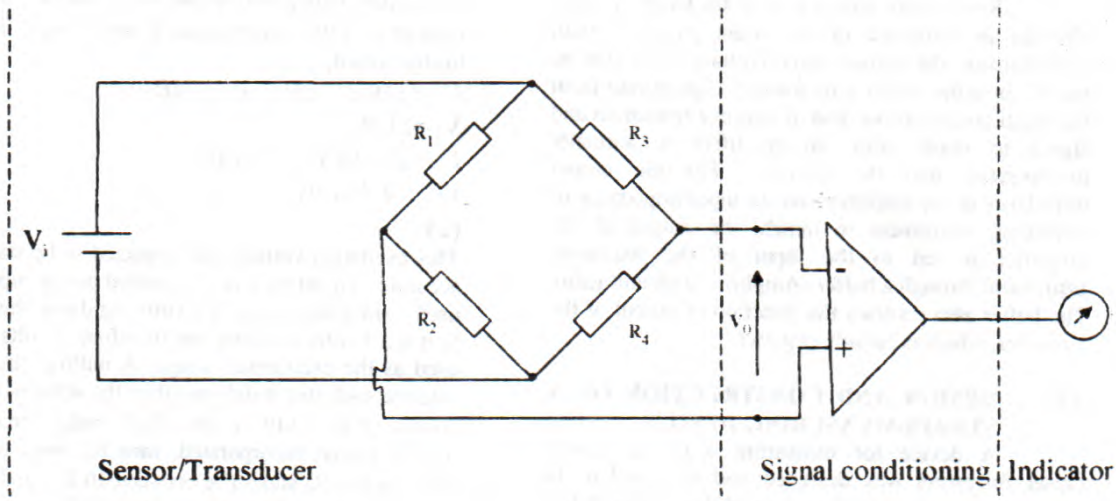


Fig. 1: Schematic diagram of stages involved in strain measurement

2. 1 Bridge configurations

Three types of bridge configurations are commonly used in strain measurements. These are quarter, half and full bridge circuits. In a quarter-bridge circuit, only one strain gage is used and the other three arms being fixed resistors. In a half-bridge circuit, two of the arms are strain gages and the other two being fixed resistors, while in a full-bridge circuit, all four arms of the bridge are strain gages. To obtain a reasonable circuit with moderate sensitivity, linear output and negligible temperature effect, half-bridge circuit is usually used. In a half bridge circuit, one of the strain gages is placed on the tension side, while the other is placed on the compression side.

For a half bridge circuit, voltage at point A,

$$V_A = \frac{V_i R_2}{R_1 + R_2}$$

and voltage at point B,

$$V_B = V_i \frac{R_G - \Delta R}{2R_G}$$

But,

$V_0 = V_B - V_A$

Therefore,

$$V_0 = \left[\frac{R_G - \Delta R}{2R_G} - \frac{R_2}{R_1 + R_2} \right] V_i$$

Let $R_1 = R_2 = R_G$

$$V_0 = \left[\frac{R_G - \Delta R}{2R_G} - \frac{R_2}{2R_G} \right] V_i$$

$$V_0 = \frac{-\Delta R_G}{2R_G} V_i$$

It is known that

$$G.F \times \varepsilon = \frac{\Delta R}{R_G}$$

Where G.F is gage factor, ε is strain and R_G is strain gage initial resistance.

This implies that

$$V_0 = -\frac{G.F \times \varepsilon}{2} V_i$$

(1)

Equation (1) shows that for constant G.F and V_i, V_0 is directly proportional to ε which is a measure of the force on the strain gage.

2. 2 Offset-nulling

The output of a bridge circuit is expected to be zero volts when no strain is applied to the strain gages, but in practice, zero output conditions is not attainable due to the strain induced by gage application, resistance tolerances, temperature effect and lead wire resistance effect. To take care of this initial offset voltage, offset nulling circuit is usually incorporated to adjust the resistance in the bridge arms to balance the output to zero volts.

