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DEVELOPMENT AND PERFORMANCE TEST
OF A THREE POINT HITCH DYNAMOMETER
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Major professor

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DEVELOPMENT AND PERFORMANCE TEST OF A THREE POINT HITCH DYNAMOMETER FOR USE IN TILLAGE ENERGY RESEARCH

By

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ABSTRACT

DEVELOPMENT AND PERFORMANCE TEST OF A THREE POINT HITCH DYNAMOMETER FOR USE IN TILLAGE ENERGY RESEARCH

By

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A three point hitch dynamometer was developed and tested for performance capabilities and limitations. The design adopted is that of Chung et al (ASAE paper No. 83-1065). The dynamometer, composed of strain gaged sensing pins supported on a quick attaching coupler was adopted because of its relatively simple and inexpensive characteristics. It measures vertical and horizontal components of tractor tillage draft forces. A micro-computer based data acquisition system was utilized in calibration, verification and field-testing of the dynamometer. Tests made were aimed at gaining knowledge of the dynamometer's capabilities, error sources, accuracy and dependability as a draft measuring device.

Approved: ______________________
Major Professor

Approved: ______________________
Department Chairman

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (cont'd)

LIST OF FIGURES (cont'd)

1. INTRODUCTION

In 1976, agriculture used approximately 12% of total energy consumed in the United States, if the total chain (including transportation and storage of manufactured food products) was considered. Of this 12%, only 3% was actually used on the farm (Joint Task Force, 1976). Although 3% is a small amount, a shortage of fuel would force undesirable decisions redirecting the use of energy supplies. Researchers must therefore be prepared to help the farmer make the best use of available energy supplies.

Based on these considerations many a researcher have sought to know more about the forces involved in tillage operations, between the tractor and implement. Drawbar pull (tractive effort less rolling resistance) of a tractor consumes a significant amount of total energy input into the tractor implement system.

Many forms of strain gaged dynamometers have been developed in recent years for measuring drawbarpull and other hitching forces. They have varied in design detail, range and types of measurement, manufacturing cost and versatility.

Not many three point hitch dynamometers are available commercially. The British Hovercraft Corporation (East Cowes Isle of Wight, England) has one commercially available in a price range between $24000 and $35000, without instrumentation.

The development of mounted and semi-mounted implements has considerably diminished the usefulness of the common drawbar dynamometer, both for measurement of tractive effort and implement draft (Kepner et al.; 1978). The performance of modern tractors is often dependent upon their use with correctly coupled mounted or semi-mounted implements and the draft resistance of a modern mounted implement is likely to be significantly less than that of a comparable trailed version. This situation has led to the demand for an instrument which will measure drawbar pull of a tractor connected to its implement by a three point linkage.

Initial attempts to measure forces between tractor and mounted implement were made by measuring forces in the links themselves (Rogers et al.; 1952). The analysis of results was a formidable problem in three-dimensional vector addition. Today, with computer capabilities, it has become possible to measure these forces using completely separate or detachable components with fast, yet relatively accurate means.

The micro-computer has made the difference. Until about 10 years ago most tractor testing was usually confined to the laboratory. Field test procedures were often complicated, cumbersome and instrumentation systems had limited capabilities. A tractor is a field machine and should be tested in the field if actual operating data is to be obtained.

Micro-computer benefits which include availability, portability, reliability, flexibilty and ease of operation have made it possible to collect and process much larger quantities of data.

A three point hitch dynamometer based on the design by Chung et al. 1983 (ASAE Paper No. 83-1035) was developed, calibrated, verified and field-tested. Reported here are details of the various steps and considerations involved in the development of hardware, software and methodology used in making it possible to obtain draft force data. The data obtained in the whole dynamometer development process and field tests are analyzed to check the capabilities and dependability of the system as a future tillage energy research tool.

2. PROBLEM DEFINITION AND OBJECTIVES

Tillage energy requirements by agricultural tractors depends on tillage depth, implement type speed and to a major extent on the soil physical properties and prevailing environmental conditions. Tillage energy data required for various tillage implements and systems on different types of soils is available in very generalized forms. Soil physical conditions may vary widely over a small area. Therefore there is need for a means by which "on the spot" or localized tillage forces can be measured. An alternative is to make a similitude-analysis-based study of the influence of various soil parameters involved in the generation of forces by the tillage operation. This kind of study would then standardize the tillage operation, compensating for variation in the prevailing soil conditions.

Regardless of the approach taken, there is obvious need to develop instrumentation to measure the various parameters involved in the energy input of the tractor, implement and soil interaction. While some of this instrumentation is available off the shelf, the uniqueness of the specific systems usually requires development of the specific parts to meet the intended use and research detail. Measurement of tillage forces encountered in work with the wide range of implements that exist called for the manufacture locally of a three point hitch dynamometer. Prototypes of dynamometers that exist have been made for specific research needs and these not available in the market place at reasonable prices. With limited resources available, the development of the dynamometer described in this study was undertaken with the objective of developing a system which would accurately measure components of tillage forces and also also have limitations and dependability that were known.

Many methods of draft force measurement have been used over the years. The particular methods selected in various research situations have been chosen according to performance required and expected results. The use of strain gages in draft measurement has been popular for many years. They have given good performance in requirements for fast response, accuracy, precision and sensitivity. These are important factors especially in tillage force measurements where changes are rapid. Strain gage performance has improved in recent years due to the specialized electronic circuitry and readout equipment that has been developed. Strain gage type load cells are now comparable if not superior to other kinds of precision force measuring equipment. The major requirement for good performance however, is proper choice and treatment of materials along with correct techniques for attachment of high-stability strain gages. The recognition of the need for traction and energy data is stimulating this development of more efficient, convenient and less expensive tractor instrumentation systems.

3. REVIEW OF RELATED LITERATURE

Since 1937 there has been an ever-increasing number of implements mounted integrally with the farm tractor. Mounted implements have many advantages such as maneuverability in the field and ease of handling and transportation. However, in recent years the size of implements and tractors has increased and this has stimulated the need for better information about forces in the tractor links and the effect of these forces on the implement and tractor.

Because draft is the major component of forces between tractor and implement many efforts have been made to develop draft measuring devices. In this endeavor, various projects have been undertaken to study the magnitude, distribution and effects of draft force on the energy requirements for the tillage operation. With this knowledge about the tractor-implement interaction, the energy use on the farm can be optimized. Considerable research effort has been directed to this end and more recent means of doing this have necessitated simultaneous development of data acquisition systems.

3.1 Three Point Hitch Dynamometer

Due to single pin hitching of "pull type" equipment it is considerably easier to measure the draft of this type of implement than it is on the more complex mounted equipment. Draft of trailed implements may be determined by a spring type dynamometer. Hoag and Yoerger (1974) developed a ring-type force transducer capable of accurately measuring draft. R. D. Singh et al. (1981) also fabricated a similar transducer. While these components gave accurate draft measurements with adequate sensitivity for a wide range of magnitudes of forces, they were limited to a single point hitch for trailed implements.

3.1.1 Pioneer Work on Measuring Three Point Hitch Forces.

Roger and Johnston (1953) were among the first people to develop a hydraulic dynamometer for measuring the draft of mounted implements. They attached a hydraulic cylinder directly to each link of the three point hitch. Their technique required photographing the Bourdon pressure gages, lined up on a board and attached to the cylinders by flexible hydraulic hoses. All the gages were mounted on the gage-board in a cluster form so they could be simultaneously photographed by a 16mm movie camera. To test the accuracy of the system, a strain gage was installed in a chain connecting the back of the plow to an anchor post. Comparison of readings to the corrected strain gage readings showed the error in the instrument was 4%, attributed to friction in the cylinders.

Data collected was enough to show magnitudes, rates and amounts of fluctuation of forces with time. From these data, weight transfer to the rear wheels of the tractor was calculated.

Roger and Johnston (1953) concluded that resistance strain gages had a high potential for use in force evaluation and with them, more accurate readings could be expected. They computed their drawbar pull as an algebraic sum of linkage forces since top and bottom links were nearly parallel to the ground surface. The normal variation in the link forces was about ± 25%, an indication of how much the soil resistance to a plow can change in an average field.

3.1.2 Later Dynamometer Designs

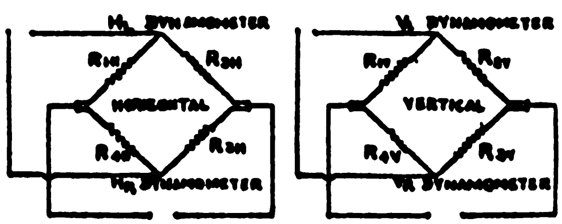
In the early days, the three point hitch dynamometers used springs or hydraulic cylinders of some form. Volkov and Klochev (1958) developed a three point hitch measurement system which consisted of dynamometer elements built into each link, and an integrating device. The movement of the front half-bar of the dynamometer link was transmitted by an unequal-arm lever mounted on the body of the link on ball-bearings. The unequal-arm lever magnified the movement and forces were measured by spiral springs and a multicontact gage. One main part of the integrating unit was a collector consisting of 15 contacts which passed impulses to the recorder in accordance with the deformations of measuring springs.

All of the systems designed with mechanical components, i.e. springs, bearings and contact points were subject to problems of inaccuracy, non-durability and were complex in connstruction and operation. Hydraulic dynamometers were an improvement over those of spring type.

The device built by Skalweit (1958) used a hydraulic cylinder which was located ahead of a large rectangular frame suspended beneath the tractor by four vertical links. This frame was connected to the rear vertical rectangular frame on which three links were attached. The implement forces were transmitted through these frames to the hydraulic cylinder.

Lal (1959) reported that to provide a complete definition of the force between a tractor and a mounted implement, it would in general be necessary to measure the axial forces in the three links, the two lift rods and the angular position of one link. A graphical analysis of the resulting information would probably be a more formidable task than to obtain the information by instrumentation in the first place. Lal came up with an interesting design. He replaced the normal cross-shaft of the plow by a straight one so that forces acting at the lower link hitch points caused only bending and eliminated torsion (see Figure 1). The section of the shaft at equal distances from the center of the ball joints at either end was reduced. The bending produced at these sections in the horizontal and vertical planes was measured separately by using strain gages. To measure the force on the top link, a top link dynamometer was built,which was supported on a frame so that it would measure only the horizontal force.The major shortcoming of this device was the difficulty of changing implements.

Jensen (1954) demonstrated the superiority of experimental stress analysis as a means of obtaining exact quantitative information about distribution of loads in structures and behavior of materials under loads. He applied this technique to develop various dynamometers for tractor field tests such as a torque meter, a drawbar dynamometer and three point hitch dynamometer.



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ARRANGEMENT AND CONNECTION OF STRAIN GAUGES ON CROSS-SHAFT.
THE [illegible] SLOT CUT INTO THE SHAFT EMBODIES THE ELECTRIC WIRES CONNECTING THE DYNAMOMETERS AT THE TWO ENDS

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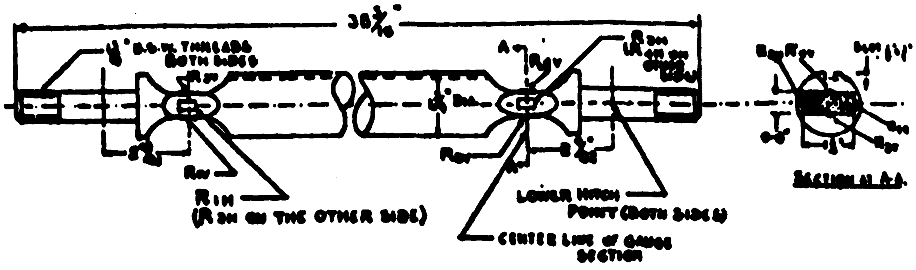


FIGURE 1. Arrangement of strain gages on the cross-shaft of the plow(Lal, 1959)

Since Jensen (1954) demonstrated specific application of the strain gage to tractor dynamometers, many trials have been made to develop more accurate and convenient three point hitch dynamometers. One of the important considerations in developing dynamometers has been the location of strain gages or the force transducer. Either one of the following four units seems to have been chosen for attachment of strain gages or transducers, a) hitch links , b) some part of the implement, c) tractor body or d) hitch frame, located between the hitch links and an implement.

Neuholt (1959) measured draft and vertical forces of the three-point links by attaching a set of strain gages connected as a wheatstone bridge on each link and a strain-gage-equipped proving ring on the upper link. The resultant pull of the implement was obtained by determining the angle of each link with respect to the direction of travel. Orlowski and Wolf (1963) used almost the same device as Neuholt but put one more set of strain gages on one of the lower links and tried to measure side draft force.

Luth et al. (1978) mounted transducers directly on the lower links to obtain reaction forces in all three cartesian coordinate directions. The geometry of the three-point hitch was not altered by the transducer system.

The third place available for attaching the strain gages or transducers is the tractor body. Jensen (1954) used three identical beams, one at each hitch point on the tractor body (see Figure 2). The beam was supported at the point indicated by a subframe to which the tractor links were attached. A set of four strain (one wheatstone bridge) gages was placed on each beam.

Thiel (1958) measured the forces by simply mounting two strain gages on each of the lower and upper link pins (see Figure 3). The system was sensitive only to the horizontal components of the forces on the links.

Reece (1961) also mounted strain gaged cantilever pins on the tractor and supported the ball joints at the inner end of the three links. The ball centers were 76.2mm out from the tractor sides, as compared with the 70mm of the manufacturer's original mountings. The sensitivity of Reece's device can be calculated from the expression:

$$Ig = VSe/(R+Rg)$$

where Ig = ammeter reading

V = strain gage exitation voltage

S = gage factor

e = tensile or compressive strain

R = strain gage resistance

Rg = ammeter resistance

The strain in the surface of the cantilever was not accurately predicted by the theory of simple bending because the cantilever was very short relative to its depth. The actual strains were found to be only 83% of those calculated from the simple bending expression:

$$e = 3PL / 3Ec^2t$$

where P = load to be measured

L = effective length of cantilever

E = modulus of elasticity

$2c$ = depth of cantilever at center of gages

t = width of cantilever at center of gages

The Stokes-Wilson equation for short beams was used and results with closer agreement were obtained:

$$e = 3P(L/2-c/\pi)/(2Ec^2t)+(P/2Ect)$$

Scholtz (1964) further developed Reece's method. He examined various factors affecting the link pin transducers. these factors included, friction in the ball joints, imperfect position of positioning the

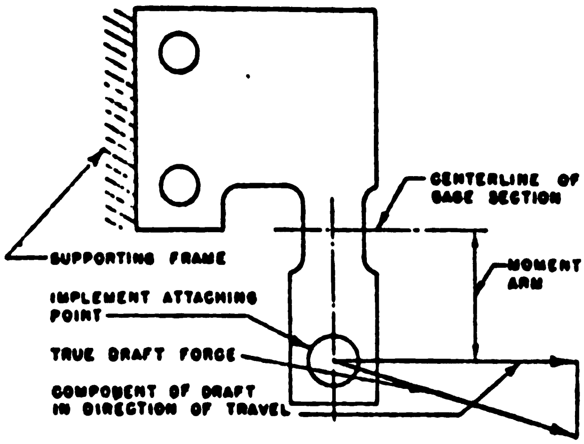


FIGURE 2. A draft transducer of the three-point hitch dynamometer (Jensen, 1954)

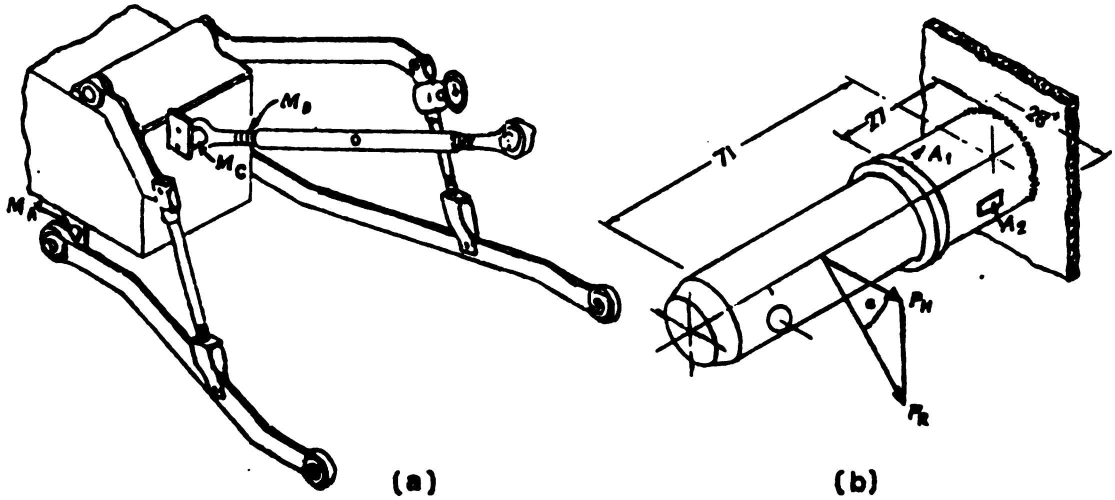


FIGURE 3. Three-point hitch dynamometer, (a) three measuring elements, (b) measuring element, M_A. Dimensions are in millimeters (Thiel, 1958)

gages, faulty cantilever position and hydraulic system characteristics. He estimated the magnitude of errors they would cause in dynamometer measurements. Results from this study were later utilized in design of link pin transducers. To reduce hysteresis effects, the nominal length of the lower beams was fixed at 165mm (see Figure 4). This gave results which, compared in a field experiment with those of a hydraulic drawbar dynamometer, the difference was insignificant at the 5% level.

As the above results show, the link pin size limits its use as a transducer. Making it longer, requires modification of tractor, otherwise errors due to link hitch position changes become inevitable.

To eliminate the requirement for modification of either tractor or implement and to make the transducer easily interchangeable among tractors and implements, a sub-frame or a hitch frame three point hitch dynamometer came into being.

Scholtz (1966) designed and built a hitch-frame type three point hitch dynamometer. It consisted of force measuring transducers firmly wedged and bolted inside vertical rectangular hollow sections (see Figure 5). The transducer on the top link was arranged to measure draft force only. While the dynamometer was capable of measuring vertical and horizontal components of draft force with good fulfillment of requirements, it was also bulky (118 Kg), and imlements were mounted

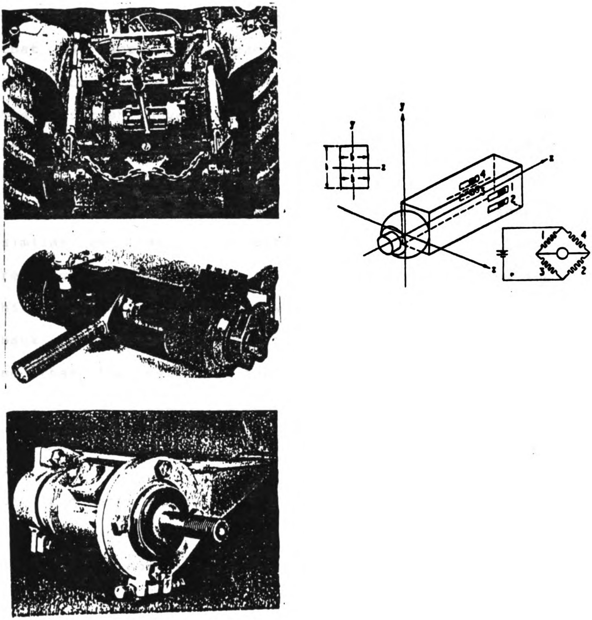
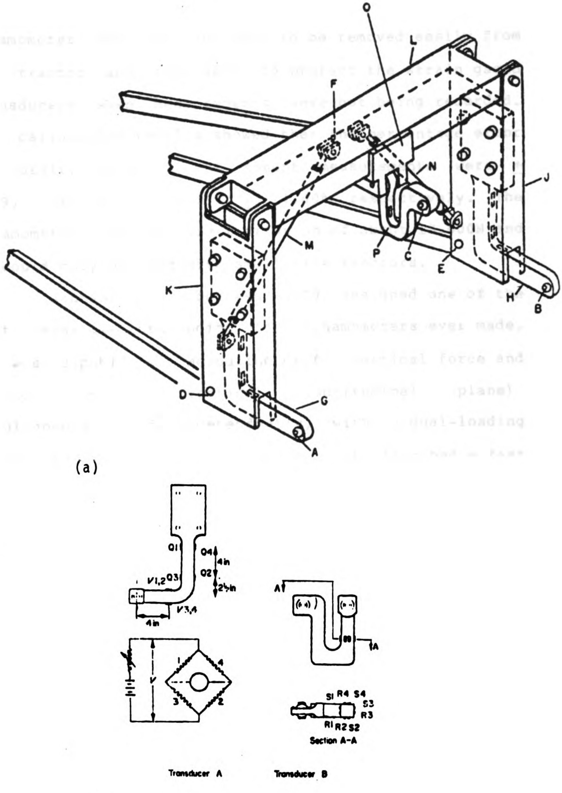


FIGURE 4. Dynamometer beams and strain gage arrangement (Scholtz 1964)

229mm further to the rear of the tractor. The dynamometer introduced significant extra resilience in the hitch. It is this Scholtz's (1966) original design that has been re-designed by the National Institute of Agricultural Engineering Silsoe, Bedfordshire, England. The British Hovercraft Corporation has adopted the re-designed product for manufacture under licence for sale.

Carter (1981) developed a dynamometer shaped similar to that of Scholtz (1966). He attached three rectangular strain beams to each link hitch-point of the hitch frame. Strain gages were applied to the front and back of three aluminium strain beams and were connected so that the vertical forces cancelled and horizontal forces on each beam were summed algebraically.

Devine (1963) developed a little different type of hitch frame dynamometer. Basing the structural design on load estimates, the frames were constructed of hot rolled rectangular tubing (76x51x5mm thick). The dynamometer consisted of two frames which were connected together by two octagonal ring transducers (see Figure 6). As Hoag and Yoerger (1975), and Godwin (1975) explained, this kind of extended ring transducer fitted with strain gages can measure strain proportional to two orthogonal forces and a torque about the center of the ring independently. Vertical and horizotal adjustment of the dynamometer was supplied so the hitch frame would fit most standard three point hitch equipment. The



(a)

(b)

FIGURE 5. Three point hitch dynamometer a) the subframe assembly b) the force transducers (Scholtz, 1966).

dynamometer was also designed to be removed easily from the tractor and implement to protect the strain gaged transducers when measurements were not being recorded. The calibration results showed that the percentage error for draft, vertical and moment measurements were $\pm$ 1.29, $\pm$ 2.10, and $\pm$ 1.60% respectively. The dynamometer has a load limitation of about 13,000N and it could only be used with small size tractors.

Johnson and Voorhees (1979) designed one of the most versatile three-point hitch dynamometers ever made. It was capable of measuring draft, vertical force and torque (in a vertical longitudinal plane). simultaneously and independently, with a dual-loading capability (low and high range). It also had a fast hitching capability. It was designed for use on both category II and III tractor hitches and also performed satisfactorily with two point semi-mounted implements. Maximum draft capacities were 66700N in the dynamometer's high range (Category III) and 36000N in low range (Category II). The dynamometer consisted of three subassemblies (see Figure 7a). A transducer subassemly made of an aluminium tube was located between the tractor and implement subassemblies (see Figure 7b). The tractor subassembly was attached at points b and c and the implement subassembly at points a and d. Thus a load applied to the transducer caused both bending and torsion. The complete dynamometer measured 1220mm wide and 790mm high. It extended the implement mounting point

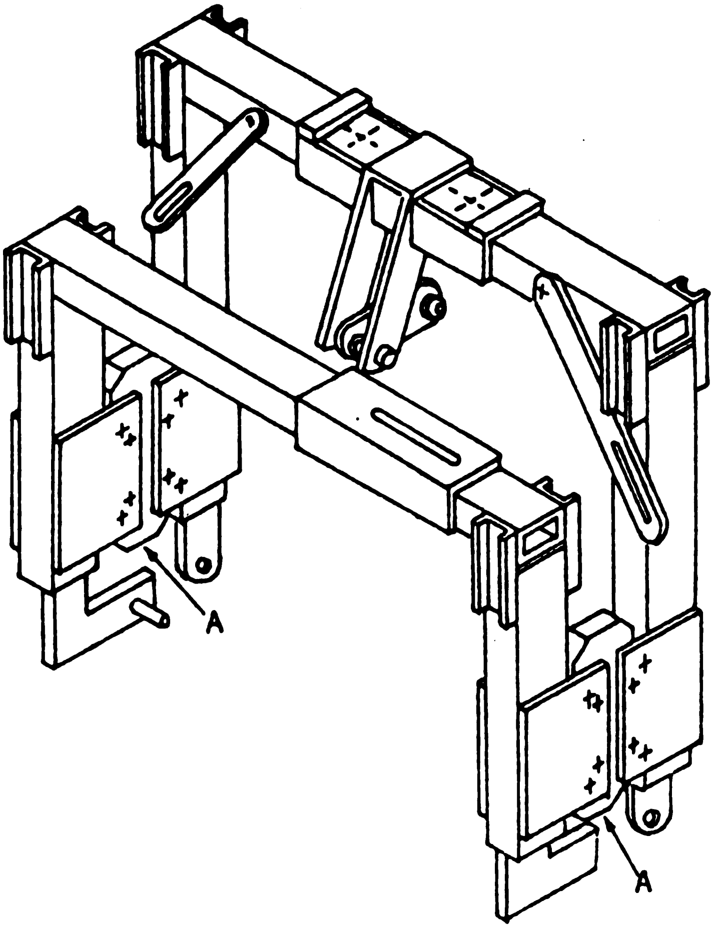


FIGURE 6: Three-point hitch dynamometer using octagonal ring transducers (Devine, 1973)

about 310mm to the rear of the tractor hitch points.

Smith and Barker (1982) developed a thin three-dimensional measuring hitch frame dynamometer (see Figure 8). It was constructed in the shape of a triangle using a 152mm steel channel. The frame was composed of two triangular halves, symmetric except for tractor, implement and load cell connectors. The dynamometer used six BLH-U2M1 load cells with capacities of 22kN. Three of them, placed at the corners and perpendicular to the dynamometer surface measured draft, two load cells located on the upper triangular arms provided vertical and side force information and prevented rotation of the halves. One load cell located in the lower triangular arms measured only the side force. The dynamometer shifted the implement 190mm to the rear, compared to 127mm for a category III type quick hitch. It was found that considerable time and effort were required, when the dynamometer was mounted, to adjust the linkage and clearances within the dynamometer so that all forces were well transferred to the load cells. The dynamometer halves had to be separated to adjust the linkage, a time consuming and tedious process.

The above review clearly indicates that there are many strong points in favor of the design and use of the hitch frame dynamometer. Problems, however, have arisen that need to be considered in this type of design. These include :

a) Construction of the hitch frame. Weight of frame, structural strength and location of transducers, type of strain beam etc. are important considerations.

b) Extension of the hitch points of the implement further away from the tractor, a cause of extra resilience (Sholtz, 1966).

c) Mounting of the dynamometer (Scholtz, 1966, Devine, 1973, Smith and Barker, 1982).

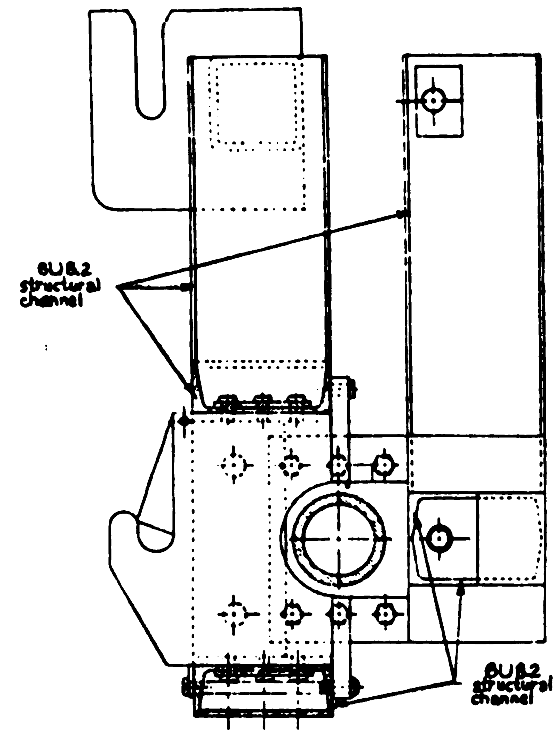
d) Use with the PTO shaft (Johnson and Voorhees, 1979, Smith and Barker, 1982).

e) Versatility and interchangeability between tractors (Johnson and Voorhees, 1979).

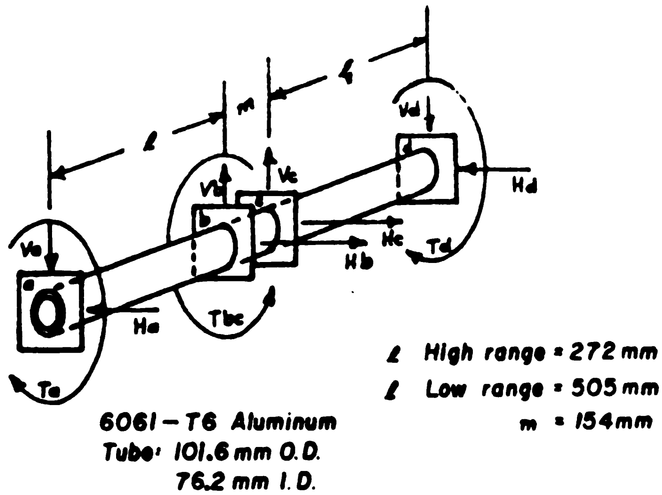
3.2 Linkage Force Analysis

Lal (1959) showed the desirability to simplify the problem of measuring total force between tractor and implement. This force had to be analyzed to see if it would be possible to ommit information concerning some of its components. Figure 9 shows Lal's (1959) concept of forces acting between a tractor and a mounted implement.

The general force P has components in all major planes of the tractor and associated with it is a couple C perpendicular to the direction of the force. The force can be resolved into three components L, V and S. Assuming the tractor is proceeding along a horizontal



a



b

FIGURE 7 a. Three point Hitch Dynamometer-right side schematic
b. Design load conditions on transducer subassembly
T=torque, V=Vertical force, H=horizontal force
(Johnson and Voorhees, 1979)

plane surface, these three force components can be refered to as horizontal, vertical and side forces. The component L, which is parallel to the direction of travel is also refered to as the draft of the implement. Being the most important component of the total force, draft is the part which determines the traction required from the tractor and directly consumes drawbar horsepower.It is the component devoted to useful work by the implement.

The vertical component V has the effect of adding load to the tractor rear wheels and removing load from the front wheels. It therefore has a profound effect on tractive ability of the tractor as well as its stability and steerability. No less important is this component's effect on the implement's ability to penetrate and maintain depth as well as on the draft on the implement because of friction forces associated with it.

The side force S exists only in the case of implements which are not symmetrically disposed about the tractor centerline. In such cases it is difficult to maintain directional stability of either or both tractor and implement. The draft of the implement is increased because of the friction produced. This component may be considered of far less importance than horizontal and vertical components because with many implements it is non-existent. Lal (1959) found it could be disregarded in the case of multi-bottom plows since even with two

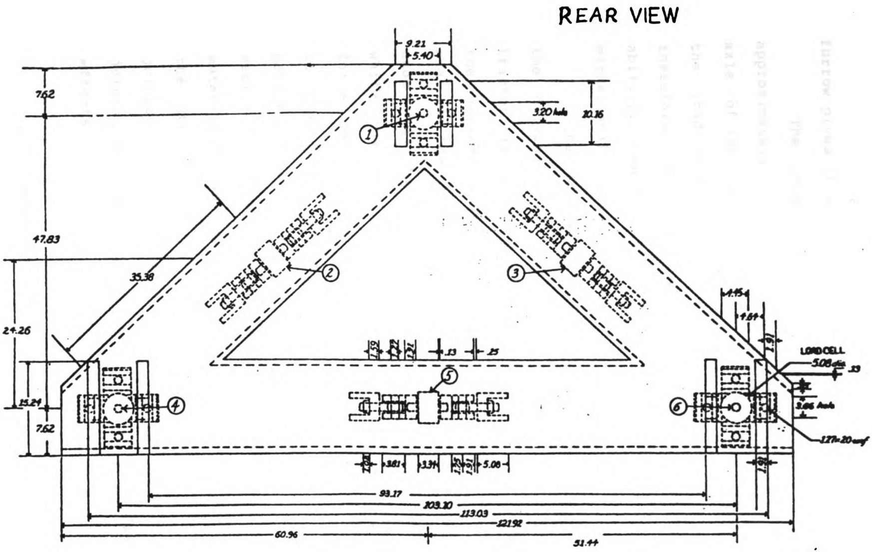


FIGURE 8. Three point Hitch Dynamometer. Encircled numbers show load cells (Barker et al., 1981)

furrow plows it was quite small.

The couple associated with the total force lies approximately in the vertical plane containing the rear axle of the tractor. Its effect therefore is to transfer the load from one drive wheel to the other and it could therefore have an appreciable effect on tractive ability. However Lal (1959) reports that this couple is either small or non-existent.

The force in the vertical plane perpendicular to the driving axle exerted by a mounted implement on a tractor is equal and opposite to the force exerted on the implement by the reactions at the lower link ends and at the top link end. Reactions at the lower link ends will have both horizontal and vertical components while the top link will have tensile or compressive force depending upon conditions. Lal (1959) went ahead to practically support his analysis. He used a two bottom plow with a straight cross shaft (see sect.3.1.2), instead of the normal offset one. Lal established an overall accuracy of $\pm$ 5%. He attributed the greater part of the error to friction in the hitch joints. Use of self-alligning bearings instead of ball joints at lower links seemed to reduce the hysteresis effects.

3.2.1 Modern Approach to Link Force Analysis

Compared to Lal (1959), the more recent work of

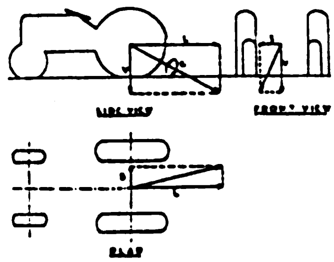


FIGURE 9. Forces between tractor and mounted implement.
(Lal 1959)

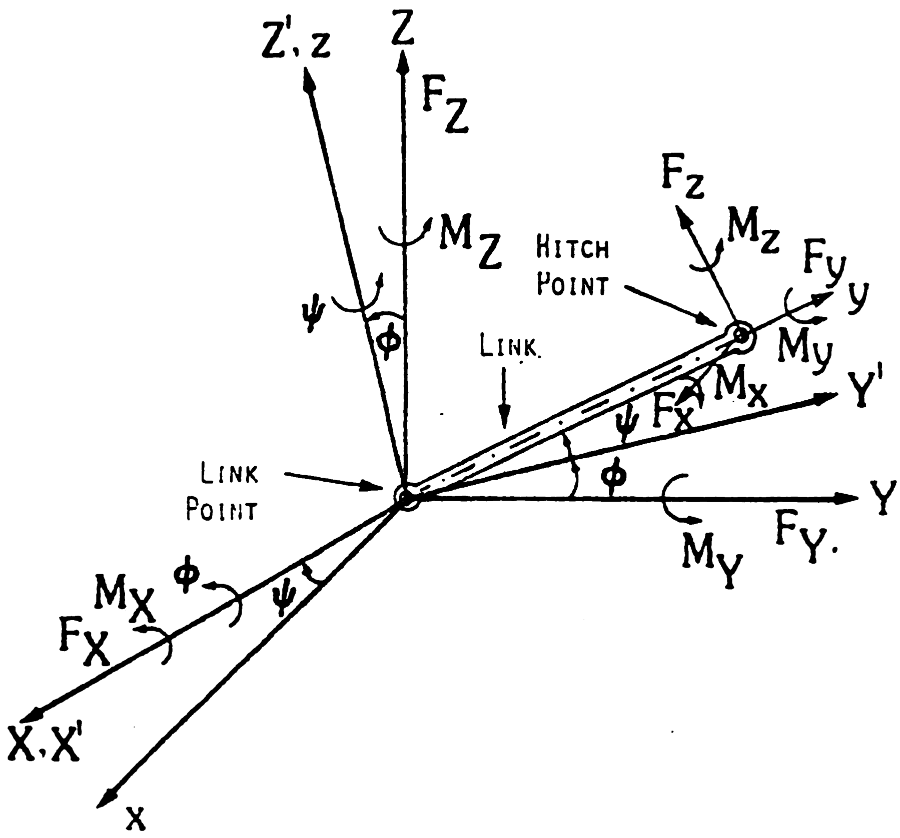


FIGURE 10. Transformation of forces and moments between the global XYZ and local xyz coordinate system. (Upadhyaya et al., 1983)

Collins et al. (1981) and Upadhyaya et al. (1983), provide an improved way of analyzing forces in the three point hitch linkage system. Following Lal's work, Upadhyaya et al. investigated the cases of:

a) A symmetric mounted implement in a free link mode.

b) A symmetric mounted implement in a restrained link mode.

c) An assymetric mounted implement in a free link mode.

d) An assymetric mounted implement in a restrained link mode.

Most tillage implements with the exception of moldboard plows and offset disk harrows are symmetric about their longitudinal centerlines, Kepner et al. (1978 pp 181). The side components of the soil forces are balanced, the horizontal center of resistance is at the center of the tilled width and the center line of pull is in the direction of travel.

Plows and offset disk harrows can withstand substantial amounts of side draft and proper hitching is necessary to minimize adverse effects on the tractor and implement. Utilizing landsides and furrow wheels, mold board plows and disk plows, respectively, absorb side forces. Offset disk harrows do it by automatically changing disk angles to create a difference between the soil-force side components for the front and rear gangs. Pull type disk plows have essentially free-link pull members whereas mold board plows and disk harrows have

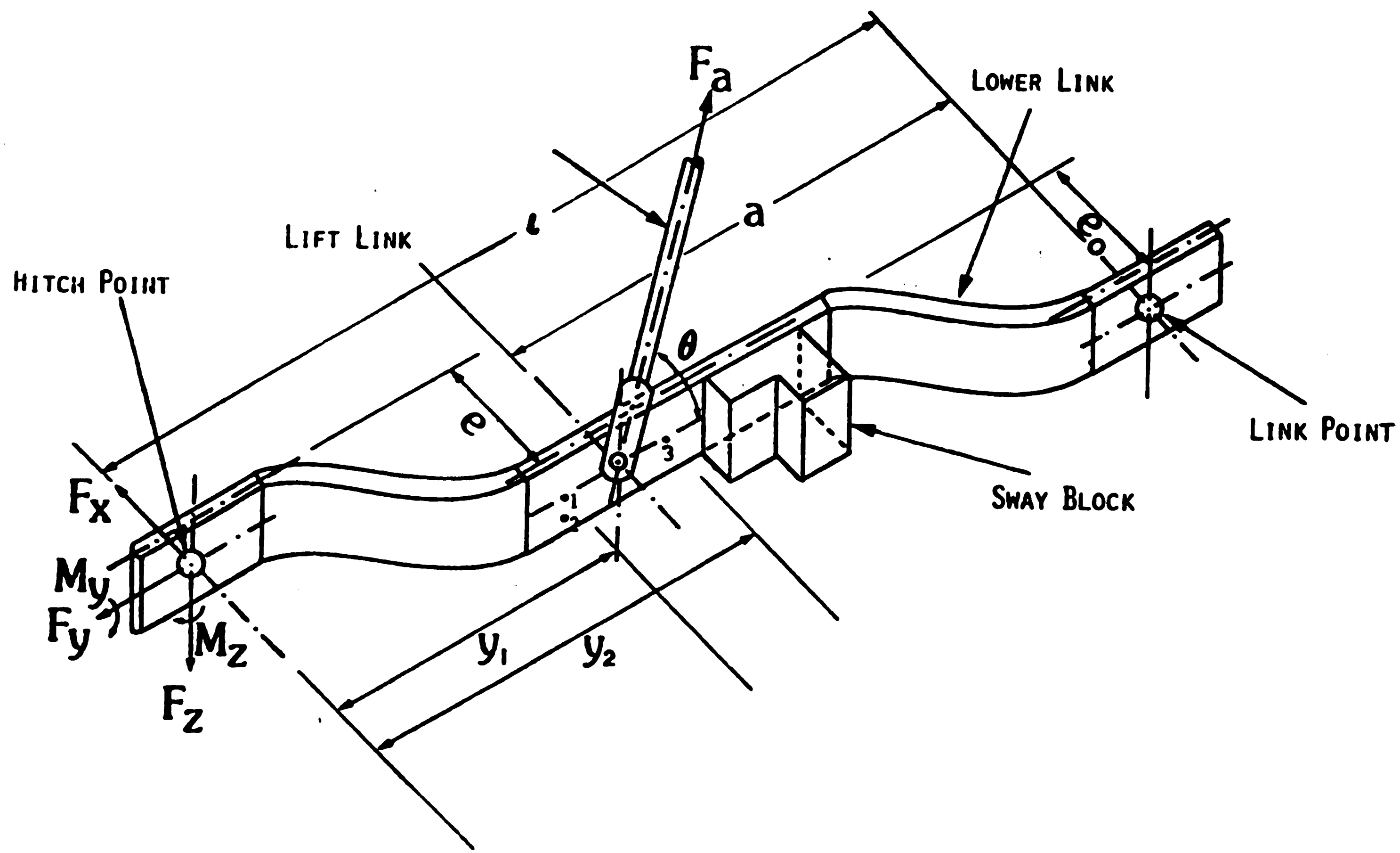


FIGURE 11. Schematic of the lower link of the three point linkage system (Upadhyaya et al., 1983)

laterally rigid pull members. If an implement cannot withstand side forces, the alternatives are a central angled pull passing through the center of pull of the tractor, an offset straight pull or an offset angled pull. If an implement cannot withstand side-draft, the only alternative is an offset straight pull. The center of pull is generally considered to be midway between the rear wheels and slightly ahead of the axle since the differential divides the torque to the wheels about equally (Kepner et al.; 1978).

It is not always possible to have the horizontal center of resistance of an implement directly behind the center of pull of the tractor particularly for narrow implements and wide-tread tractors. This is why Upadhyaya et al. (1983) categorized their investigation as above. A central angled pull does not affect tractor steering, whereas the offset pulls do. An angled pull (either central or offset) introduces a side force on the rear wheels which sometimes is of sufficient magnitude to be objectionable.

Upadhyaya et al. (1983) in the mathematical analysis of their link-force defined right-handed XYZ global and xyz local coordinate systems.The global coordinate system was defined such that the Y-direction coincided with the direction of travel and YZ plane vertical. The y-axis of the local coordinate system coincided with the longitudinal axis of the link and yz plane was vertical (see Figures 10 and 11)

The local coordinate system was considered to be the result of rotating the system which was initially coincident with the global coordinate system about the X-axis by an angle ϕ to obtain X'Y'Z' and then rotating about the Z'-axis by an angle Ψ to obtain xyz system (Greenwood 1965). The force and moment components in the two coordinate systems were related by the following transformation:

$$\begin{Bmatrix} F \\ F \\ F \\ M \\ M \\ M \end{Bmatrix} = \begin{bmatrix} [\ T\ ] & [\ 0\ ] \\ & \\ [\ 0\ ] & [\ T\ ] \end{bmatrix} \begin{Bmatrix} F \\ F \\ F \\ M \\ M \\ M \end{Bmatrix}$$

where

F_X , F_Y , F_Z = Force components in the global coordinate system.