2.3 Signal Conditioning

Since small changes in strain leads to small changes in resistance of the strain gage in strain measurement, the output signal (voltage) will also be small. In order to get a reasonably high output from the small bridge output, and to improve resolution and signal to noise ratio, an amplifier is normally incorporated into the circuit. For the output impedance of the amplifier and the input impedance of indicating instrument to match, the output of the amplifier is fed to the input of the indicating instrument through a buffer (Amplifier with unit gain). The buffer also reverses the direction of output of the amplifier, which is already negative.

3.0 DESIGN AND CONSTRUCTION OF A STRAIN-MEASURING DEVICE

A device for measuring strain on model chisel furrowers was designed and constructed. In order to get a circuit with high reliability, repeatability and reasonable sensitivity, the components for the bridge and signal conditioning circuit were carefully determined and selected. The excitation voltage for the bridge circuit was also taken into consideration.

The strain-measuring device constructed in this study was centered on a half bridge circuit (Fig. 2). The resistances of the strain gages used were 120 ± 0.5 Ω and a gage factor of 2.05 ± 1%. After mounting the strain gages on the specimen under test (tension and compression sides, respectively) and connecting to 6 m of lead wire, the resistances of the strain gages increased to 140 Ω. One of the conditions for balancing is that the resistances of all the four arms of the bridge circuit be equal to R_G (strain gage resistance), which in this case were 140 Ω. The rated current for 140 Ω strain gage, I_g was 15 mA. In a half bridge circuit,

$$V_i = I_g [R_G + \Delta R + R_G - \Delta R$$

$$V_i = 2 I_g R_G$$

$$V_i = 2 \times 15 \times 10^{-3} \times 140$$

$$V_i = 4.2 \text{ volts}$$

(2)

This excitation voltage was expected to be stable and accurate. To obtain this, a regulated power supply was used. Since there is no 4.2 volts regulator, the nearest to it is a 5 volts regulator and therefore, 5 volts d.c was used as the excitation voltage. A nulling circuit was selected such that it did not affect the sensitivity of the circuit. If R_G =140 Ω for a half bridge circuit with nulling circuit incorporated, then R_N must be about 100 Ω while R_P should be between 10 KΩ and 50 KΩ. Figure 2 shows the resulting circuit of the transducer (half bridge circuit). The signals obtained from the Wheatstone bridge (transducer) were too small for meaningful interpretation. The output of the bridge circuit was amplified using a differential amplifier. The output of the amplifier was fed to a buffer. If the closed loop gains of the amplifier is

$R_i = 1000\Omega$, then $R_f = 1000 \times 1000 = 1000\ K\Omega$

Taking R to be 1KΩ, the resulting circuit is as shown in Figure 3. Figures 2 and 3 were combined to give the complete arrangement of the instrumentation system presented in Figure 4

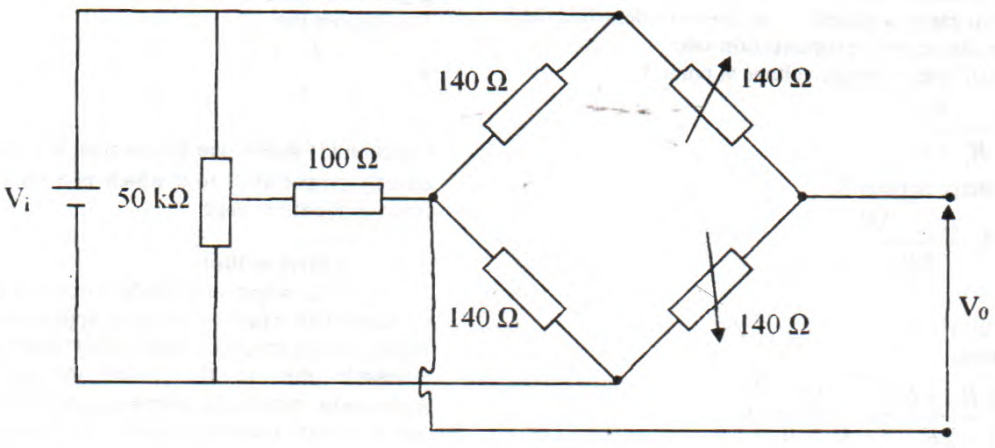


Fig. 2: Circuit diagram of the instrumentation system (Half bridge)