M_X , M_Y , M_Z = Moment components in the global coordinate system.

F_x , F_y , F_z = Force components in the local coordinate system.

M_x , M_y , M_z = Moment components in the local coordinate system.

$$[\ T\ ] = \begin{bmatrix} \text{Cos}\,\Psi & -\text{Sin}\,\Psi & 0 \\ \text{Sin}\,\Psi\,\text{Cos}\,\Psi & \text{Cos}\,\Psi\,\text{Cos}\,\phi & -\text{Sin}\,\phi \\ \text{Sin}\,\Psi\,\text{Sin}\,\phi & \text{Cos}\,\Psi\,\text{Sin}\,\phi & \text{Cos}\,\phi \end{bmatrix}$$

where Ψ = Eulerian rotation angle about Z' axis (Figure 11)

ϕ = Eulerian rotation angle about X axis (Figure 11)

$[0]$ = 3x3 null matrix

The force component F_Y from each link contributes to draft, F_Z and M_X influence weight transfer and dynamic weight on traction wheels. The force component F_X and moment component M_Z influences rotational stability of the tractor-implement system about the direction of travel and weight distribution between both front and rear, left and right wheels.

Neglecting friction in the ball joints at the hitch and link pins for the various hitch categories outlined above, Upadhyaya et al. went on to find the forces, moments and angles that needed to be measured for an error-free analysis.

Utilizing the above mathematical relationships and applying Hooke's Law Upadhyaya et al. went on to make a computer simulation which helped compute errors in draft and vertical force when side force F_X and angle Ψ were neglected. Using parameter ranges corresponding to the dimensions on an instrumented 72 kW diesel tractor plowing with 3 to 5 bottom plow they had the following results:

Maximum error in vertical force = -2.23%

Maximum error in draft force = 8.66%

If sway block was adjusted for a $\Psi < 10$, maximum % error in draft reduced to 3%

Magnitude of these errors was therefore small and measurement of F_X was unwarrated. Upadhyaya et al. concluded that for a complete mathematical analysis of tractor-implement linkage forces:

a) Axial forces in top link, bottom link and lift links should be measured.

b) Orientations of links to vertical plane transverse to the direction of travel must be measured.

c) Rotations of links about a vertical axis and side forces, if present did not seen to affect the draft and vertical forces significantly in normal range of parameters encountered in the field.

3.3 Data Acquisition and Analysis Systems

Until the 1950's, data were obtained directly from spring or pressure type indicators, or electrical meters. Rogers and Johnston (1953) measured forces on three-point links using hydraulic cylinders and Bourdon pressure gages. A camera was used to record the pressure indicated by six gages.

Jensen (1954) used a D'Arsonval galvanometer consisting of magnets and coils to indicate strain gage outputs. The galvanometer was later developed to record the data on chart paper and in this form it was extesively used (Reznicek et al., 1957, Reece, 1961, Paulson and Zoerb, 1971, Devine, 1973). A high density digital tape recorder was later introduced (Flis and Cupp, 1974).

At this time the major problem with the developed instrumentation systems was satisfactory reception of the signal input. Attempts were made to compute and control the data signals. Volkov and Klochev (1958) used an electric impulse counter that was very simple. Later, analog signal devices were widely adopted. Zoerb and Popoff (1967) designed a tractor wheel slip indicator using electrical circuits, which consisted of resistors, potentiometers and capacitors. Barker (1974) and Peterson (1974) developed level detectors which caught and stored the level of analog signals.

Arithmetic calculations had not been satisfactorily accomplished until an analog computer was applied for data analysis. The analog computer developed by Prather and Schafer (1969) to measure wheel slip consisted of operational amplifiers for summing and inverting, a multiplier-divider for dividing , and precision resistors and potentiometers to set the required gains and references. Paulson and Zoerb (1971) also built an analog computer for a slip meter. Grevis-James and Bloome (1982) measured not only wheel slip but also drawbarpull using a monitor operating mainly with analog computations. Ridge et al. (1979) indicated that the conventional analog computer was very sensitive to shocks, vibration, dust and extreme temperatures and had to be maintained in a sophisticated stationary environment. He developed a mini-analog computer that could simultaneously analyze four analog and two digital signals.

Development and application of integrated circuits (IC) and digital electronics has greatly affected the development of tractor instrumentation. Today, much of the measurement equipment has been replaced by digital devices or control logic IC gates and chips. Some researchers have used direct measurement devices,such as a digital voltmeter and digital strain indicator (Herron et al., 1977) or a frequency counter (Carter, 1981). The digital signals coming from the wheel or fuel flow transducers were measured by digital counters (Shelton and Bashford, 1977, Beppler and Shaw, 1980). More sophisticated devices such as a digital data logger (Lyne and Meiring, 1977) and a digital monitor (Summers and Frisby, 1980) have been gradually developed.

Within the past few years, hard wired control logic consisting of IC chips have been replaced by a microcomputer-based data acquisition systems. The term data acquisition has been widely used since the computer began to be applied. According to the Encyclopedia of Computer Science (Van Nostrand Reinhold Co., 1976), a data acquisition system, also called a data collection system, scans digital and analog inputs in an order and at a rate controlled by a program. This reference also defines a data acquisition computer as one used to acquire and analyse data generated by instruments such as voltmeters, thermocouples and electromechanical relays in factories, refineries, missiles or aircraft. Typically data acquisition computers have fast memory-cycle times and short word sizes. Floating points are generally unnecessary, since data are inherently scaled within ranges scaled by the processes under measurement.

A typical microcomputer or single-board computer has a microprocessor IC as a central processing unit (CPU), some read-only-memory (ROM) to hold the program, a random-access-memory (RAM) to hold data, and at least one input/output (I/O) port (Carr, 1982). The data signals are sent to the microcomputer through the interface board which usually carries an analog to digital (A/D) converter and latches to receive data inputs. Displays and a key-board or switches are placed on the panel.

Applying the micro-computer in tractor instrumentation has advantages such as lower hardware cost, small size and flexibility (Wilhelm et al., 1981). The computer also provides a means for an immediate identification of malfunctioning transducers or problems with other system electronic equipment (Luth et al., Wendte and Rozeboom, 1981).

Various kinds of micro-computers have been used for tractor data acquisition systems. They have typically consisted of eight or sixteen-bit microprocessor; memory chips have ranged from 1 kilobyte to more than 64 kilobytes, one or several interface chips, and a data recording unit.

Examples of microcomputers used so far for tractor data acquisition systems are MOS Technology's 6502 (Horter and Kaufman, 1979), Heathkit ET-3400 (Clark and Gillespie, 1979), Campbell Scientific CR5 (Culpepper, 1979), Heathkit H-8 (Lin et al., 1980), Motorola 6802 (Clark and Gillespie, 1982), Rockwell AIM 65 (Grevis-James et al., 1981), Intel iSBC 80/20-4 (Garner et al., 1980), Intel iSBC 80/30, (Hendrick et al., 1981), Intel iSBC 569 (Lambert and Miles, 1981), Apple II (Carnegie et al., 1983), and Digital Equipment Corporation PDP11/03, (Tompkins and Wilheim, 1981, Wilheim et al., 1981). Among these the AIM 65 is one of the more relatively inexpensive ones.

Bedri (1982) designed and built a micro-computer or a large DIP plugboard, in the laboratory, composed of an Intel 8035 single chip microcomputer, an erasable programmable ROM and a display module. Construction required considerable time and it was not less costly than purchasing a commercially manufactured one. It was also relatively unreliable.

Strange et al. (1982) tried not only to collect data but also analyze it in the field. They used a Hewlett Packard (HP-85) desk top type micro-computer.

Reynolds et al. (1982) used two computers. They collected data using a single board micro-computer located in the tractor which was later driven to a van which carried a bigger data processing computer. The data transfer took three to six minutes for a run of fifteen to thirty seconds.

Orme (1976) and Luth et al. (1978) described a big data acquisition system that utilized radio telemetry. Data collected through telemetry were analysed in a trailer and truck. The system on the trailer was divided into two sections; telemetry data acquisition and data reduction. The data reduction section included a Modular Computer Systems ModComp 11/220 mini computer, a Diablo dual hard-disk drive, 48 channel A/D converter, two Tektronix CRT graphic terminals with a hard copy unit, a digital tape recorder. This very advanced instrumentation system cost over $10000.

One of the other important but rather difficult aspects of the data acquisition system is data recording. Speed of data recording is an important consideration; record systems use different approaches. A printer used by Harter and Kaufman

(1979), and Grevis-James et al., (1981) was too slow and did not function well under vibrations. An audio-cassette tape recorder can be used with some of the micro-computers. These are inexpensive and easy to handle except for difficulties of transfering the data collected to a main frame computer as is usually required in data analysis. The procedure requires a special device to convert the data digital format. A digital tape recorder eliminates this complication but is expensive. Some that have been used in tractor instrumentation are a Techtran 8400 (Garner et al., 1980) and Digital Equipment Corporation's TU58 (Tompkins and Wilhelm, 1981). There have been efforts to record data on EPROM, a simple and compact system but one of small memory capacity, (Johnson and Wipperfurth, 1981); (Wiedemann and Cross, 1982). This system has proved convenient only for collection of small amounts of data.

4. MATERIALS AND METHODS

4.1 Three Point Hitch Dynamometer

As indicated in the review of literature three point hitch dynamometers have been developed by attaching strain gages or force transducers to hitch links, implements, tractor bodies or hitch frames. Of these the hitch frame as a dynamometer has been considered the most effective method.

In the original design of the dynamometer described in this study, Chung et al. (1983), in realization of the above considerations, designed a hitch frame dynamometer which would have the following features:

a) Ease of mounting.

b) Ability to measure three dimensional forces

c) Permit the use of a PTO shaft (to run powered implements).

d) Allow easy interchange of implements and tractors.

e) Be suitable for use with a category II three point hitch.

f) Maintain minimum rearward displacement of the implement.

g) Be economical and simple in construction.

4.1.1 Dynamometer Frame

A quick attaching coupler available in the market was chosen as the hitch frame of the dynamometer. This reduced time and cost of construction of the dynamometer. The quick-attaching coupler used was a Category II Jeffers Quick Hitch model J300 (Warrior Manufacturing Company). The coupler was the base for attachment of the beams that supported the force transducers (see Figure 12).

4.1.2 Strain Beam Support

Supports for the transducers were developed and attached at each of the original positions for the tractor links on the coupler frame. On the other end of the supports was a place for attachment of the force transducer. The transducers were to be the new attachement places for the tractor links. Each of the three supports was made out of a 6.4mm thick, 51x102 mm rectangular steel tube (see Figures 12 and 13). On each, two holes were drilled, 28.6mm diameter each, one for the link-attaching pin and the other for the transducer. The link-attaching pins were removed and replaced with 28.6mm diameter and 168mm long heat treated bolts. The bolts were to secure the supports onto the quick coupler frame. About half of one side

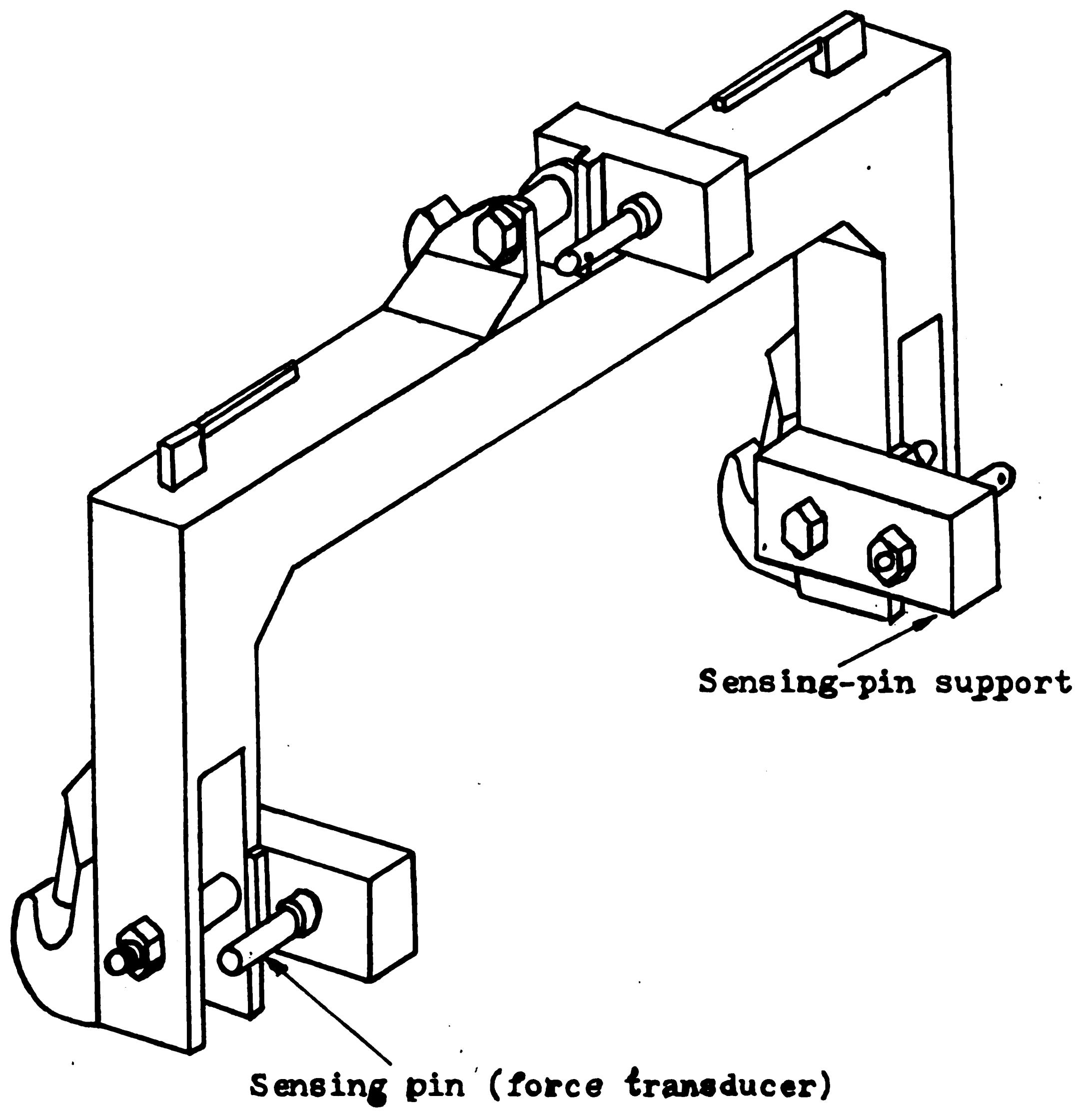


FIGURE 12: Dynamometer assembly drawing

(the side with transducer hole) of the 204mm long tube was then cut for later installation of the sensing pin. On the inside, opposite the cut was welded a 12.7mm thick 105mm long plate. Short thick steel bars were used on the welds to increase strength. Utilizing the original hole as a guide, the newly installed plate was drilled to the same 28.6mm diameter. The cut-out plate had been secured back in place with a C-clamp. Still in place (the plate), concentric to the transducer hole and at a diameter of 72mm two opposite holes 5mm in diameter were made and threaded for screws. These screws would later secure the cut-out plate (as a transducer cover), onto the inside welded plate (see Figure 13). Plates 3mm thick and 51x102mm were welded to the ends of the tube to cover them. To ensure the supports stayed horizontal on the frame structure during tillage operations a collar was welded on the side of the strain beam support lying against the coupler frame structure.

4.1.3 The Force Transducers

The strain beam (sensing pin) was made out of Category II hitch pins manufactured by Highland Manufacturing Company (Cleveland, Ohio). The lower hitch sensing pins were 165mm long and 28.6mm in diameter. The top pin was originally the same size

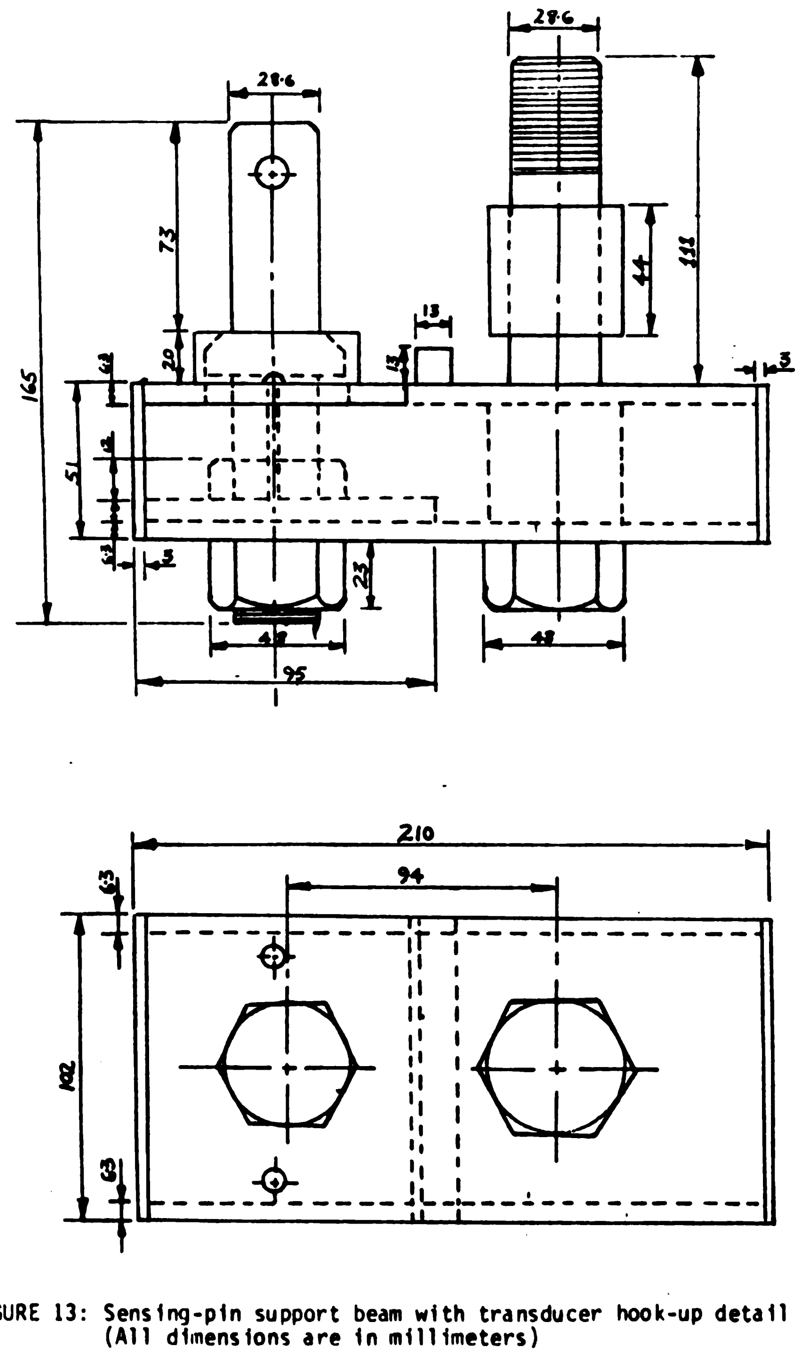


FIGURE 13: Sensing-pin support beam with transducer hook-up detail
(All dimensions are in millimeters)

but the link supporting end was reduced to 25.4mm in diameter to match the top link hole size. All pins had link-support-collars as shown on figure 14.

Strain gages were attached on the smooth surface between the collar and threads. Each of the two lower pins had a total of 8 gages (two Wheatstone Bridges) and the top pin had 4 gages. Each of the lower pins measured vertical and horizontal forces in the vertical longitudinal plate. The top pin measured the horizontal force only. Each complete Wheatstone Bridge made-up a temperature compensated channel. One type of strain gage was used on all pins, the EA-06-125PC-350 (Measurements Group Inc., N.Carolina). It was 5.21mm long and had a dual element pattern with longitudinal grid centerlines spaced 2.16mm apart. It was selected because it is recommended for work on steel transducers and the dual pattern is ideal for bending-beam transducers.

Gages needed to be installed with great care to assure good alignment. After installation, delicate soldering and cleanup, a stability check was made. This was made by attaching the brigdes to a signal conditioner, balancing them for a zero voltage output and leaving them connected for observation of output over a length of time. Bridges that were unstable were resoldered or replaced. Stability of transducers in the form finally used showed a maximum instability of 0.83V over a 27 hour period. This was considered negligible for field tests that would last a maximum of 4 minutes.

The maximum allowable draft of each pin was obtained using the equation:

$$F = \pi d^3 Y / 32L$$

where F = draft (N)

d = diameter of pin (28.6mm)

Y = yield strength of pin (365MPa-AISI cold drawn

steel)

L = effective length of cantilever (distance

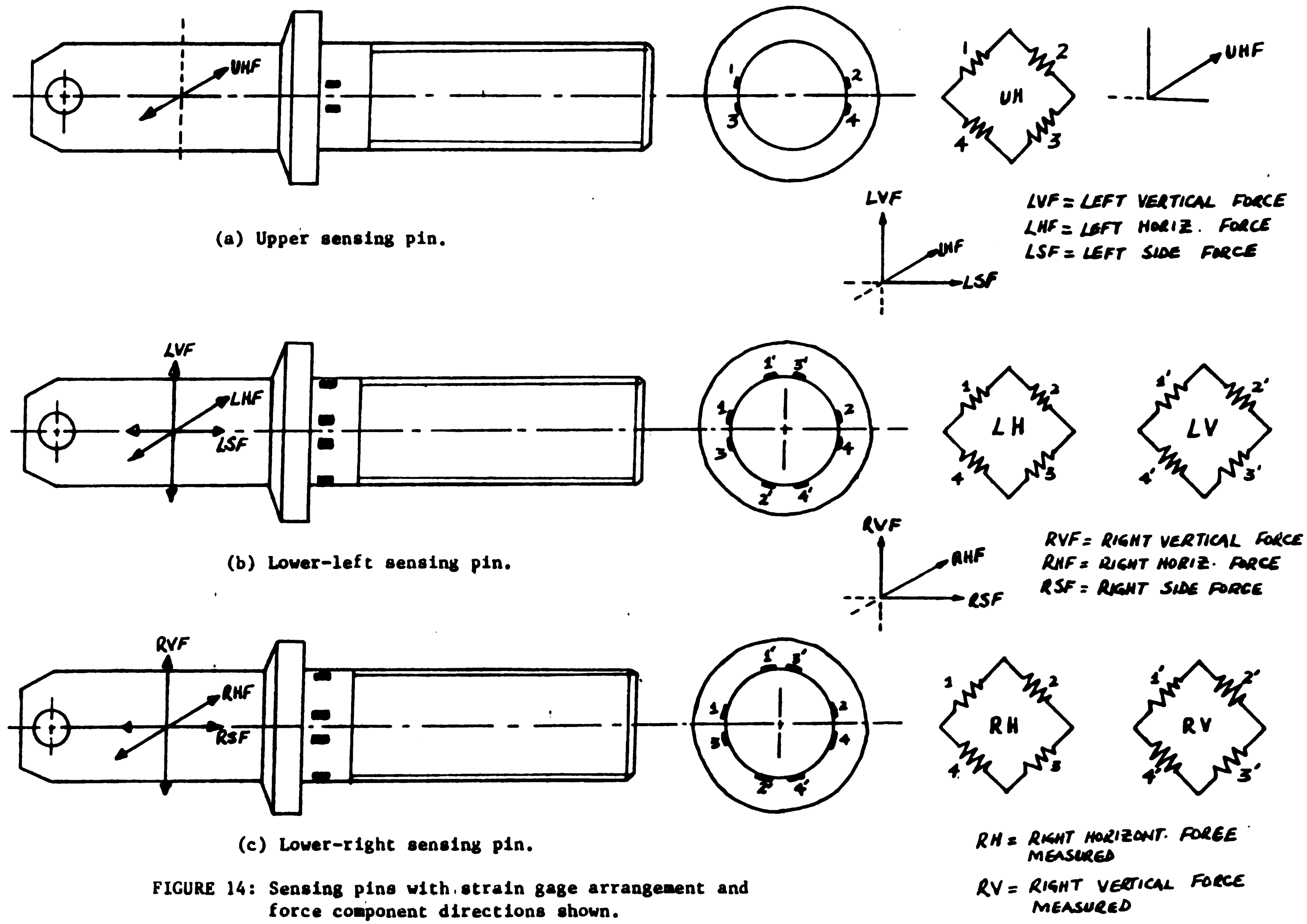
between edge of support and center of tractor link on the

surface of the pin)

When the effective length of 54.3mm was applied the maximum draft force of 15442N was calculated for each pin.

The sensing pins were held on their supports by a half nut on the inside of the supports, tightened against a full nut on the outside (see Figure 12 and 13). Some holes were made on the supports for signal cables to pass through to the signal conditioners.

In the transducer making process, strain gages were attached using M-Bond 200 cement



(a) Upper sensing pin.

(b) Lower-left sensing pin.

(c) Lower-right sensing pin.

FIGURE 14: Sensing pins with strain gage arrangement and force component directions shown.

(Measurements Group Inc.). Fine wire was used for making eletric circuit connections between gages. These fine wires ended up at terminals where they met larger conductors that continued the circuitry. The larger conductors were those from the shielded-four-conductor, insulated cable which supplied excitation voltage and carried output signals to signal conditioners. The cable was firmly held against the sensing pin with a hose clamp safeguarding the delicate wiring from damage by any possible external pull. Each of these cables constituted a channel. On its other end the cable's conductors were each soldered to the inner end of the pins of a 5-pin Amphenol terminal connector. The cable's shielding made the conductor for the fifth pin. It is this connector that plugged into the female connectors at the back of the signal conditioner composing a channel.

Strain gages and the delicate wiring were protected and secured from the surroundings by a thick coat of silicon rubber. This water, shock and heat resistant substance also kept dust and chemicals away from the gages. It also pealed off easily for rechecking circuitry after hardware failures and for other needs.

4.2 The Data Acquisition System

The data acquisition system consisted of the strain gage circuitry, signal conditioners, interface box, a data acquisition control unit (HP3497A) and the central command and control unit, the HP85 microcomputer (see Figure 15). Power supply to run the system was obtained from the tractor battery through a 12V DC - 120VAC power inverter (Vanner Inc., Columbus, Ohio).

4.2.1 The Signal Conditioners

Two units were used each capable of handling four channels. Each channel was composed of a card (module) plugged into a mainframe. The card had an amplifier, Wheatstone bridge circuit completion (1/4, 1/2 or full bridge) resistors and balancing circuitry. A power supply of a well regulated 0, 5 or 10V was available for strain gage excitation. The mainframe front panel had a voltage output readout display, calibration references and knobs for adjusting sensitivity, voltage supply and bridge-type selection. Each channel could be programmed individually with a choice of fine or coarse balancing.

The amplified output analog signal leaving the conditioner was directed into an interface box which was labeled to assist channel numbering. The signal conditioner units measured about 25x25x30cm

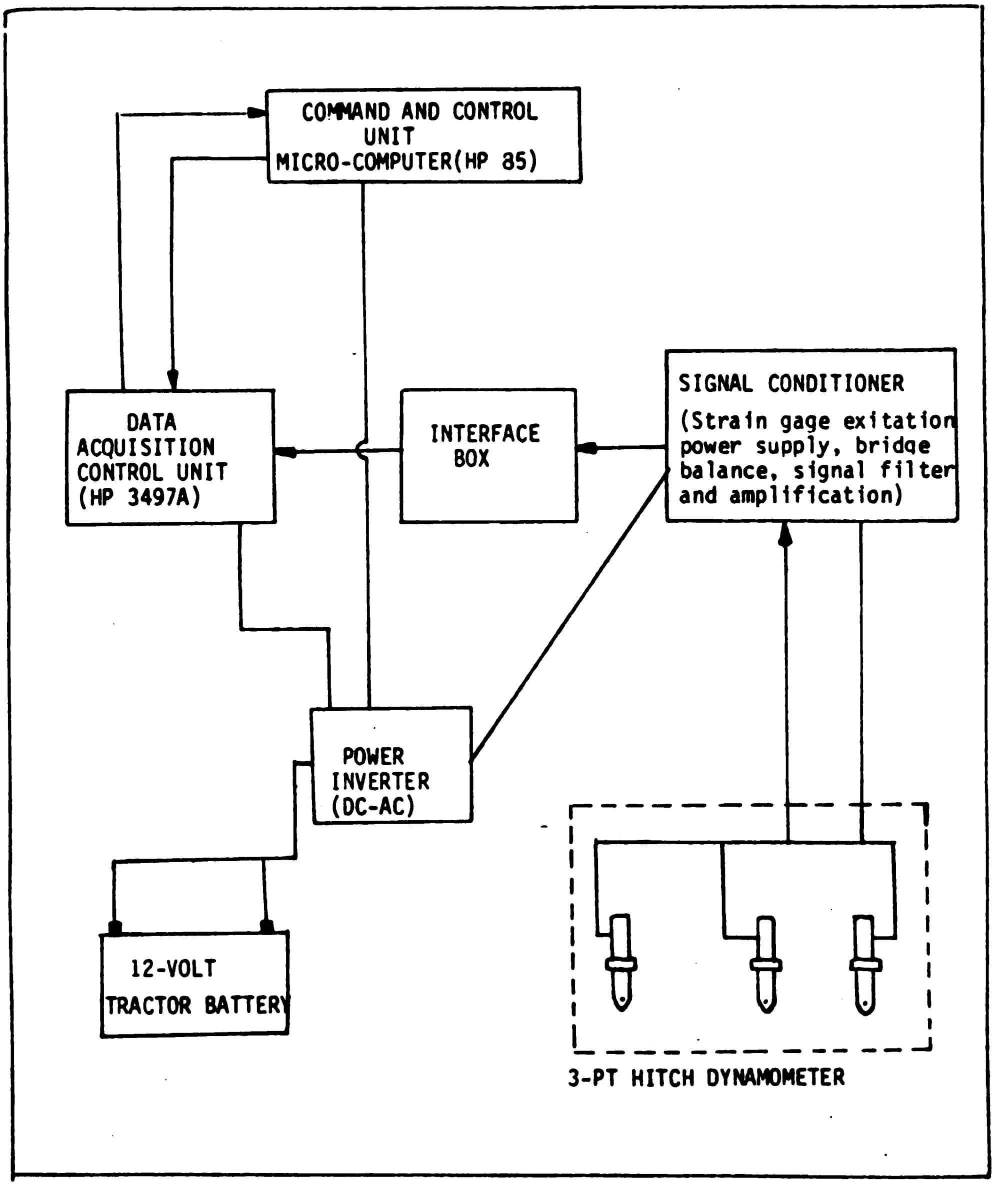


FIGURE 15: Schematic of microprocessor-based data acquisition system for tractor tillage forces.

each. The signal conditioners had a maximum full bridge input of 0.1V, and a maximum DC input of 10V. They had a maximum allowable input overload voltage of ± 15V, maximum usable output load of 10ma (10V @ 1k load) an input impedance of 200 MEG. OHMS and a maximum usable excitation current of 100ma. Their frequency response was -3 db @ 10 kHz.

4.2.2 The Data Acquisition Control Unit

The analog signals from all channels interfaced travelled in one coaxial cable into the Data acquisition Conrol Unit (HP3497A, Hewlett Packard Inc.) The unit consisted of a mainframe which provided interfacing power supplies and support structure for optional plug-in cards and assemblies. It had an Outguard Controller capable of receiving instructions via front panel and/or the remote control interface. Instructions decoded into binary format became useable by the Inguard Controller and plug-in cards. Information returning from these areas was encoded into data suitable for output to the front panel display or remote control interface.

Other interfaced parts included the timer which had date options, timer interval (for slow paced 24 hour range scan sequences) timer output (fast scan 100 micro second and 1 second (± 0.1s) and an internal voltmeter.

An Interface Bus Address Switch inside the unit selected "talk" and "listen" address, which made a two way communication possible with remote control interface. The HP3497A measured about 429 widex521 deepx191mm high with a maximum weight of 20.4kg (45lb). It was capable of accepting upto 20 different transducer outputs.

4.2.3 The Central Command Unit

The central command unit consisted of a microcomputer, the HP85 (Hewlett Packard Inc.). A data acquisition program written in BASIC language controlled the whole sampling, analyzing storage and retrieval of data.

The HP85 had a CRT display, printer, tape drive, keyboard and room at the back for plug-in modules. The keyboard consisted in part of a typewriter keyboard, display control keys, 8 special function keys (user defined), system command, numeric and program control keys. Plug-in modules were the HP-Interface, 16 kilobyte extra memory module, ROM (Read Only Memory) drawer and plotter/printer ROM. The unit measured about 400mm wide 160mm high and 500mm deep.

4.2.4 The Power Supply

In the use of micro computers and other components of a data acquisition system to obtain farm-tractor performace data, electric power can be a critical consideration. Generators have been used in many such applications but they have not been the most reliable, portable or convenient power source. Vanner Corporation (Columbus, Ohio) has developed a sinusoidal voltage inverter that was used in this study. The Vanner (Model 20-500) 12 VDC-120 VAC, 60 Hz, 500 Watt sinusoidal voltage inverter measured 22x24x40cm, weighed about 7kg and was therefore very convenient for use on the tractor. Input power for the inverter was obtained from the battery posts on the tractor to which the inverter was connected. An earlier test of the inverter showed its no-load output voltage to be 120.8 VAC with a voltage spike at points of maxima and minima in the output waveform. Frequency was contant at 60 Hz with and without load. At intervals between field-tests tractor engine idle was kept high to maintain the necessary tractor battery charging capacity. With a tractor battery that was in a relatively good condition, this inverter proved a very reliable power source even for the delicate computer hardware. The inverter had two outlet power sockets and a circuit breaker switch which always had to be turned off before the tractor engie was stopped. The unit also had a plug-in remote switch.

4.3 Theoretical Considerations

In recent years there has been a great increase in the use of digital computers and special-purpose digital circuitry for performing varied signal processing functions that were originally achieved with analog equipment.

Stanley et al. (1979) define an analog signal as a function defined over a continuous range of time and in which the amplitude may assume a continuous range of values. The same reference defines a digital signal as a function in which both amplitude and time are quantized (may assume only distinct values). The process by which an analog sample is quantized and converted to a binary number is called analog to digital (A/D) conversion. In general, the dynamic range of signal must be compatible with that of the A/D converter employed and the number of bits employed must be sufficient for the required accuracy.

In the A/D conversion the signal is sampled only at discrete intervals of time and the fundamental question is whether something might be missed in the intervening time intervals. In sampling, if the sampling rate is greater than or equal to twice the highest frequency, the signal can theoretically be recovered from its discrete samples.

$$f_s \geqslant 2f_h$$

where f_s = sampling rate

f_h = highest frequency in spectrum (Nyquist frequency)

$2f_h$ = minimum sampling theoretical rate (Nyquist rate)

This corresponds to a minimum of two samples per cycle at the highest frequency (Stanley et al., 1979).

If a signal is not sampled at a sufficiently high rate a phenomenon known as aliasing results. This concept results in a frequency's being mistaken for an entirely different frequency upon recoverly. Given a set of sampled values we cannot relate them specifically to one unique signal. If the incoming signal content is restricted to frequency components less than

$$f_o = f_s / 2$$

then no errors due to aliasing are possible. Ideally therefore the input signal spectrum should not extend beyond f_o:

$$\text{i.e. } f_N \leqslant f_o$$

or $f_N \leqslant f_s / 2$

or $f_N \leqslant 1 / 2T$

where f_N = frequency of highest spectral component

T = sampling interval

The signal from the tillage operation is expected to have a relatively low frequency. It is also of a very random nature, (have a wide spectrum) and might therefore be difficult to filter in attempting to hold f_s at a specific value without losing part of the wanted signal. Also if a signal-plus-noise spectrum is sampled, even though the spectrum of signal contains no frequency component above f_h , the noise contribution may have them, resulting in a broadening of the sample-wave spectrum and a creation of significant errors.

With no knowledge of the highest desired frequency, appropriate sampling interval for the tillage operation cannot be computed. In this study, f_s was selected dependent on memory space available in the micro-computer. A sampling rate of 5Hz was used. This would require f_N to have a value of at most 2.5Hz.

As discussed above, at this relatively low sampling frequency there is a chance of aliasing. With the lack of knowledge of nature of f_N, in this study, a test was made to search for a more severe error, that due to presence of a noise signal.

4.3.1 Resolution and Accuracy of Measurement

The force measurement error resulting from the analog to digital signal modification depends on the number of bytes used in the converter. In this study an 8-bit converter was used. The output range was 0 - 10 Volts.

Resolution of an Analog to Digital Converter (A/D) is an expression of the smallest change in input which will increment (or decrement) the output from one code (000, 001, 010, 011 etc. on Binary scale) to the next adjacent code. It is defined as the number of bits or 1 part in 2 . As mentioned above, the A/D used in this study had a 1 part in 256 resolution (0.3663%). Quantization Uncertainty is a direct consequence of the resolution of the converter. Since all analog voltages within a given range are represented by a single digital output code there's an inherent conversion error. If the midpoint of the range is assumed to be the nominal value, there's an Uncertainty of ±1/2 LSB (Least Significant Bit). It is common practice to offset the converter 1/2LSB in order to reduce the Uncertainty to ±1/2 LSB. Quantization Uncertainty is expressed as ±1/2

LSB or as an error percentage of full scale (+0.1832% FS in the case of this study).

The error in this study was therefore ±0.001832 * 10 = ±0.01832V. In this study the sensitivity was adjusted to give a maximum output of 7V. A maximum output reading of 7V therefore would actually have a range (7 ± 0.018)V.

During calibration the load measuring dial was analog and had divisions of 445N (100lb) and could therefore be read within a ±223N (50lb) error.

The largest calibration factor encountered was 3626 N/V. With reading error incorporated this was (3626 ± 223)N/V. Therefore the force output of:

$$(7 \pm 0.018)V * (3626 \pm 223)N/V$$

has maximum error:

$$[(7.018 * 3849) - (7 * 3626)] / (7 * 3626) = 0.0623 = 6.23\%$$

The smallest change in load that the dynamometer would sense in the 10V range was 0.018V equivalent. For a calibration factor of 3626N/V this is equivalent to 65.27N (290lb). At the maximum load producing 7V (25382N), 65.27N is 0.26% (of maximum load).

4.3.2 Force Components Measured and Circuit Analysis

The resultant draft force between a tractor and implement has three components when a side force exists. Part of the horizontal and the whole of the vertical force components in a longitudinal plane were measured by the lower transducers. The upper transducer measured the remaining fraction of the horizontal force. The strain gage arrangement (to make the wheatstone bridge and circuitry determines which force component is sensed by which bridge (see Figures 14 and 16) The total horizontal and total vertical forces were obtained by summing the fractions measured by the various transducers. It is therefore desirable that the bridge measuring horizontal force does not sense the vertical force and vice versa.

The basic circuit used with the metal variable-resistance strain gages is the four arm bridge (see Figure 16) with constant voltage power supply.

Potential drop across the diagonal b-d is originally equal to zero for the balanced bridge.

It can be shown easily that for a balanced bridge:

$$R_1 / R_2 = R_4 / R_3 \quad \cdots\cdots(1)$$

For a change in potential across the diagonal b-d (dE_{bd}) due to small changes in R_1 (dR_1) R_4 and R_3 remain constant and the potential at point d is unchanged. Current flow through R_1 is:

$$I_1 = E / (R_1 + R_2) \quad \cdots\cdots(2)$$

and potential drop across R_1 is:

$$E_{ab} = I_1 R_1 = ER_1 / (R_1 + R_2) \quad \cdots\cdots\cdots(3)$$

Change in E_{ab} due to small changes in R_1 may be determined by differentiation:

$$dE_{ab} = R_2 dR_1 E / (R_2 + R_1)^2 \quad \cdots\cdots(4)$$

Since $E_b = E_d$ at balance and E_d remains constant, the difference between b and d due to dR_1 is equal to the change in potential of b and the change in potential at b is equal to the change across ab since potential at a remains constant:

$$E_{bd} = E_d - (E_b + dE_b) = -dE_b = -dE_{ab}$$

$$E = - R_2 dR_1 \, E \, / \, (R_2 + R_1)^2 \quad \text{.............(5)}$$

Using the same approach the equation can be written for changes in R_2, R_3 and R_4 If R_1, R_2, R_3 and R_4 undergo small changes simultaneously due to temperature change or load, the total effect on E_{bd} is the sum of these effects:

$$E_{bd} = \left[\frac{-R_2 dR_1}{(R_1+R_2)^2} + \frac{R_1 dR_2}{(R_1+R_2)^2} - \frac{R_4 dR_3}{(R_3+R_4)^2} + \frac{R_3 dR_4}{(R_3+R_2)^2} \right] E \quad \text{...(6)}$$

By substituting the definition of gage factor:

$$F = (dR / R) / \epsilon \quad \text{................(7)}$$

and considering the bridge circuit is made up using equal resistance strain gages:

$$R_g = R_1 = R_2 = R_3 = R_4$$

$$E_{bd} = (FE / 4) \, (- \epsilon_1 + \epsilon_2 - \epsilon_3 + \epsilon_4) \quad \text{....(8)}$$

$$= (FE / 4) \epsilon_{net} \quad \text{..............(9)}$$

From the above analysis it can be concluded that the imbalance of the bridge E_{bd} is proportional to the sum of strain (or resistance) changes in opposite arms and to the difference of strain (or resistance) changes in adjacent arms.

A temperature change will produce a strain ϵ_T on all four gages. A look at equation (8) will show that the overall effect on E_{bd} will be zero. Therefore the 4-arm bridge is fully temperature compensated.

A look at Figure 14 will show that a force LS (on the lower left sensing pin for example) will cause equal strain on all four gages. The effect of this load will therefore not unbalance the bridge. The force component LV will cause the same strain on all four gages 1, 2, 3 and 4 and will therefore not be measured. The same force (LV - vertically downwards) will cause a tensile strain on gages 2' and 4' while producing a compressible strain on gages 1' and 3'. Applying equation (8) and assuming all strains on the individual gages are equal;

$$\epsilon_{net} = \epsilon_{2'} + \epsilon_{4'} - (-\epsilon_{1'}) - (-\epsilon_{3'})$$

$$= 4\epsilon$$

where $\epsilon = \epsilon_{1'} = \epsilon_{2'} = \epsilon_{3'} = \epsilon_{4'}$

If strain gages are improperly placed equation (9) does not hold, in which case gages 1, 2, 3 and 4 will sense some of the load LV (cross-sensitivity).