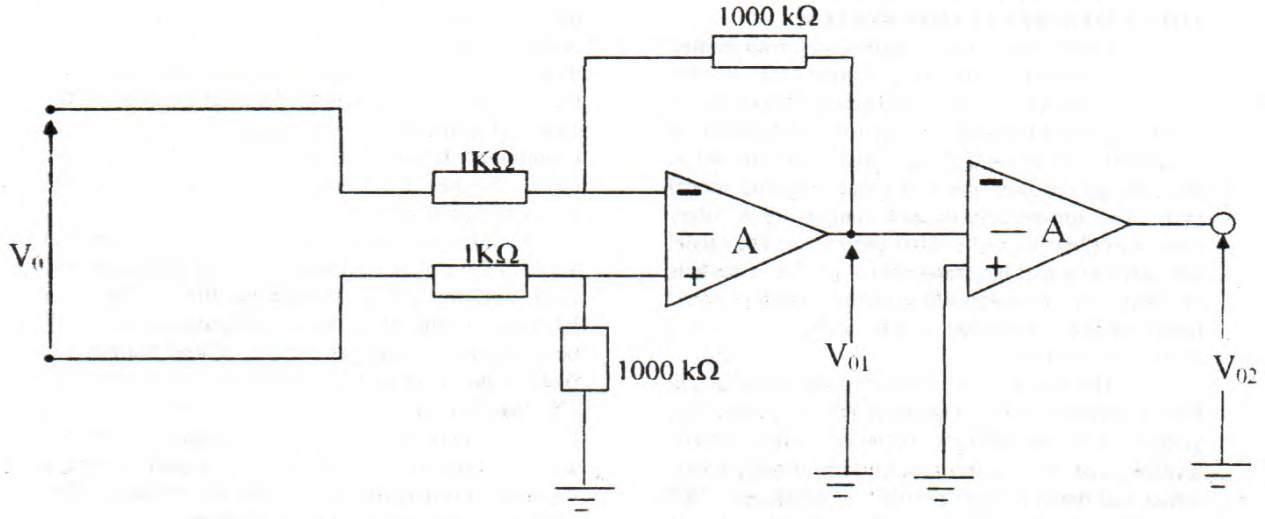
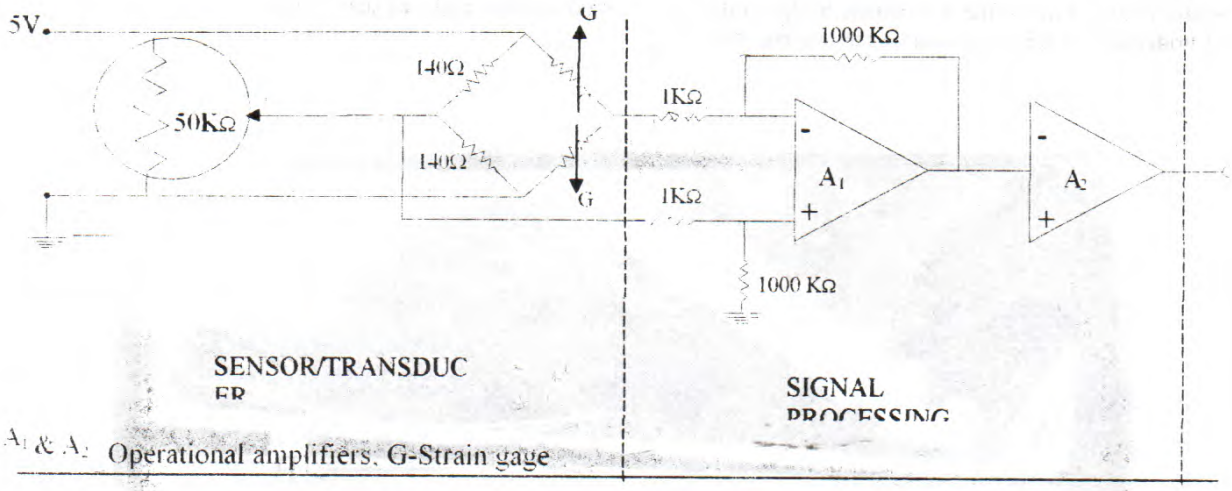


Fig. 3: Circuit diagram of the signal-conditioning unit (Amplifier)



4.0 PERFORMANCE EVALUATION OF THE INSTRUMENTATION SYSTEM

The instrumentation system was incorporated into a laboratory soil bin constructed in the Department of Agricultural Engineering, University of Ilorin, Nigeria (Mamman)[21]. The soil bin consisted of a stationary soil bin and a single-axle tractor served as the carriage for both the soil processing and model tools. The soil-processing unit consists of a rotary tiller, a soil leveller and a roller compactor. The model tool unit has a tool bar frame and a tool bar. Draughts of thirty-six geometrically similar model chisel furrowers were measured at four levels each of soil depth and travel speed.

The soil bin was filled with an artificial soil for the performance evaluation of the instrumentation system. Soil preparation involved rotary tilling, levelling and compaction to a uniform density along, across and down the soil profile. Six passes of a 39.5 kg roller gave an average uniform density of 1.76 Mg/m^3. Six roller passes were required for each soil preparation. A 3.73 kW, three-phase electric motor, powered the common carriage. The tool bar was bolted to the tool bar frame and the model tool was mounted on the tool bar. The two strain gages that formed the two arms of the Wheatstone bridge in the half bridge circuit were mounted on the tool bar. One of the strain gages was mounted on one face of the tool bar in direction of travel (tension) and the other one was mounted on the opposite face of the tool bar (compression). Figure 5 shows the tool bar with the model tool and strain gages mounted. The draught on the tool bar was picked in form of signals by the electrical resistance strain gages. The signals were conditioned and an S-T plotter recorded them on a chart. Figure 6 shows the assembly of the instrumentation system.

The instrumentation system was calibrated in terms of force. A static load calibration procedure was used. This was down by mounting the tool bar on a laboratory clamp in the same configuration, as it will be used in the actual experiment. A load hanger was fixed at the point of tool attachment on the tool bar. The load hanger was used to subject the tool bar to known weights. The tool bar was loaded in steps and at each step; the pen of the S-T plotter moved a distance corresponding to the load on the hanger. The same procedure was used for unloading.

After the soil preparation, the tool bar that carried the model tool and the strain gages was mounted on the carriage and pulled through the soil. The signals recorded by the S-T plotter were interpreted and computed. The mean values of draught obtained were analyzed statistically.

Fig. 5: Strain gaged tool bar with a model tool attached A- Model tool; B-Tool bar clamp