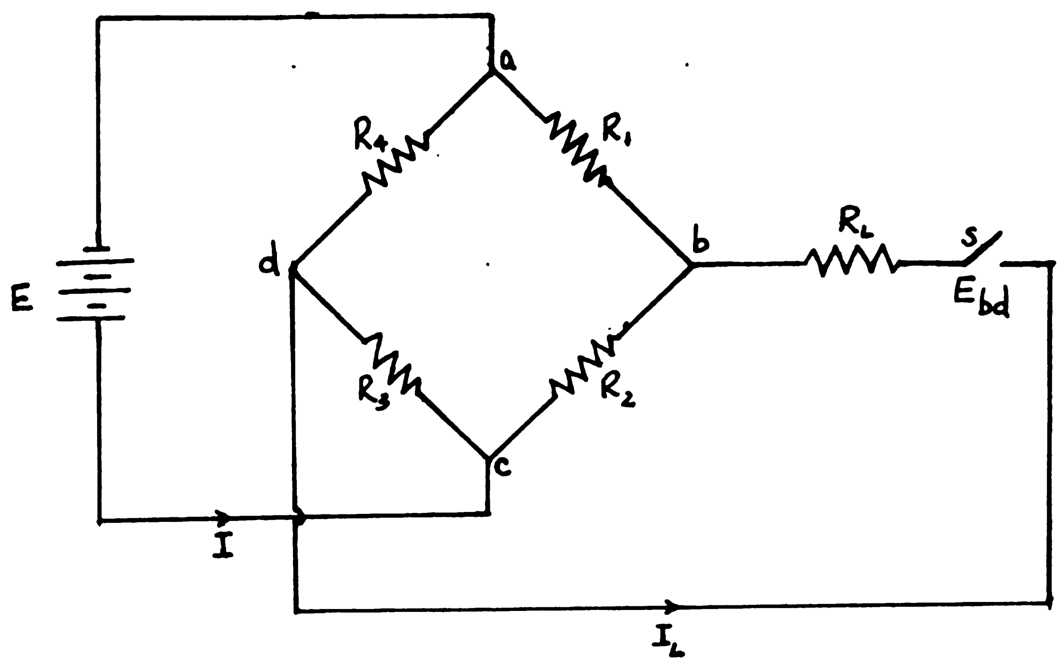


FIGURE 16: Strain Gage Circuitry (Wheatstone Bridge)

4.4 System Configuration

For both calibration and field tests, the whole data acquisition system and three point hitch dynamometer system were fully mounted on the tractor. The signal conditioners, data acquisition unit and microcomputer were carried on specially cushioned wooden structures and held in place with rubber straps. The computer and data acquisition unit was positioned on the operator's left side while the signal conditioners were on the right side, directly above the rear wheels. For these units to fit properly, tractor side-windows had to be kept open. Polythene sheeting was used to cover over the open windows - this kept dust, rain and mud out of the tractor. Continuity between the left and right-placed components was maintained through cables connected to the interface box which was secured on the window glass behind the operator. Signal cables from the transducers were held together in a bunch with tape and then directed through the slightly open back window for connection to the signal conditioners.

Power supply cables leaving the tractor battery were bundled with those on the input side of the power inverter. The power inverter was positioned on the tractor floor under the operator's legs. A single cable leaving one of the plug-in positions on the inverter directed power to a socket box to which the various data acquisition system units' power cords were connected (see Figure 15). The whole data acquisition system could be operated by one person, who also operated the tractor during a typical field test. However, if external data like slippage or fuel consumption data was required, then a second person was necessary.

4.5 The Computer Program and Data Acquisition Procedure

Computer programs for data collection, analysis and storage were written in BASIC (see Appendix). It is apparent from the flow diagram shown in Figure 17, that five of the eight available specially defined soft keys were utilized in controlling the various data collection operations. Before each run, whether in calibration, verification or field test, the channels were balanced to read zero voltage. However in the event of a shift from zero, resulting off-zero readings were sampled and averaged so as to be subtracted later from the readings obtained.

Soft key No.1 was pressed whenever the operator was ready to start data sampling while key No.2 was pressed to stop data sampling for whatever reason. On pressing key No.2 all data obtained at a

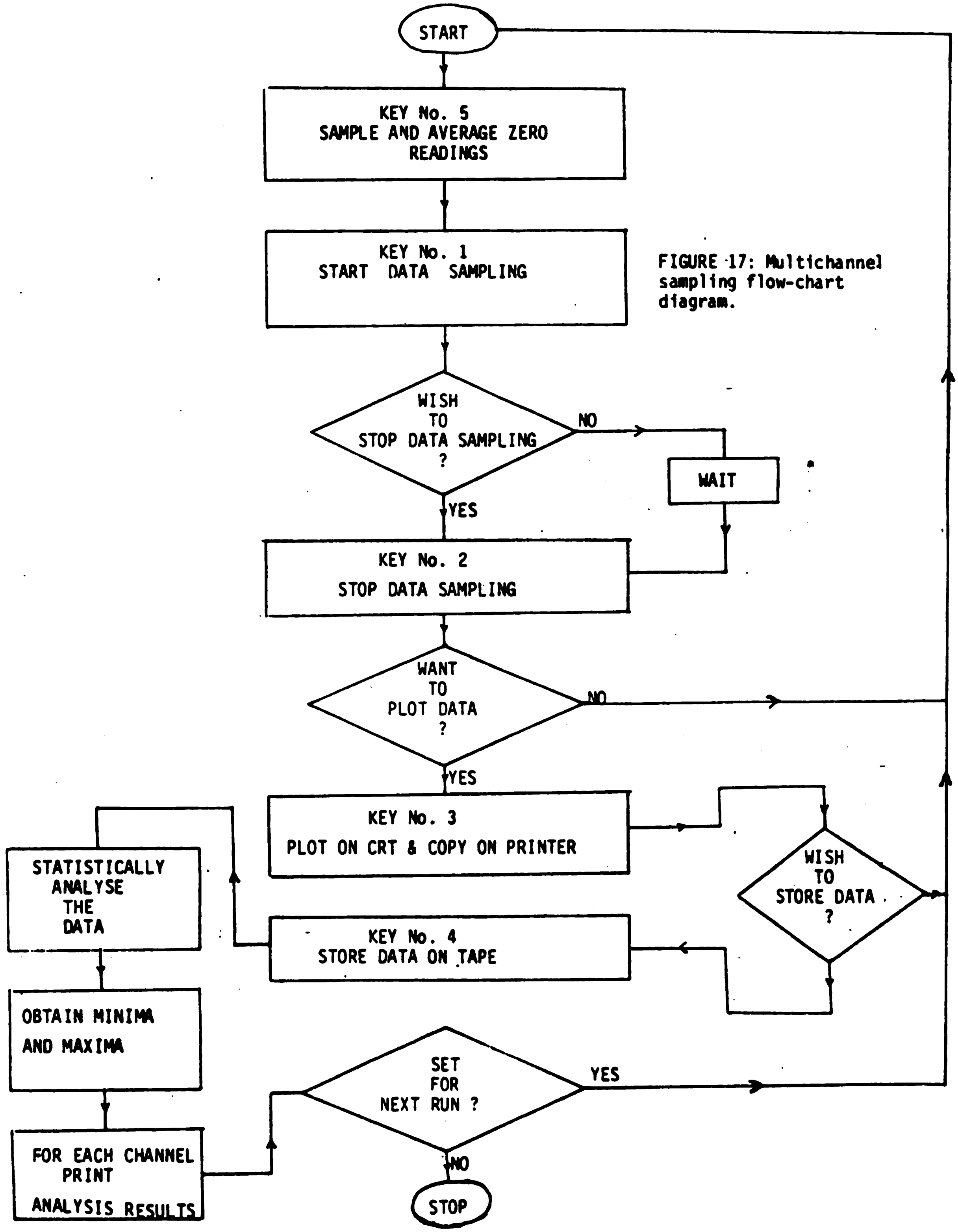


FIGURE 17: Multichannel sampling flow-chart diagram.

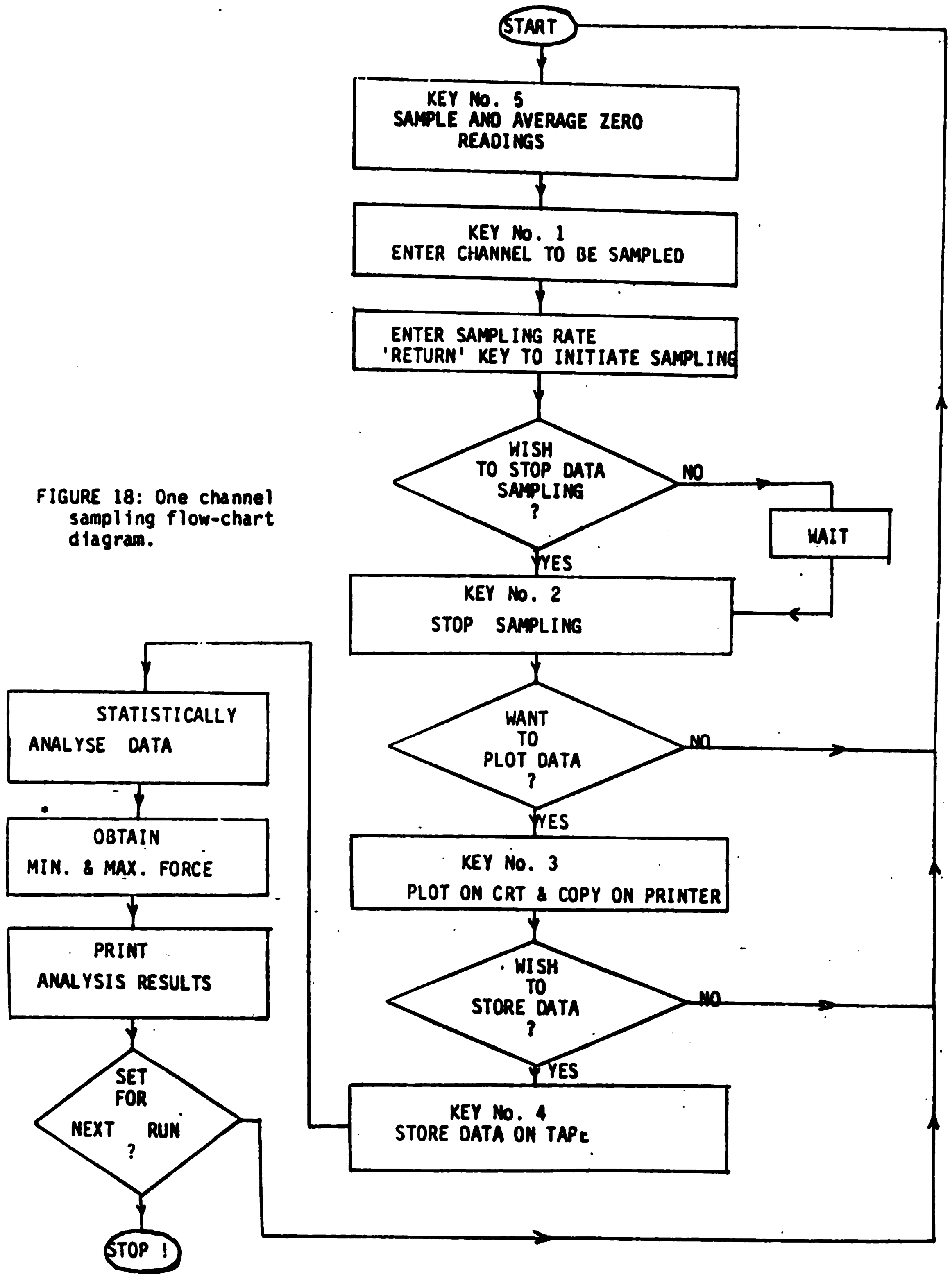


FIGURE 18: One channel sampling flow-chart diagram.

given time t from all channels measuring horizontal force were summed. The same occured for data from channels measuring vertical forces at time t, t+ t, t+2 t etc. This added an additional two arrays of data for storage to the other five, (three for horizontal force and two for vertical force). To check the nature of data collected, and utilizing key No.3, a plot was made (force vs time), for each channel, sum of horizontal and sum of vertical forces. After a look at the plots a decision was made on whether to store and analyze the data. To store the data, key No.4 was pressed. The statistical analysis to obtain the mean, standard deviation and coefficient of variation for each channel's sampled data was done in a subroutine. This analysis was also done for total horizontal and total vertical force. In a second subroutine the minimum and maximum obtained readings were sorted out. This was done for each channel, and for the total horizontal and total vertical force. A printout of results was obtained. It was important that data were stored before sorting it for minimum and maximum values. This was because the sorting process left data in order of size from smallest to largest and it might have been necessary to reproduce a run at a later time. Storage was done on a tape catridge and after this the memory was cleared for another run.

Two separate data acquisition programs were used (see Appendix). The multichannel sampling program (see Figure 17) sampled 5 readings per second for five channels simultaneously at a given time t. At this rate a four and half minute typical field-test run could be made before the available memory was filled. The single-channel sampling program (see Figure 18) was developed to check the nature of data obtained with a variety of data sampling speeds, equal or higher than the standard 5 readings per second of the multichannel program. Sampling speeds upto a sample every 0.1ms (maximum possible) were tried with the single channel sampling program. At these higher sampling speeds the number of channels sampled needed to be reduced, in order that the available 32k memory space was sufficient. Hence the single channel program.

4.6 System Calibration

The calibration process required application of forces on the various transducers individually. Forces and the Wheatstone bridge imbalance voltages they produced were recorded and plots of force vs voltage (calibration curves) were made (see Figures 23 to 25). The gradients of these graphs (F Newtons/Volt) were the calibration factors, (different for different channels) used in the data acquisition computer program. Draft forces measured were obtained from the equation:

$$P \text{ (Newton)} = F \text{ (Newton / Volt)} * (V - Z)$$

Volts

where P = Force to be measured

F = calibration factor

V = resulting off-balance voltage

Z = zero-balance voltage

During calibration the pin sensitivity was adjusted using the signal conditioner sensitivity resistors. Sensitivity for each channel was adjusted to give an output reading of about 6 to 7V (60 to 70%) at maximum expected operation load. The 0 to 10 output range was used , with a 10V steady strain gage excitation voltage. After optimal sensitivity setting, the sensitivity and calibration-resistor voltage readings were recorded for each channel. Before each test process these values would then be reset for reproducibility of operation along original calibration curves. The calibration resistor voltage output readings also helped check on possible acquired permanent strain (hysteresis) on gages due to yield or repositioning of the sensing pins under load. Quick system checks for shifts in original calibration were possible even between tillage operation runs during field tests.

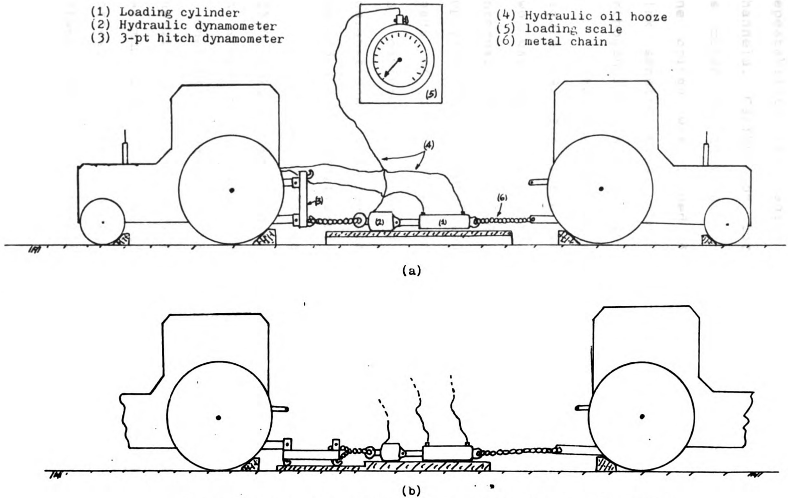


FIGURE 19: Calibration loading set-up (a) -simulation of horizontal force
(b) -simulation of vertical force

A test on effect of hysteresis on repeatability of loading curves was made for all channels. Calibration forces were applied in a line as close to horizontal as practically possible. As one bridge was loaded during calibration of lower link sensing pins, the effect of the load on the orthogonally placed bridge was monitored.

The loading mechanism was set-up as shown on Figure 19. The force was applied by a retracting a two way hydraulic cylinder. The cylinder had a 7.6cm internal and 3.2cm rod diameter and was capable of applying forces upto 45000N during retraction. At loads of magnitude within the range 0 to 17000N used in calibration, leakage around the piston was insignificant and reasonably steady loads could be applied over a significant period of time.

Each sensor-pin was loaded to at least 15568N (3500 lb), in each loading direction. The loading was in steps ranging from 890N (200lb) to 2670N (600lb). A Chatillon hydraulic tensiometer, type HLC (John Chatillon and Sons, New York), capable of handling a maximum load of 44482N (10000 lb),was used to measure forces. The tensiometer was put in the loading-line between the loading cylinder and sensing-pin.

Chains were used to couple the loading-mechanism together. Heavy blocks of wood placed behind tractor wheels and locked parking brakes, together with tractor static weight, supplied the required resistance to pull effectively. The loading cylinder was remotely operated with oil from the tractors internal hydraulic oil reservoir. Readings of the load force magnitudes were obtained on an analog scale coupled to the tensiometer by a hydraulic hose. At the adaptor joining the hydraulic hose there was a dampening valve which was utilized in adjusting scale-arrow speed of response.

θ: Loading angle*
VF: Vertical component (bidirectional)
HF: Horizontal component
R: Resultant force
(Applied load)

* see Fig. 20

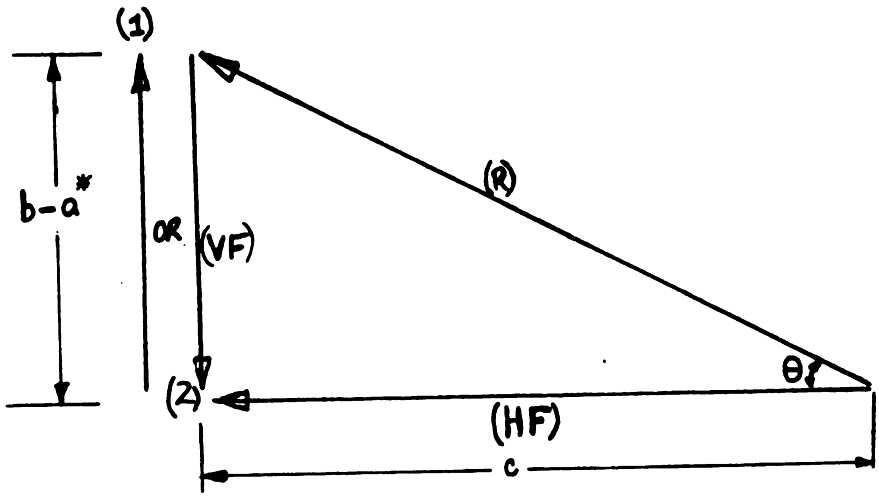


FIGURE 21: Vector diagram for verification force

4.7 System Verification

The calibration process produced data in form of forces and the imbalance voltages they produced. Plots of these data produced calibration curves (straight lines through the origin) whose gradients were calibration factors F (N/Volt). The calibration factors were incorporated into the computer program.

At this point, the program was ready to control a field test run. However, to be sure measured forces were correct verification tests were necssary.

With signal conditioners set at original sensitivities and bridges balanced, a single line pull was made on the three point hitch dynamometer (see Figure 20). The program was run sampling the voltages produced on all channels. Summations of vertical and horizontal forces were carried out and their listings printed out. As the loading took place, a visual monitor of the load applied was made and recorded. This was displayed on the Chatillon tensiometer scale. Comparisons of applied and sampled loads were made.

The computer printout of loads separated horizontal and vertical loads, the resultant of which was load R (as read on the tensiometer scale- see Figure 21). Figure 21 is a force triangle derived from figure 20. (R) was the applied load of which the computer sampled the magnitude of horizontal and vertical components separately. The vertical component was bidirectional and could have been positive or negative depending on (R). The loading angle was approximated by measuring distances a, b, and c shown on Figure 20. Then the horizontal and vertical loads could be computed (components of (R)) and compared to those on the computer output as a verification check. Vertical forces in the direction of vector (2) (see Figure 21) were sampled as negative while those in direction of vector (1) (same load direction as used in calibration), came out positive.

During verification, loads were raised consecutively in increments from zero to forces varying in magnitude between 2224N (500lb) and 30136N (7000lb). Before each consecutive loading, the force was allowed to drop back to zero. Meanwhile plots and data storage of the current loading were made. The chain used to load the system was adjusted so that the relatively large verification forces were evenly distributed between the two lower pins and that only about 20% of the load was carried by the top-link pin.