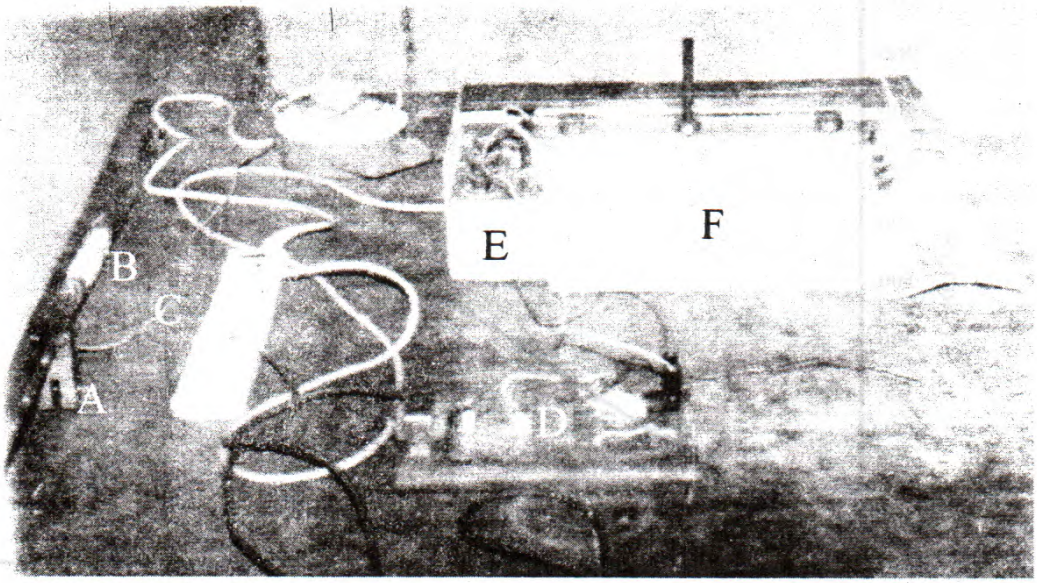


Fig. 6: Assembly of instrumentation and recording system showing strain gaged tool bar, amplifier with signal conditioning and S-T plotter
A=Tool bar clamp; B=Strain gage protection; C=Lead wire; D=Amplifier; E=S-T plotter paper; F=S-T plotter; G=Recording pen

5.0 RESULTS AND DISCUSSION

5.1 Calibration

The values obtained from the calibration indicated a linear response within the load range. There was no hysteresis in any of the outputs. The data was fitted to a linear regression model. The regression equation for the calibration was found to be:

$$Y = 4.905 + 9.81X \quad (R^2 = 0.998) \qquad (3)$$

Where Y is load (N) and X is the distance moved by the pen of the S-T plotter. The equation of the calibration was then used to compute the draught recorded by the S-T plotter for each of the model tools tested. Figure 7 shows the calibration graph of the instrumentation system. Some samples of the signals recorded by the S-T plotter at different speeds are presented in Figure 8.

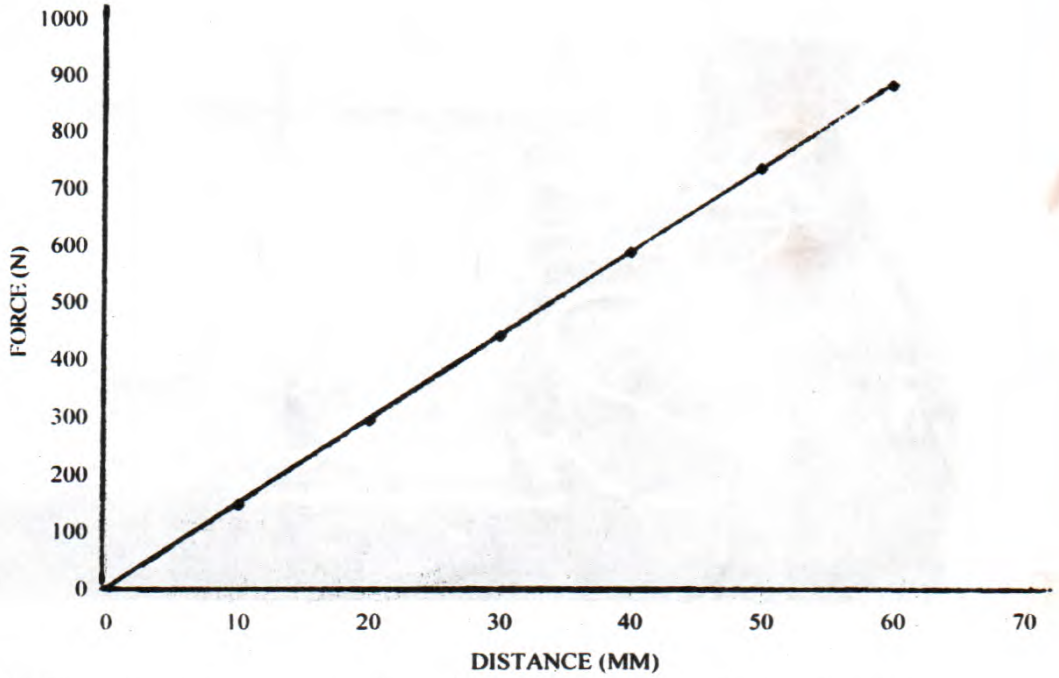


Fig. 7: S-T Plotter pen calibration graph

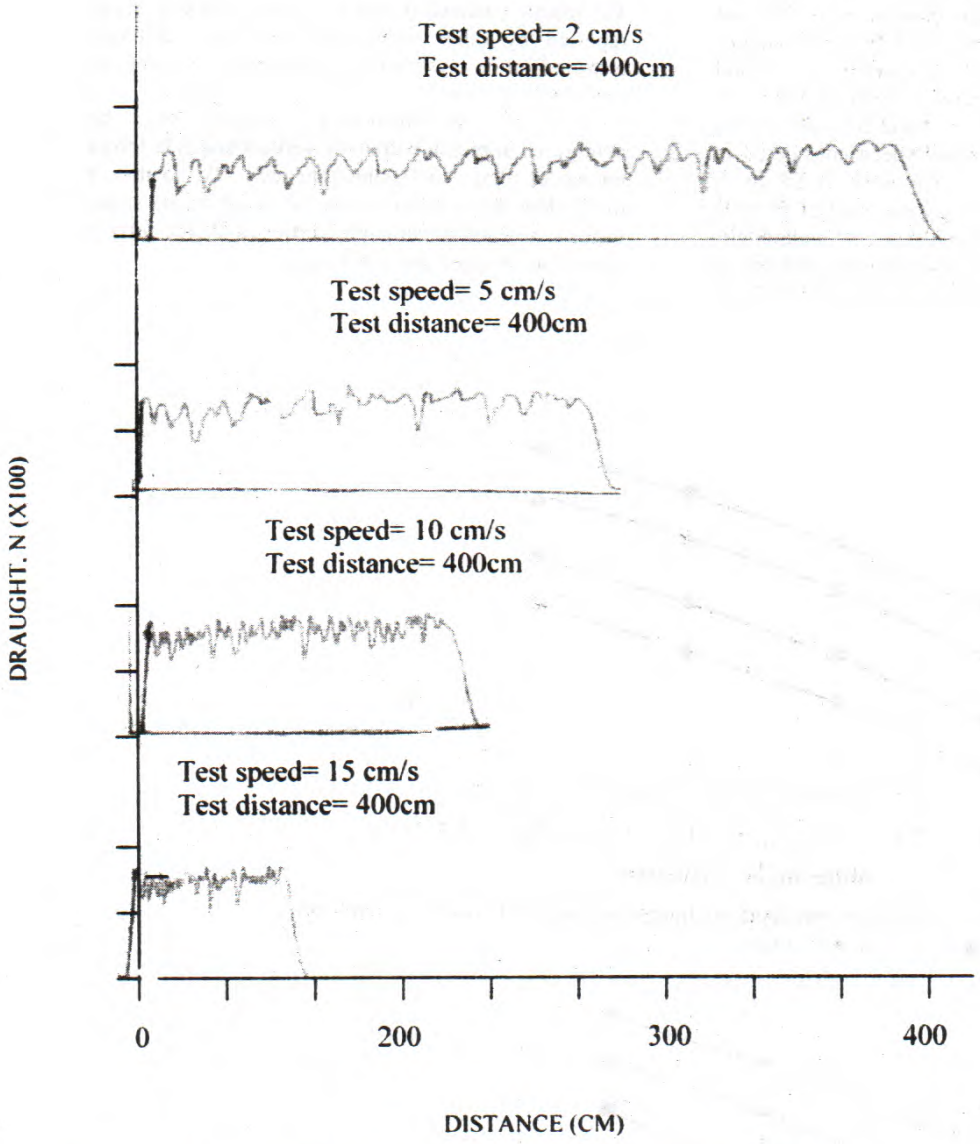


Fig. 8: Sample output of S-T plotter recorded signals at different speeds

5.2 Draught of model tools

Draught recorded by the S-T plotter at different levels of tillage depth, tool travel speed, slide angle, nose angle and cutting edge height were computed using the calibration Equation (3). The mean values obtained were analyzed to determine their levels of significance using a statistical package, Genstat 5. Results obtained showed that most of the two, three and four-factor interactions were significantly affected by both the design and operational parameters of the model tools. Those that were statistically significant were either plotted or tabulated. Figures 9-12 show typical plots of the effects of the interactions of slide angle and depth on draught at different levels of speed. At each level of speed of operation, draught increased with increases in slide angle and tillage depth. For all slide angles and tillage depths, draught increased with increases in tool