After the verification process the sensing pins were recalibrated - a check on possibly attained permanent strain. The recalibration was done by switching the calibration-resistor (switch S on

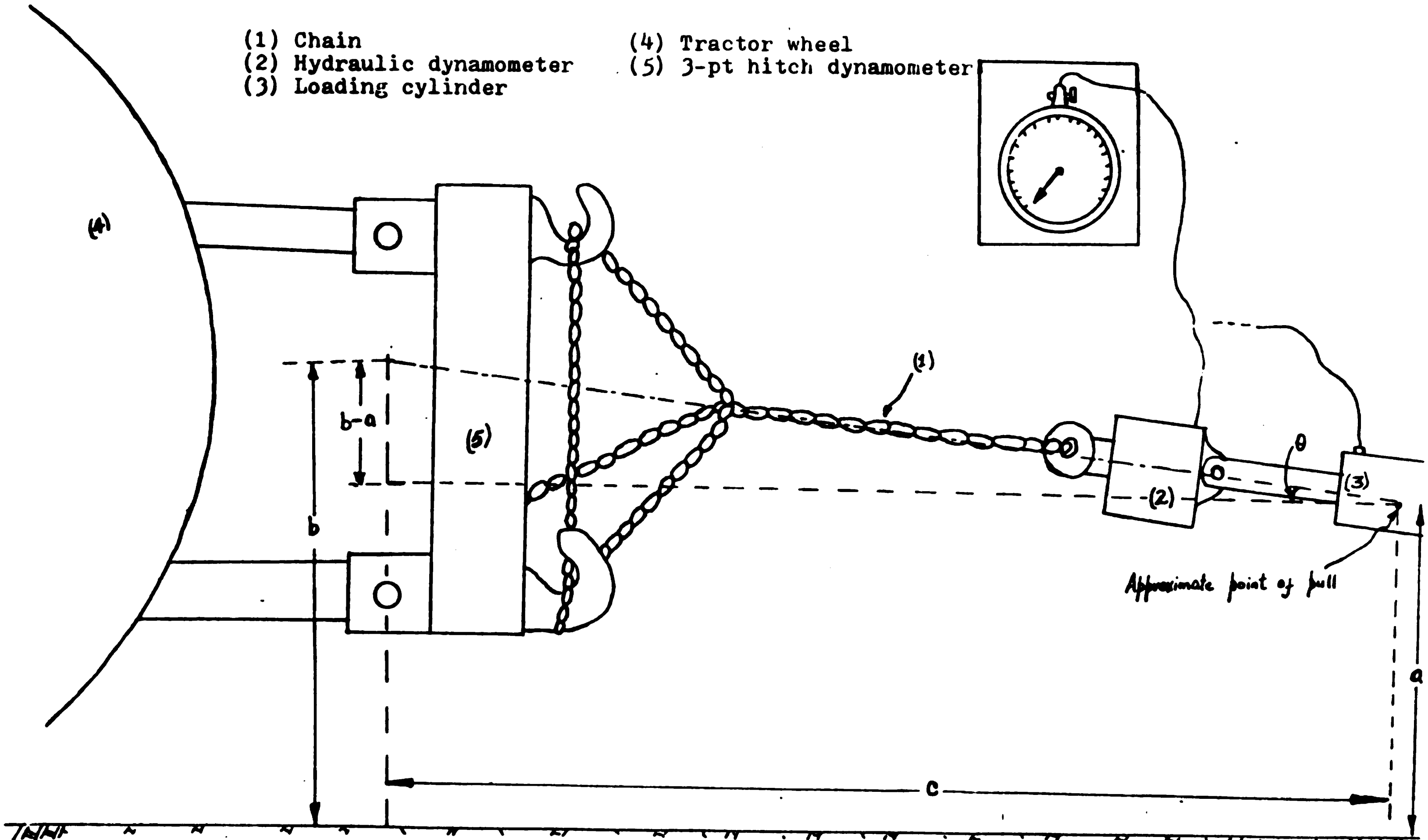


FIGURE 20: Verification dynamometer loading hook-up.

Figure 16) into the circuit and comparing the output voltage displayed to that recorded during the calibration process. With the loading mechanism used, it was not possible to simulate the expected tillage shock loads. This was because the hydraulic loading cylinder could only retract at a uniform and relatively slow rate.

FIGURE 22: Recording-penetrometer probe (seen being forced steadily into the ground)

4.8 Field Tests

The verified data acquisition system was assembled on a Ford 8700 tractor, ready for field work. Tractor windows and force transducers were carefully covered with polythene sheets. The transducers were also covered as added protection against rain and water finding their way through the silicon rubber coating, onto the delicate strain gage wiring.

Field tests made in the middle of summer were arranged to be done in the early morning and late afternoon. Temperatures at these times were bearable and safe for the data acquisition system which operated in a non-airconditioned cab.

Any hardware failures that required the disassembling of sensing pins and a gage reinstallation, required a recalibration and reverification. A reassembled pin required a series of at least six "load and unload" operations. This eliminated the obvious hysteresis and as the pin was retightened it showed a better repeatability of output signal for the same load.

The most satisfactory test results were obtained in early fall 1984. When conditions were similar to those in mid-Summer 1984, the data acquisition system never showed any weaknesses as a result of dusty conditions or mid-summer temperatures. As with any new system, "bugs" had to be worked out. In the absence of the Vanner power inverter, at one point, a gasoline generator was used as the power source. This operated the system satisfactorily until some mechanical failure caused it to stall. The stalling reduced the voltage supply causing the computer to draw excessive current resulting in considerable damage. This re-enforced the need for dependable power supply. During the course of the field tests, several hardware failures on the dynamometer occured, which were rectified as they took place. The most severe one was a deformation of the top pin support beam. This occured as a result of excessive load on the top sensing-pin during implement transportation between test runs. The pin was not damaged but its support was deformed.

A relatively level field was selected for field tests. It had been left fallow for a year. The soil was a sandy loam type and a 15 to 80cm growth of grass and other weeds was growing on it at the time of the test (whose data is reported here). The growth did not cause much implement clogging as the first implement tested was a moldboard plow.

Field work was carried out to observe and study the reliability and capabilities of the developed system. Draft maesurements with two different tillage implements, a 3-bottom White moldboard plow and a cultivator were made. Data were also obtained on distribution of moisture, penetrating pressure and tillage depth along the length of the 20mx100m selected portion of the field which was used for the testing.

Soil moisture samples were obtained using a cylindrical cone sampler. Samples were taken at an approximate depth of 5 to 9cm, below the soil surface. Penetrating pressure measurements were made close to the same randomly selected spots where moisture samples were taken. A recording soil penetrometer developed by Robertson L.S. and Hansen C.M. (Departments of Crops and Soil Science and Agricultural Engineering, Michigan State University, 1950) was utilized (see Figure 22). This mechanically actuated functional instrument of adequate performance was considered accurate within 9%. The penetrometer results were made up of the pressure required to force a selected probe into a soil, recorded on the abcissa of a graph whose ordinate was the depth penetrated by the probe. Four probes of various sizes were available and the one used depended on the soil conditions. The graph chart was standardized from calibration and factors for penetrating pressure were supplied for the various probes.

In determining the complete data acquisition system's limitations, error sources and generally to observe performance, areas of particular interest were:

a) Draft force distribution between the three tranducers as affected by type of implement and tillage depth.

b) Influence of moisture content and penetrating pressure on draft magnitude and distribution.

c) Possible electrical noise generation by tractor tillage operation or surroundings.

d) General reliability of the system hardware and ability to maintain calibration and repeatability.

4.8.1 Test Procedure

The tillage plot was divided along its length into five sections each 20m long and 6m wide. An additional five sections were measured parallel to the first five. In each section four soil samples were randomly taken. Close to the spots where these samples were obtained, penetrometer measurements were also made. The tillage operation was done along the length of the plot, one section at a time.

After an implement was attached to the three point hitch dynamometer the, various channels were balanced and calibration resistor voltages checked. This was done with the implement lowered to the ground surface. The system was then ready for a test-run.

The White moldboard plow's cross shaft needed some adjustment to fit properly on the lower hitching points of the dynamometer. The adjustment was necessary because of the shaft's offset design. Also, to avoid any play of the shaft fit to the dynamometer, the implement hitch pins were fitted with adaptors for both lower hitch points. A test run outside the test plot was made after any implement change to be sure implement was well levelled. This was done by checking performance and assuring that none of the transducers was excessively loaded.

Working from one section into the next, a 15 to 20m tillage run was made in each. For all tests, engine speed was maintained at 1400 rpm and 4th gear which maintained an average speed of 6.4 Kph. After each run within a section the data were summed (to obtain total vertical and horizontal forces). Plots of force variation with time for each channel and the sums were made. Data were stored on tape after statistical analysis computations were obtained and results printed out. A listing of both horizontal and vertical forces was also printed out. From observation of the plots and statistical analysis results, any hardware failures or excessive loads on one of the pins could be detected.

Each run took about 10 to 20 seconds while the summing, plotting, analysis and storage processes took about 5 to 7 minutes. During the latter time, measurements were made of tillage depth. Four measurements of tillage depth were made of which an average was computed and recorded. A total of 10 runs with the moldboard plow were made.

Without collecting data the rest of the selected plot was moldboard-plowed to provide enough tilled land for the test using the cultivator. After this, an implement change was made to work with the cultivator over the same testing plot. Data sampling process was the same but fewer runs were made with this much wider implement. The cultivator required no modification to sit well on the dynamometer. Forces were therefore expected to be distributed better between the pins with the cultivator than with the moldboard plow.

After the test with the cultivator was completed, the implement was removed from the tractor, the small bridge imbalances removed (using signal conditioner balance resistors) and the system was ready for a noise-signal-test. For this test a variety of sampling rates other than the 5 readings/second, (used in tillage tests) was needed so the single channel sampling program was utilized. Channel No. 1 was selected for the test. To check whether environmental signals other than those from the bridge imbalance were sampled into the output, a run over the relatively rough tilled ground was made with bridge excitation voltage switched off. The data sampled underwent the same analysis process as that of tillage test. Two different ground speeds averaging 6.6Kph and 10.1Kph (at 1400rpm engine speed) were used. A second set of data were then obtained, this time with bridge excitation voltages switched on. Same sampling and ground speeds were maintained and the data underwent the usual analysis.

5. RESULTS AND DISCUSSION

To complete the performance test of the three point hitch dynamometer developed in this study, it was necessary to make close observations of performance in field tests and in the earlier processes of transducer calibration and verification. The main objective of this study was to determine the system's capabilities and limitations and these are reported and discussed in this chapter. Thus the dynamometer's potential and qualities as a future research tool can be easily judged.

5.1 Calibration Results

Figures 23 through 25 show typical calibration curves obtained. Very high (see Figures 23 through 25) correlation coefficients were obtained, for the linear regression of a load (input)/voltage (output) relationship. Calibration curve data for all five channels are summarized on Table 1. Table 1 includes calibration factors used in the data acquisition program. Note that calibration factors were different for each channel. This is because each channel was calibrated individually.

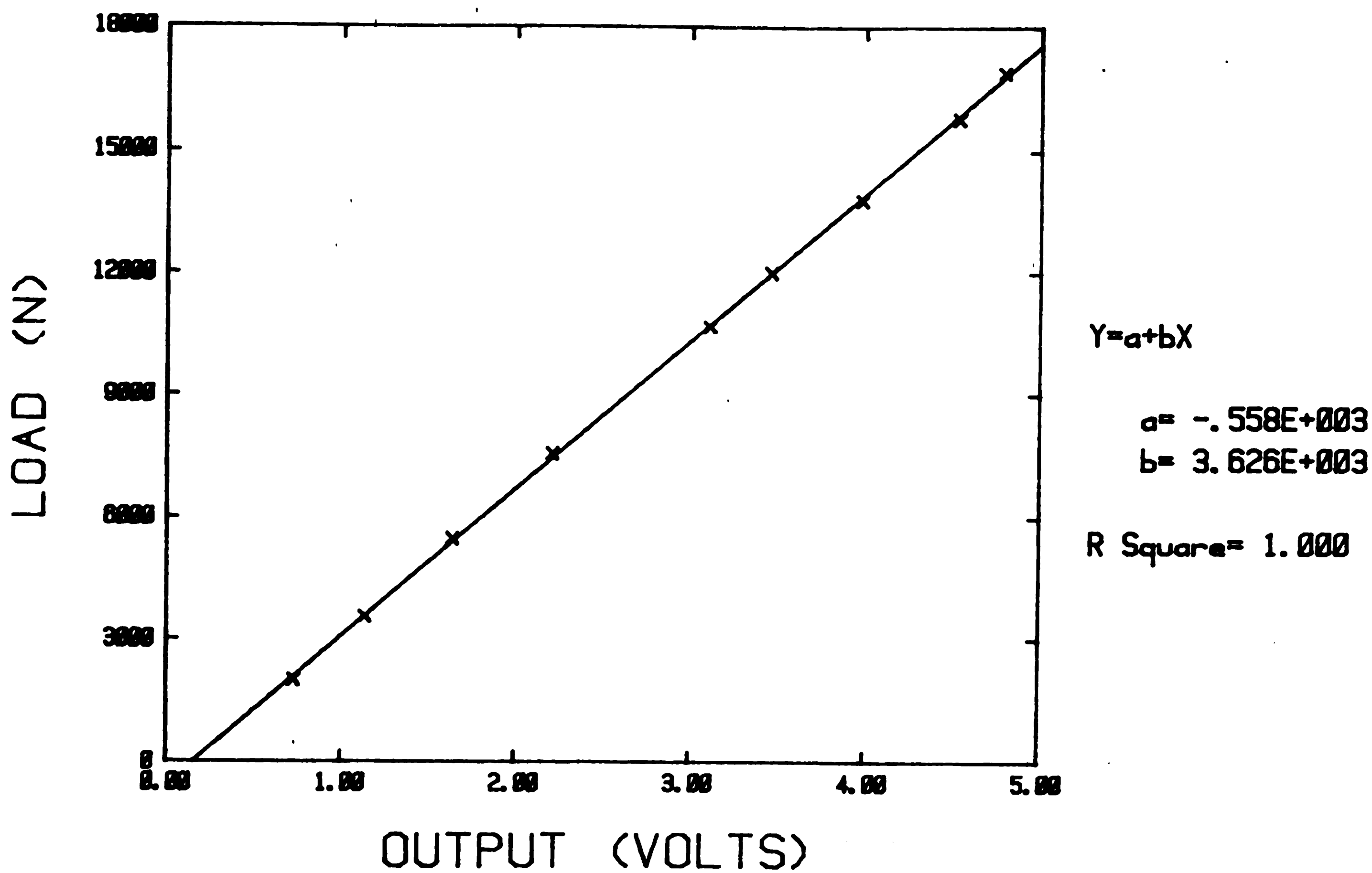


FIGURE 23: Calibration curve of acceptable linearity (Channel 1)

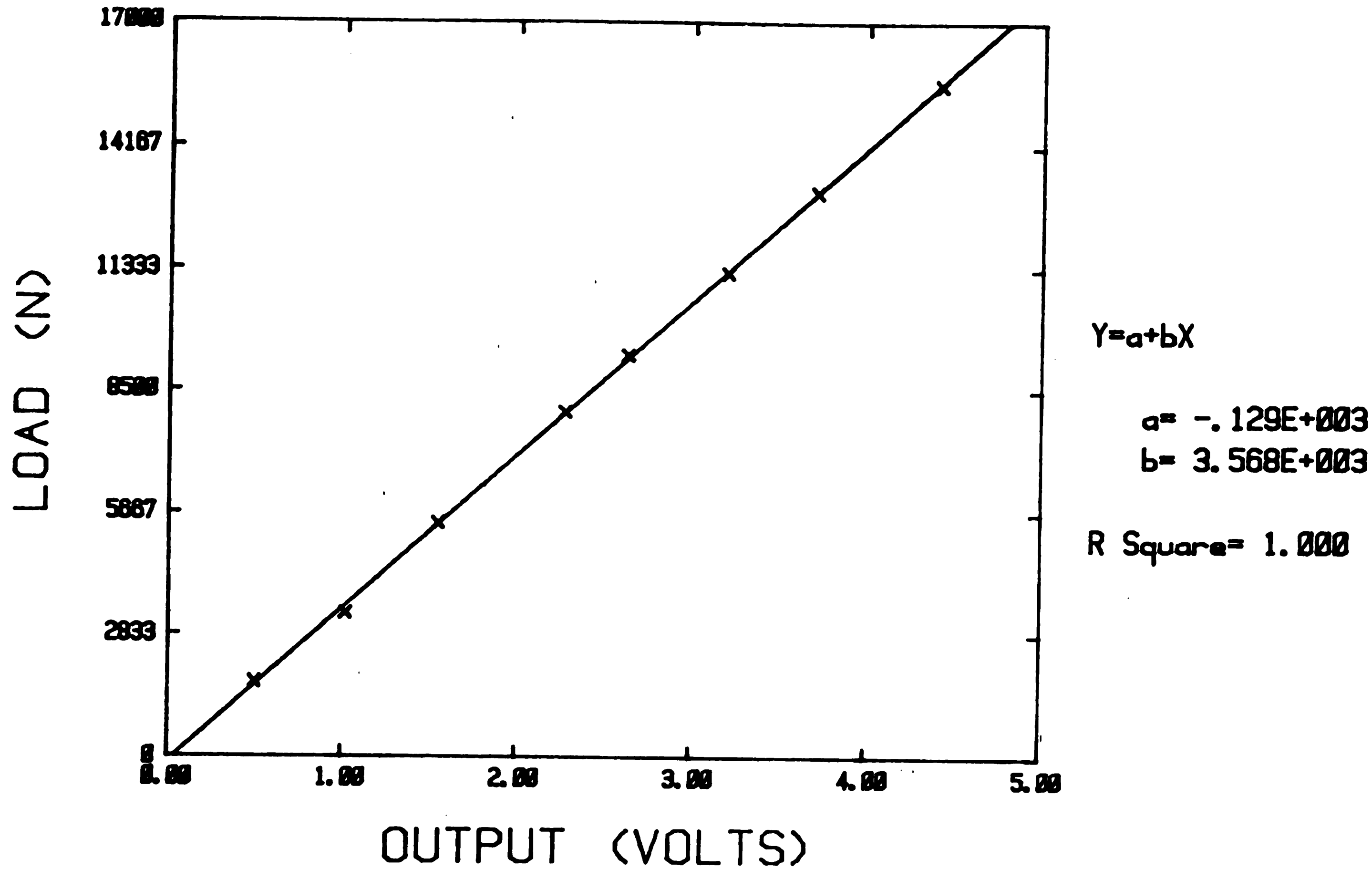


FIGURE 24: Calibration curve of acceptable linearity (Channel 2)

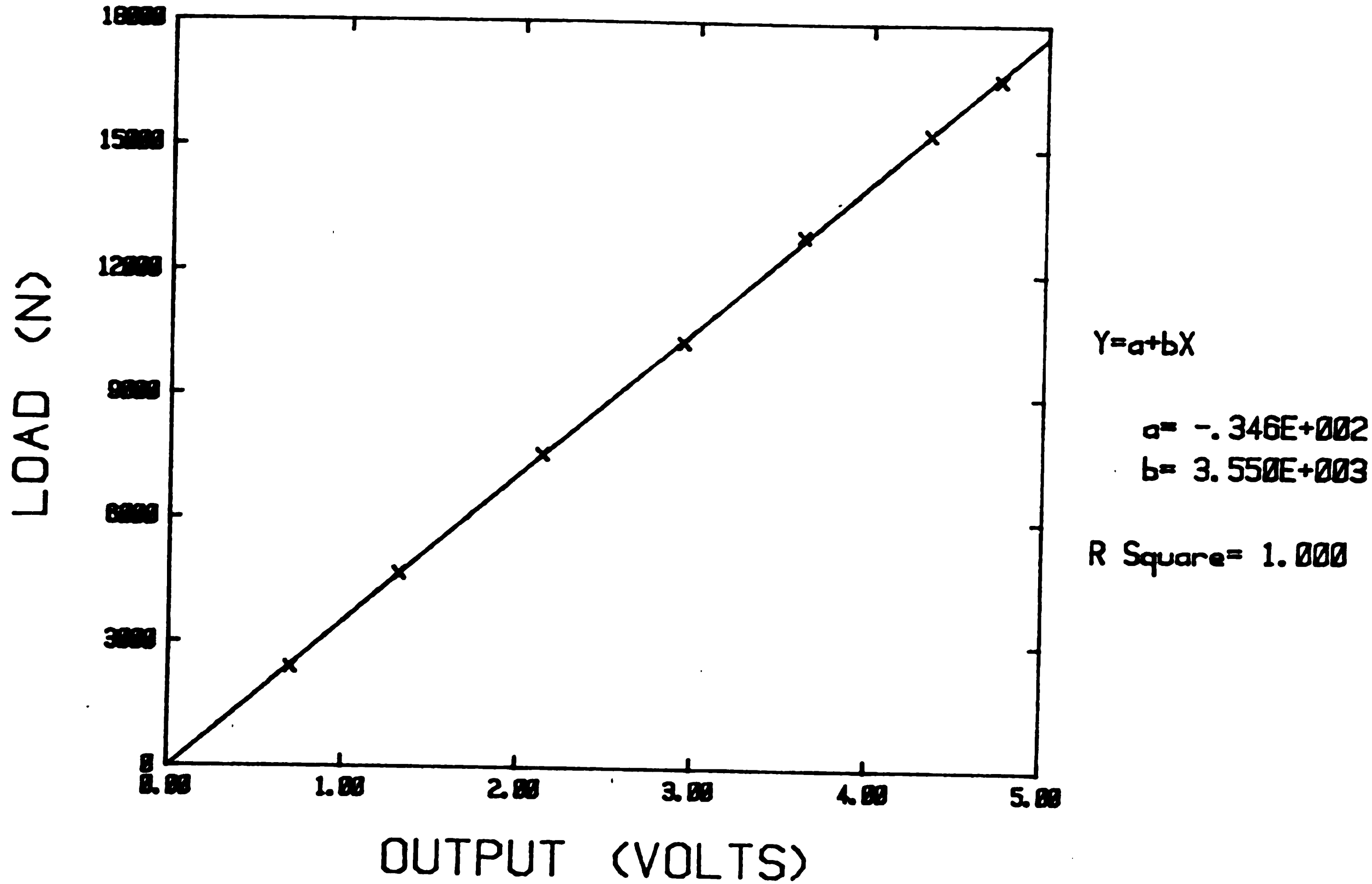


FIGURE 25: Calibration curve of acceptable linearity (Channel 4)

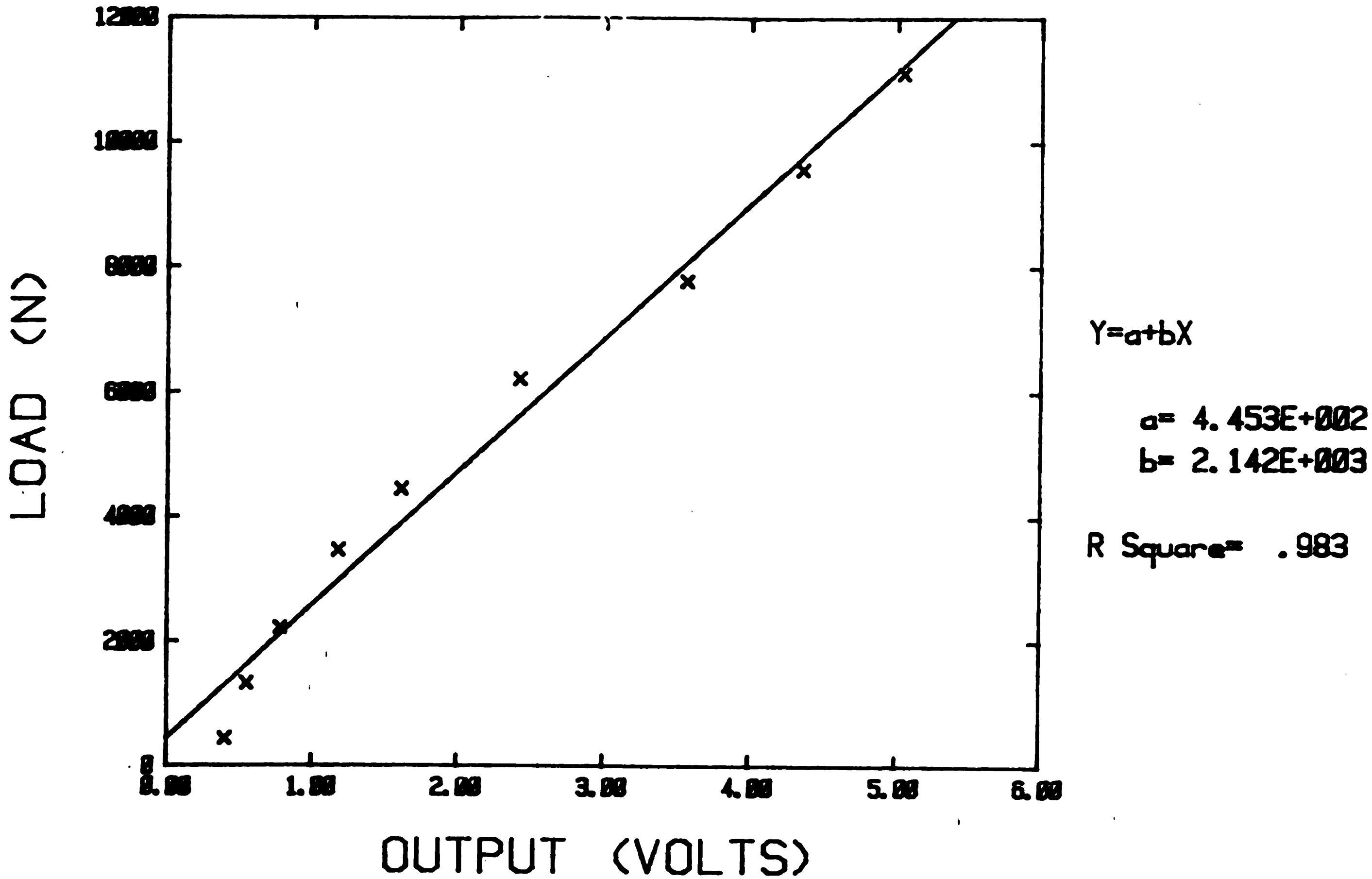


FIGURE 26(a): Unacceptable straight line plot of channel 3 calibration data. Data from a first assembly loading.