travel speed. At a tool travel speed of 2 cm/s and tillage depth of 2.5 cm, a mean draught of 76.70 N and 117.64 N were recorded at 5° and 20° slide angles, respectively. For the same tool speed (2 cm/s) and tillage depth of 10 cm, a mean draught of 118.32 N and 156.89 N were obtained at 5° and 20° slide angles, respectively. At the highest tool speed considered in the study (15 cm/s) and at tillage depth of 2.5 cm, a mean draught of 122.83 N was recorded at 5° slide angle and 154.04 N was obtained at 20° slide angle. For the same tool speed (15 cm/s) and tillage depth of 10 cm, a mean draught of 159.34 N and 188.35 N were obtained at 5° and 20° slide angles, respectively. The results obtained in this study are similar to those reported by other researchers who used different instrumentation systems for measuring draught on model tillage tools.

The instrumentation system can be configured to measure draught, vertical and side forces on model tillage tools simultaneously. To do that, a tool holder that has provisions for mounting six strain gages (two each for draught, vertical and side forces) should be designed and constructed.

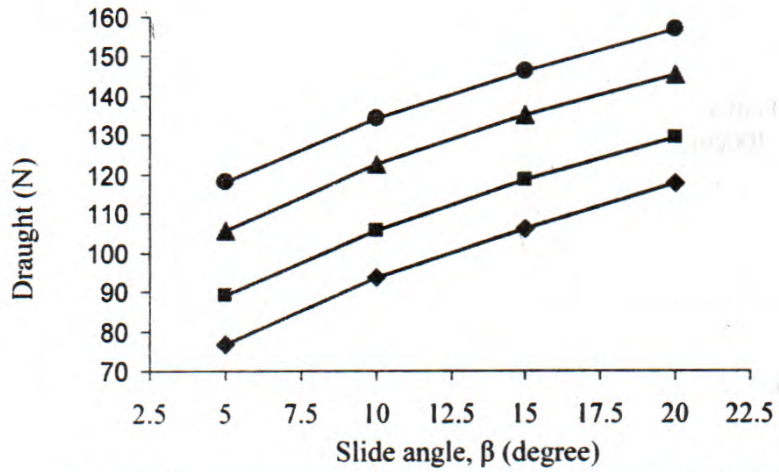


Fig. 9: Influence of slide angle and depth on draught at a speed of 2 cm/s: d=depth; ♦d_1= 2 cm; ■d_2=5 cm; ▲d_3=7.5 cm; ●d_4=10 cm

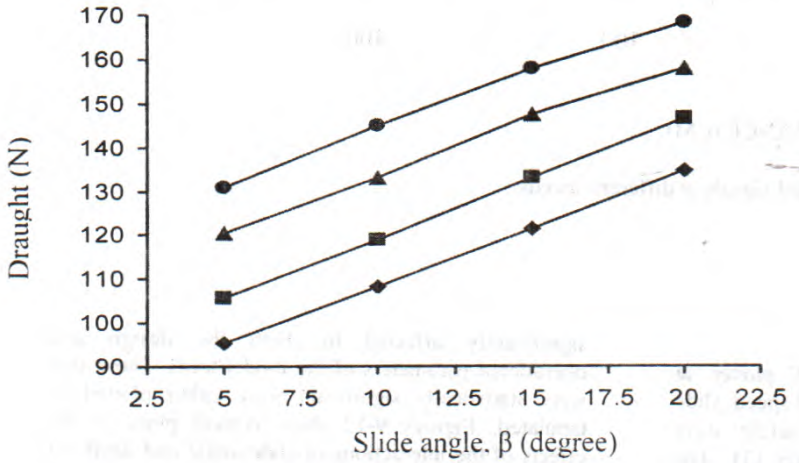


Fig. 10: Influence of slide angle and depth on draught at a speed of 5 cm/s: d=depth; ♦d_1= 2 cm; ■d_2=5 cm; ▲d_3=7.5 cm; ●d_4=10 cm