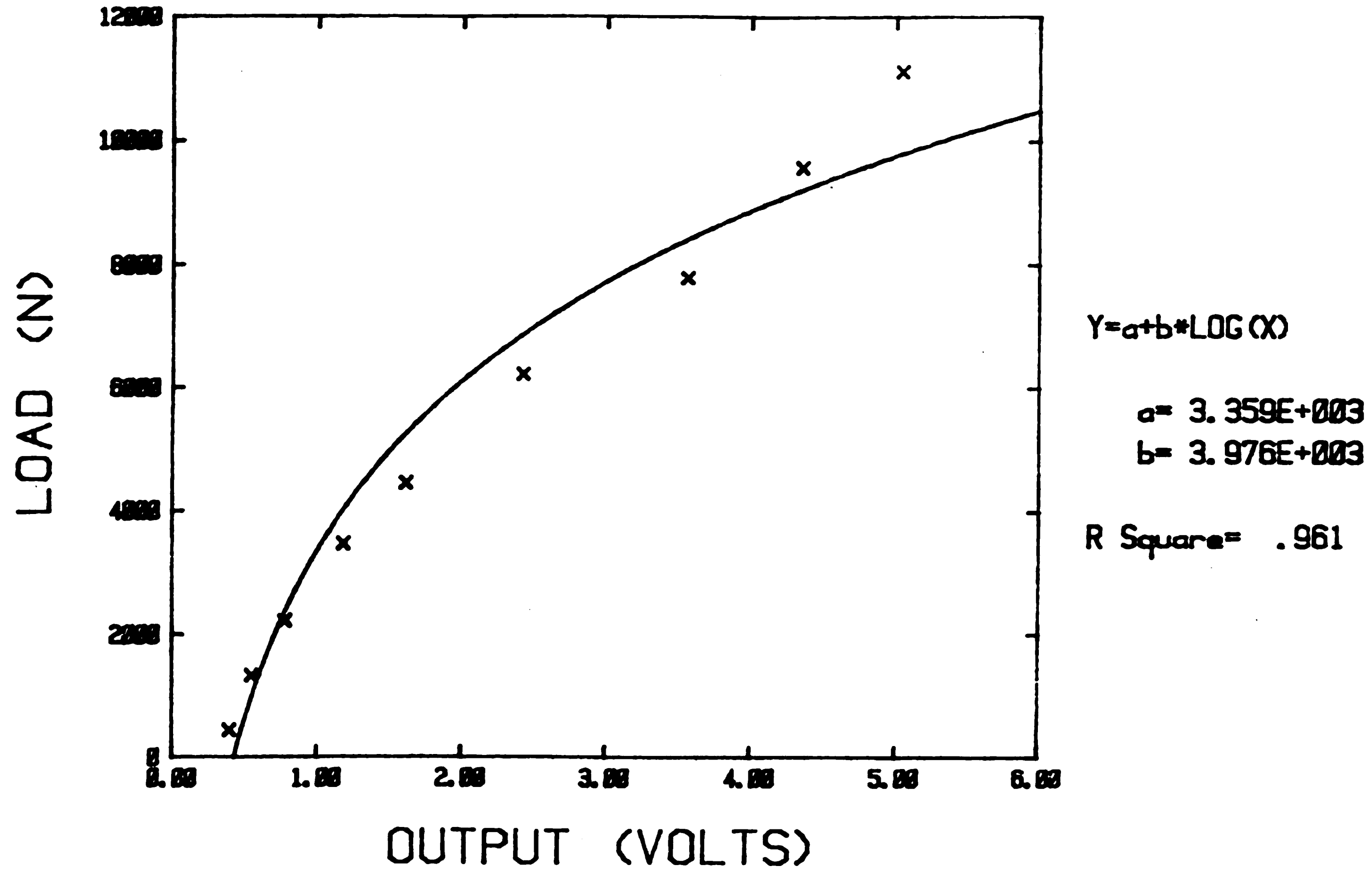


FIGURE 26(b): Logarithmic plot of calibration data for Channel 3. Data is from a first loading following sensing pin assembly.

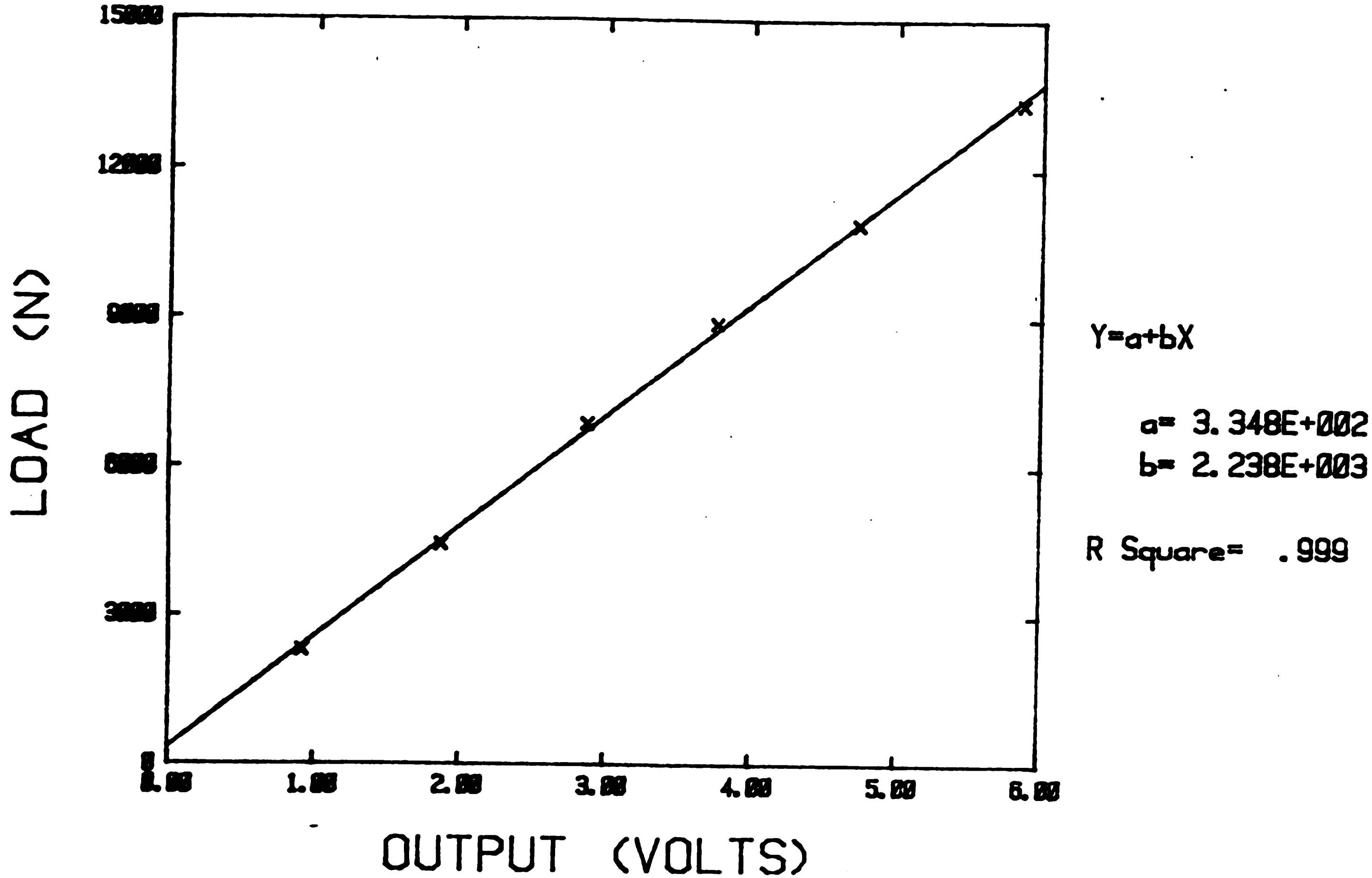


FIGURE 27: Acceptable repeatability calibration plot for channel 3. Obtained after a series of load/unload sequences.

Figures 26 and 27 are calibration curves for channel 3 for the first recorded calibration loading after the sensing pin was assembled, and after several load/unload operations respectively. Calibration curves of a correlation coefficient (R Square) less than .97 were considered unacceptably linear (see Figure 26). The linear regression on Figure 26 had a correlation coefficient of .983 but considering that most of the non-linearity occured at low loads it was considered unacceptable. Therefore the magnitude of the correlation coefficient alone was not enough to consider calibration-curve acceptability. Localized non-linearity magnitudes were also considered. The curves on Figures 23 through 25 were therefore considered acceptable and in order to obtain the adequate linearity shown several loading cycles were required. This seemed to reduce the hysteresis effects considerably (see Figures 26 and 27).

The transducers were to undergo considerable numbers of load cycles in the work situation. One of the features that determine the quality of a transducer is repeatability. This feature is very dependent on a characteristic called hysteresis. In the loading operation all the energy put into straining the transducer material is not recoverable upon unloading (second law of thermodynamics). The non-coincidence of loading and unloading curves is due to internal friction (hysteretic dumping of stressed parts. A measure of the amount of hysteresis effects present in the transducers was made.

Figures 29 and 30 respectively show the greatest and least cases of hysteresis encountered. They were obtained from plotting data for a complete loading cycle.

The numerical value of hysteresis can be measured in terms of either input or output and is given as a percentage of full scale. The largest value encountered was 35%.The transducers used to obtain data in this study had a maximum hysteresis of 3%. Any value above 10% was considered unacceptable.

Table 1

Calibration Curve Data

CHANNEL No.	FORCE COMPONENT MEASURED	Y INTERCEPT (N)	CALIBRATION FACTOR (N/V)	CORR. COEFF. R	MAX % ORTHOGONAL LOAD (e)	STABILITY %
1	LRH	-558	3626	.999	6.3	0.4
2	LRV	-129	3568	1.000	-1.2	0.2
3	LLH	33	2238	.999	12.7	3.1
4	LLV	-35	3550	.998	-1.8	8.3
5	UH	-598	3280	.980	-	1.3

LRH = Lower right (from operator's seat) horizontal

LRV = Lower right vertical force

LLH = Lower left horizontal force

LLV = Lower left vertical force

UH = Upper horizontal force

A comparison of Figure 26a to Figure 27 shows the sensing pin was unstable the first time it was loaded. This is attributable to the 'settling' of the transducer support hardware, transducer cement and the strain gage conditioning which must take place before acceptable linearity and consequential repeatability is acquired. Figure 26b is a logarithmic plot of calibration data used on Figure 26a. The plot shows that it did not fit the desired straight line. The correlation coefficient of the two fits compare well (0.961 for logarithmic plot compared to 0.983 for a straight line). Clearly evident is the fact that the more the hardware 'settled down' the more repeatability of the transducer improved, unless excessive strain took place.

Figure 28 shows the effect on channel 3 as channel 4 was loaded from zero to maximum load. Channel 3 sensed the lower left horizontal (LLH) draft components while channel 4 (a bridge on the same transducer) sensed the lower left vertical (LLV) draft component. As channel 4 was loaded for calibration, Channel 3 output was also monitored. This observation gave either the amount by which the applied force was not totally horizontal (and therefore had a small vertical component) or error resulting from off-axis placement of strain gages on the transducer. While the load was made as horizontal as practically possible. Figure 28 is supposed to be a measure of extent of the latter error source.The orthogonal load effects for other channels on the lower link transducers are recorded as e on Table 1. The plotted relationship between channel 3 and 4 was the worst case encountered (12.7% orthogonal sensitivity). e is the maximum percent of the horizontal component of draft measured as a vertical component or vice versa. In some cases during the tillage operation these cross sensed components may be oppositely directed and therefore cancell. Although in the final analysis total horizontal and total vertical forces add up separately, the orthogonal force sensing was considered an error because various channels were calibrated separately. In other words a channel supposed to measure the horizontal component may have a different calibration factor from that measuring the vertical component and does therefore not qualify to measure part of the vertical component being sensed horizontally or vice versa. Magnitudes involved as can be seen on Table 1 were fairly negligible.

Immediately after strain gages are attached to make a transducer there's a heat-up that results as excitation voltage is fed through the bridge circuitry. The gage cement and soldered joints etc., respond to the resulting heatup in a way that determines the stability

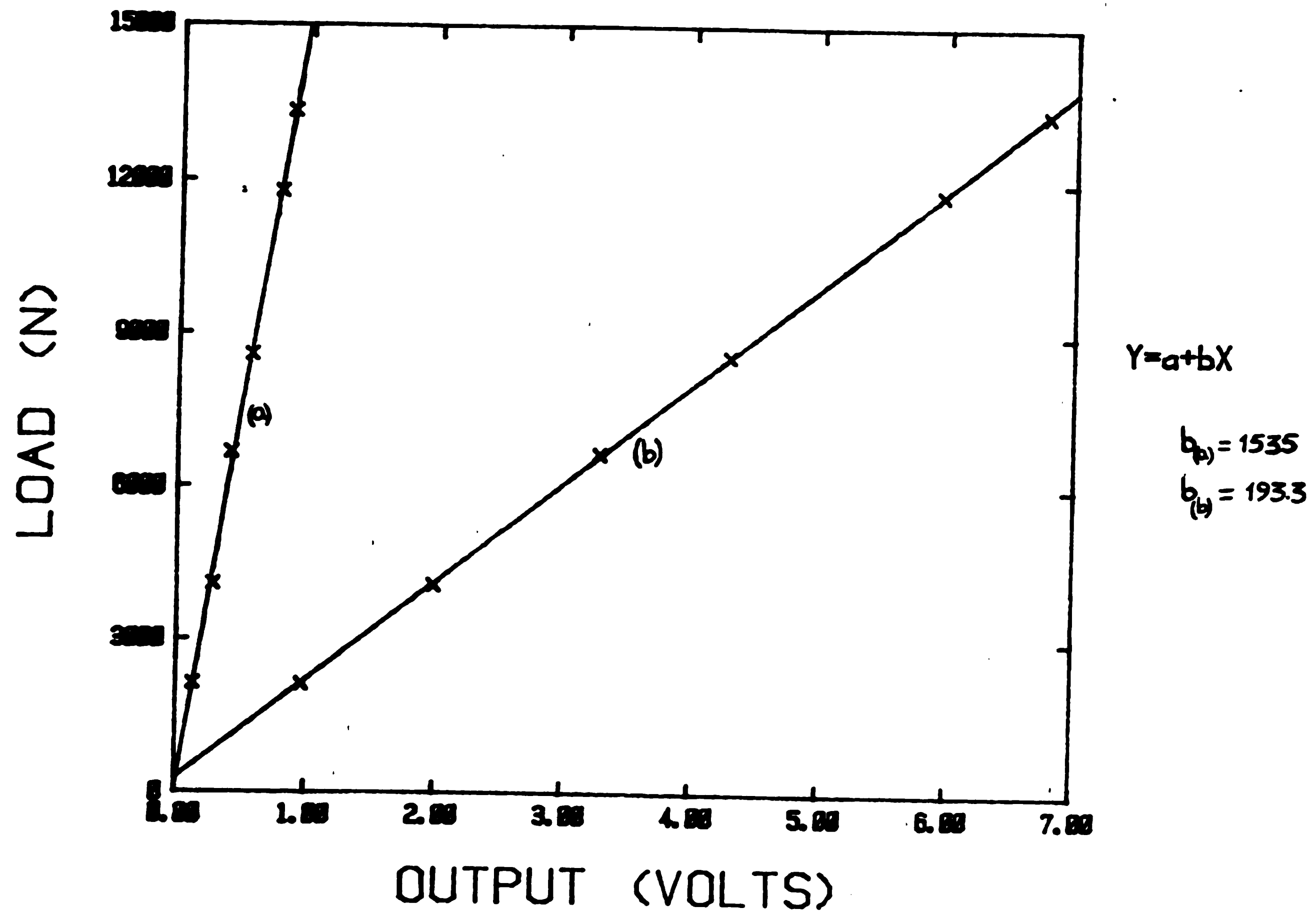


FIGURE 28: A comparison plot of outputs of orthogonally placed channels as one is loaded for verification a)-output of orthogonal channel b)-output of actually loaded channel.

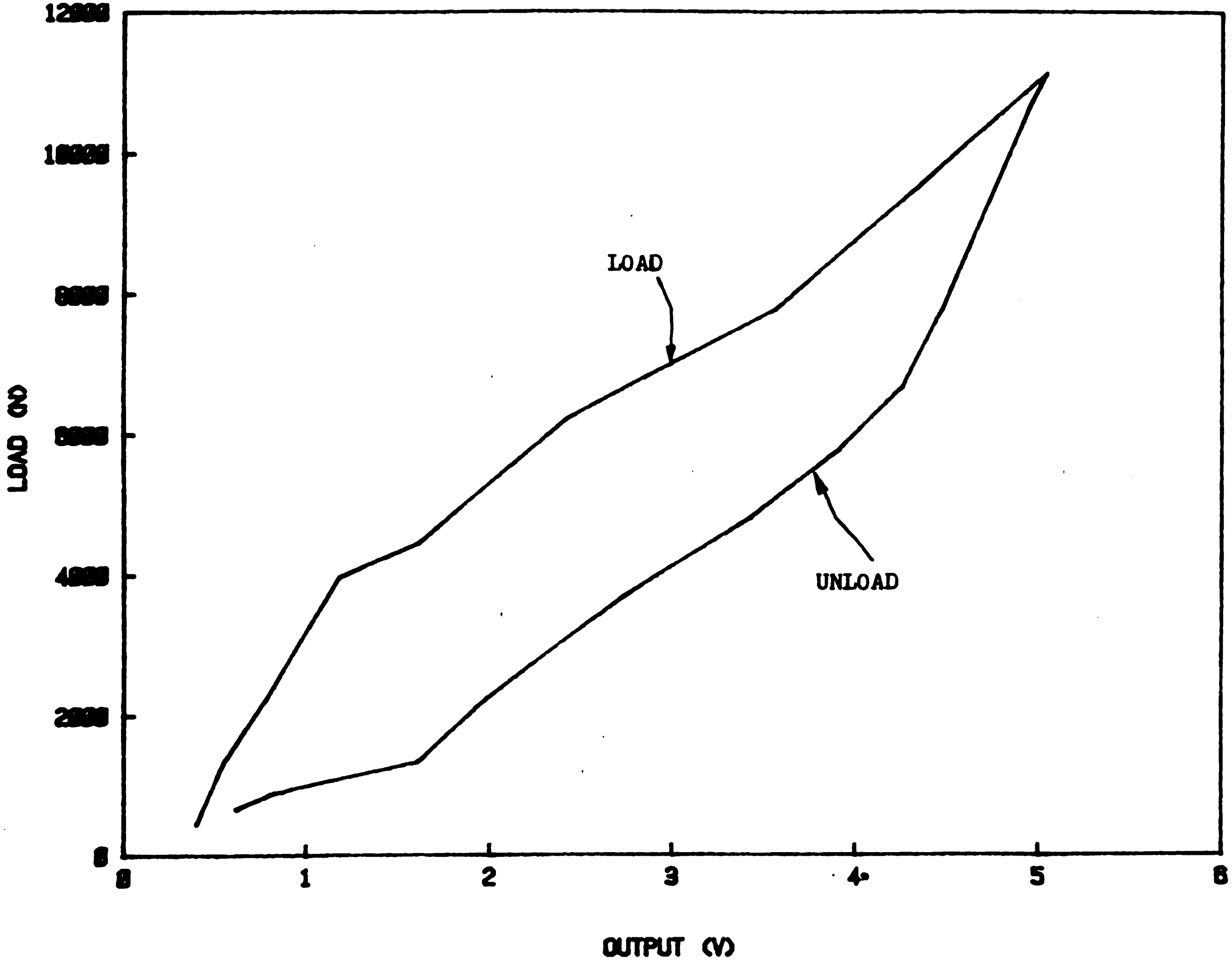


FIGURE 29: A plot showing load/unload hysteresis as encountered in unacceptable amounts.