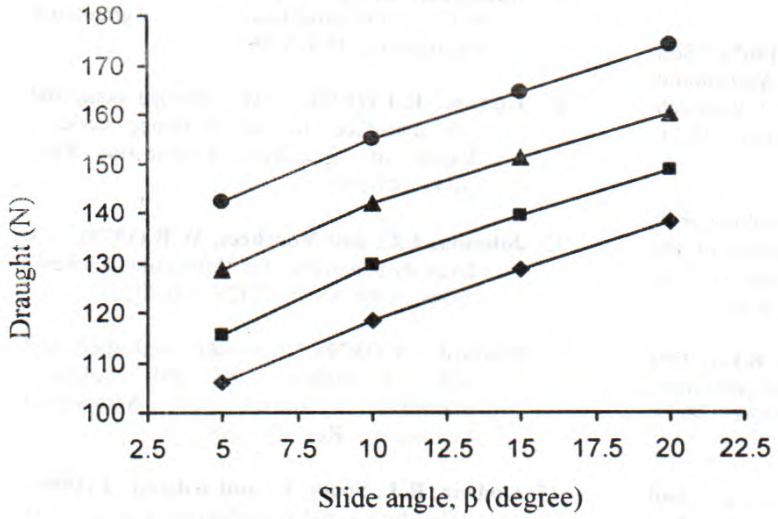


Fig. 11: Influence of slide angle and depth on draught at a speed of 10 cm/s: d=depth; ♦d_1= 2 cm; ■d_2 =5 cm; ▲d_3=7.5 cm; ●d_4=10 cm

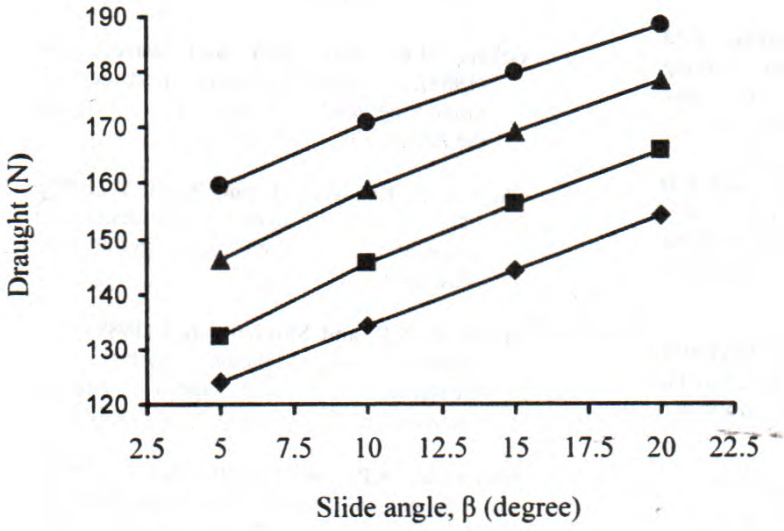


Fig. 12: Influence of slide angle and depth on draught at a speed of 15 cm/s: d=depth; ♦d_1= 2 cm; ■d_2 =5 cm; ▲d_3=7.5 cm; ●d_4=10 cm

6. 0 CONCLUSION

An instrumentation system was designed and constructed for measuring tool forces on model tillage tools. The result of calibration of the instrumentation system was linear and there was no hysteresis. The performance of the instrumentation system was evaluated by measuring draught on model chisel furrowers in a laboratory soil bin. Results obtained were in agreement with those reported by other researchers who used different tools and instrumentation systems but under similar operating conditions. The instrumentation system could be configured to measure draught, vertical and side forces on model tillage tools simultaneously.

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