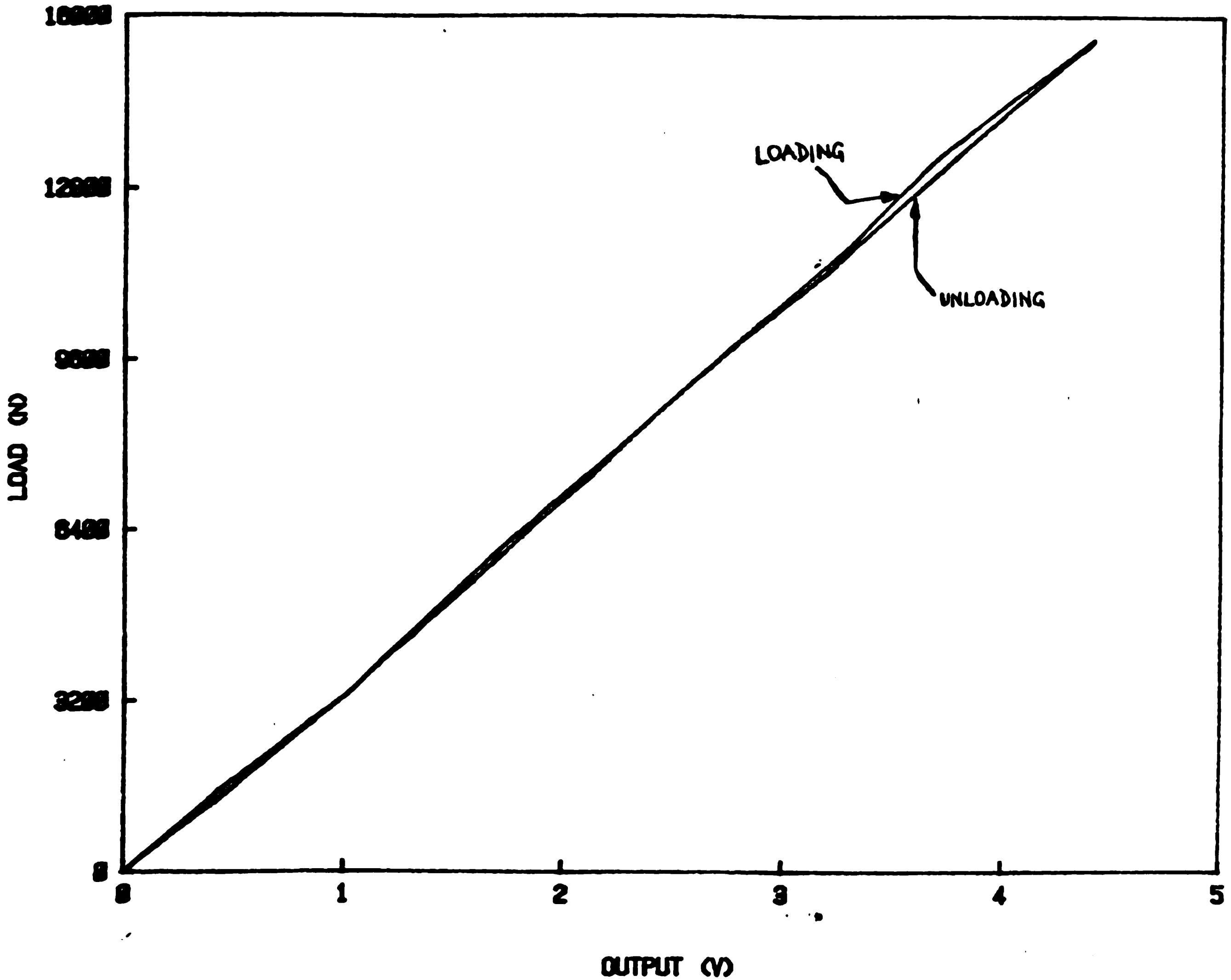


FIGURE 30: A plot showing load/unload hysteresis as encountered in acceptable amounts.

HORIZ FORCE (445N)	VERT. FORCE (445N)
1530.8	-236.98
1771.3	-227.93
1834.7	-225.07
1984	-217.16
2208.1	-209.02
2378.3	-200.93
2505.5	-197.39
2588.3	-194.4
2672.3	-190.87
2716.7	-189.18
2729.2	-186.87
2737.9	-185.15
2746.5	-183.31
2752.4	-181.32
2753.5	-182.11
2750.8	-181.11
2751.4	-179.76
2752.9	-181.72
2752.4	-179.03
2749.5	-181.22
2752.1	-182.05
2753.1	-179.28
2759.3	-179.1
2758.8	-178.68
2757.9	-179.26
2759.7	-179.44
2758.4	-180.06
2759.2	-179.15
2762.2	-179.84
2765.3	-178.57
2766.4	-178.26
2761.3	-180.67
2769.4	-176.33
2770.9	-177.28
2775.9	-178.23
2779.8	-177.99
2778.4	-177.49
2776.7	-176.97
2781.3	-181.2
2822.6	-185.41
2838.5	-187.94
2832.1	-187.1
2828.1	-184.21
2825.4	-182.23
2817.2	-178.07
2811.7	-176.52
2810.5	-175.67
2811.2	-177.24
2816	-177.25
2808.5	-175
2807.5	-176.49
2807.6	-175.71
2803.8	-170.5
2807.5	-166.39
2807.1	-149.24
2805.1	-136.02
2811.9	-112.9
2813.8	-90.623
2817.3	-82.245
2822.4	-72.908

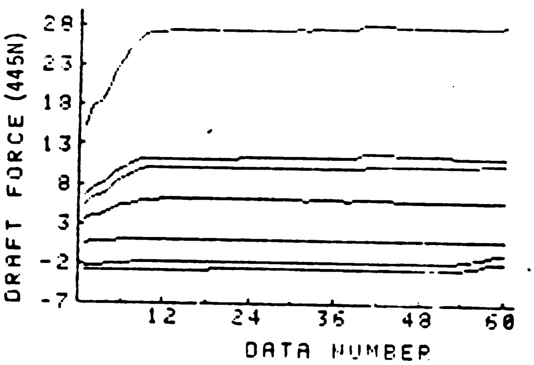


FIGURE 31(a) Typical verification output at medium size loads

```
STATISTICAL DATA FOR CHANNEL   1
--------------------------------

AVERAGE       -268.3
MINIMUM:      -287.1
MAXIMUM       -167.7
STD DEVN:           25.000
COEFF. OF VARTN (%):        -9.32

STATISTICAL DATA FOR CHANNEL   2
--------------------------------

AVERAGE        983.2
MINIMUM       -287.1
MAXIMUM       1064.9
STD DEVN:          106.178
COEFF. OF VARTN (%):        10.80

STATISTICAL DATA FOR CHANNEL   3
--------------------------------

AVERAGE       1114.8
MINIMUM        642.8
MAXIMUM       1205.5
STD DEVN:          108.960
COEFF. OF VARTN (%):         9.77

STATISTICAL DATA FOR CHANNEL   4
--------------------------------

AVERAGE          91.1
MINIMUM:         50.2
MAXIMUM          98.9
STD DEVN:            9.754
COEFF. OF VARTN (%):        10.70

STATISTICAL DATA FOR CHANNEL:  5
--------------------------------

AVERAGE:        591.0
MINIMUM:        352.9
MAXIMUM         626.7
STD DEVN:            55.713
COEFF. OF VARTN (%):         9.43

STAT.DATA FOR TOTAL HORIZ. FORCE
--------------------------------
--------------------------------

AVERAGE:      2689.0
MINIMUM:      1530.8
MAXIMUM:      2838.5
STD DEVN:          268.971
COEFF. OF VARTN (%):        10.00

STAT. DATA FOR TOTAL VERT. FORCE
--------------------------------
--------------------------------

AVERAGE       -177.2
MINIMUM:      -237.0
MAXIMUM        -72.9
STD DEVN:           28.394
COEFF. OF VARTN (%):      -16.03
```

FIGURE 31(b): Typical statistical analysis of output from verification at medium size loads.

HORIZ.FORCE (445N)	VERT. FORCE (445N)
5965.2	103.64
5944.6	103.05
5939.5	104.34
5935.2	105.72
5932.2	103.88
5930.3	105.55
5924.5	104.35
5925.1	104.25
5917.4	104.59
5916.5	105.15
5913.4	105.35
5909.1	105.76
5906.1	107.75
5901.3	105.25
5898.3	105.43
5898.7	106.01
5893	108.04
5888.3	108.98
5887.1	106.68
5884.5	106.95
5883.3	108.26
5877.9	107.21
5874.3	105.38
5874.3	109.16
5873.9	109.31

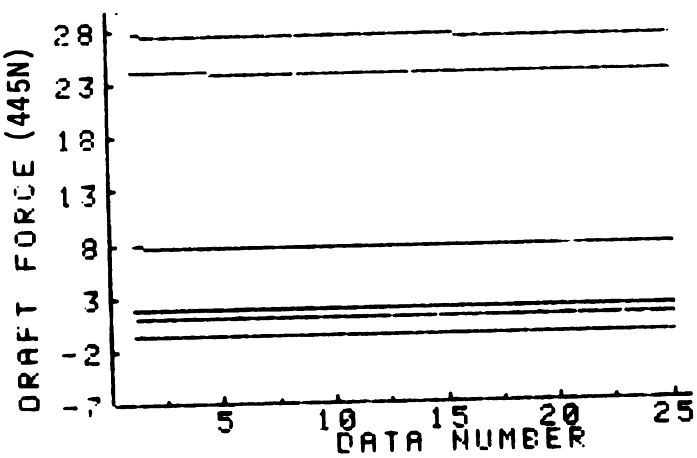


FIGURE 32(a): Typical verification output at large size loads. (Sampling begun after load had stabilized)

```
STATISTICAL DATA FOR CHANNEL   1
--------------------------------

AVEPAGE      2397 3
MINIMUM      2382.9
MAXIMUM      2420.6
STD DEVN:          9.698
COEFF. OF VARTN (%):       40

STATISTICAL DATA FOR CHANNEL:  2
--------------------------------

AVERAGE       -68.7
MINIMUM      2382.9
MAXIMUM       -67.0
STD DEVN:          1.100
COEFF. OF VARTN (%):    -1.60

STATISTICAL DATA FOR CHANNEL:  3
--------------------------------

AVERAGE      2743.0
MINIMUM:     2726.4
MAXIMUM:     2768.2
STD DEVN:         11.506
COEFF. OF VARTN (%):      .42

STATISTICAL DATA FOR CHANNEL:  4
--------------------------------

AVERAGE       174.7
MINIMUM:      173.6
MAXIMUM:      176.3
STD DEVN:           .795
COEFF. OF VARTN (%):      .46

STATISTICAL DATA FOR CHANNEL:  5
--------------------------------

AVERAGE       767.5
MINIMUM       760.9
MAXIMUM       776.4
STD DEVN:          3.997
COEFF. OF VARTN (%)       .52

STAT.DATA FOR TOTAL HORIZ. FORCE
--------------------------------
--------------------------------

AVERAGE:     5907.8
MINIMUM:     5873.9
MAXIMUM:     5965.2
STD DEVN:         24.952
COEFF. OF VARTN (%)       .42

STAT. DATA FOR TOTAL VERT. FORCE
--------------------------------
--------------------------------

AVERAGE:      106.0
MINIMUM:      103.1
MAXIMUM:      109.3
STD DEVN:          1.792
COEFF. OF VARTN (%):     1.69
```

FIGURE 32(b): Typical statistical output of large size load verification output

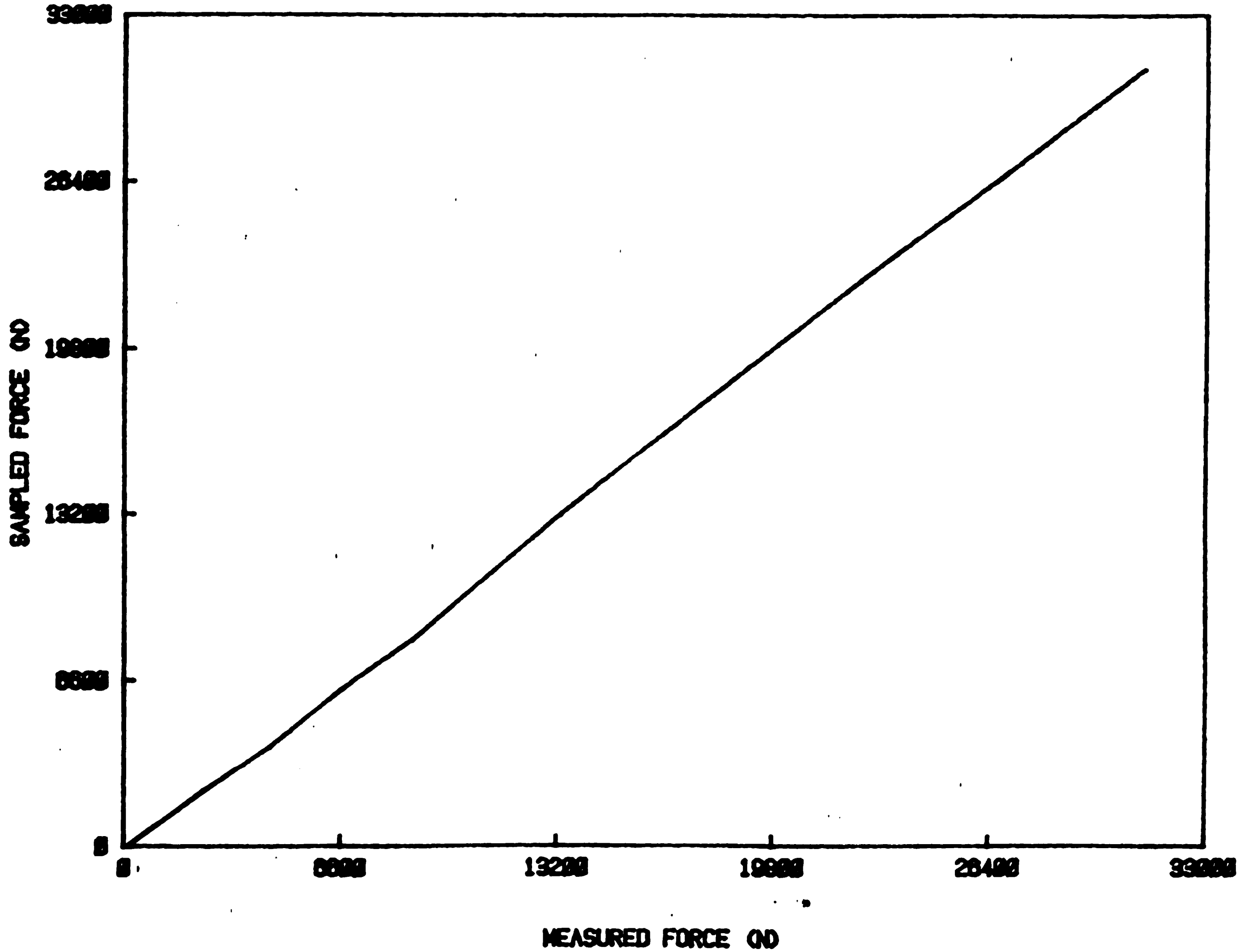


FIGURE 33(a) A comparison plot of measured and sampled draft force using actual verification data.

of the bridge output. This stability is measured by monitoring bridge output over an extended period of time following gage installation. Stability depends on quality of transducer construction. Externally induced electrical noise is also a stability determining factor. In this study bridge stability was determined by recording output approximately every three hours over a 24 hour period. Voltage (output) shift away from the balanced zero reading over the 24 hour period was the measure of stability. The last column on Table 1 gives percentage shift of output voltage (shift volts/10 volt-maximum output range).

From Table 1 it can be seen that the worst case of stability encountered was 8.3%. In the field test measurements made were over a maximum period of 30 seconds. Therefore assuming a linear output change it can be concluded that instability error was very negligible.

Column 1 of Table 1 shows the y-intercept values (output at no load). The existing outputs at no load can be attributed to both hysteresis and the nature of the loading mechanism used. The loading mechanism (see Figure 19) support was rather unstable and at the end of each loading operation the chain work and hydraulic cylinder took positions that tended to put some load on the hydraulic dynamometer. However as long as the linearity of calibration graphs was at acceptable levels, it did not matter that y-intercepts were

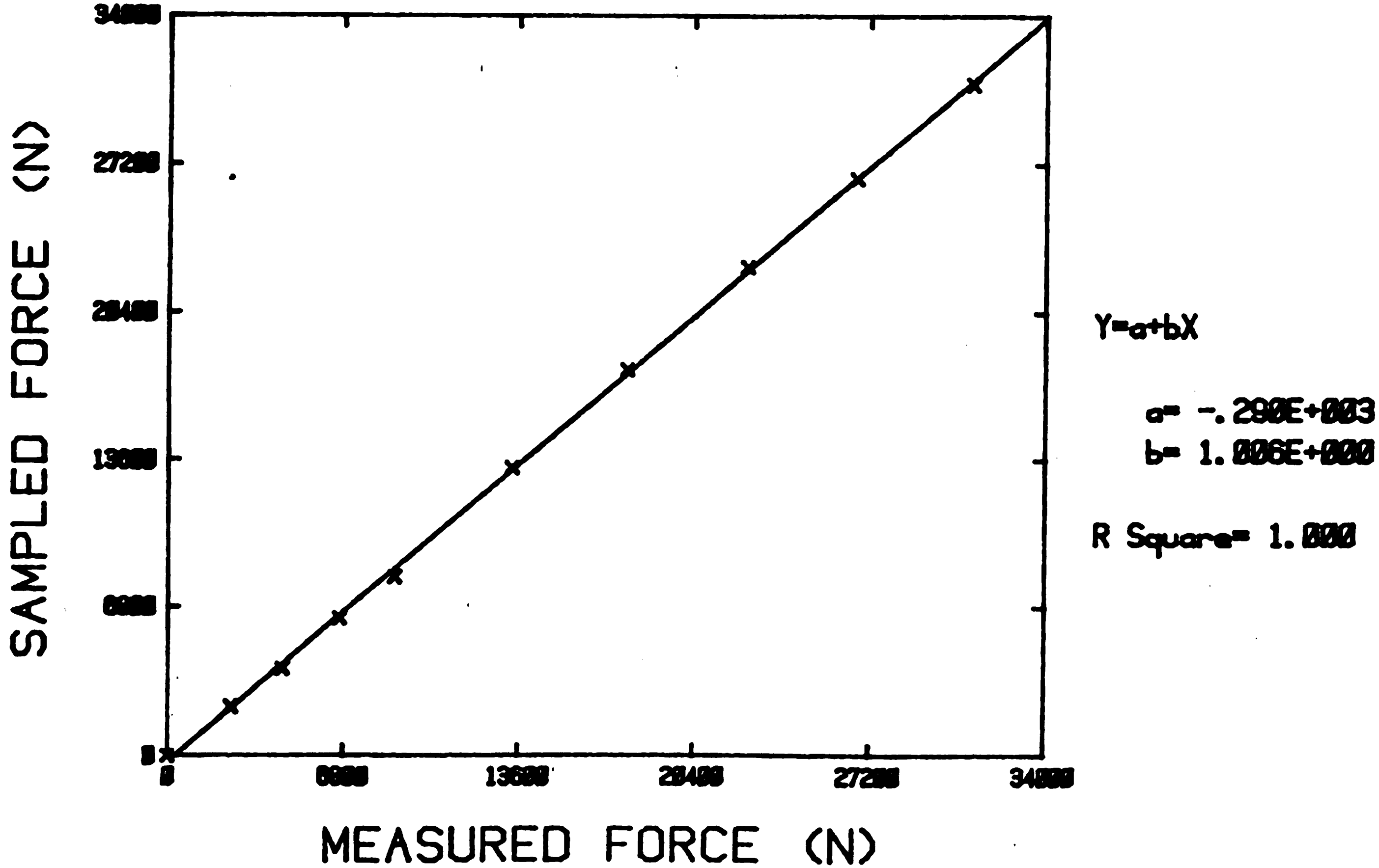


FIGURE 33(b) A curve fitting comparison plot of measured and sampled draft force using verification data.

Table 2

Averaged Verification Data

Measured Force (N)	Sampled Force (N)	Difference (N)	Error (%)
2446	2255	191	8
4448	3977	471	11
6672	6267	405	6
8807	8189	618	7
13344	13246	98	.7
17792	17801	-9	-.05
22462	22494	-32	-.14
26688	26546	142	.5
31136	30900	236	.8

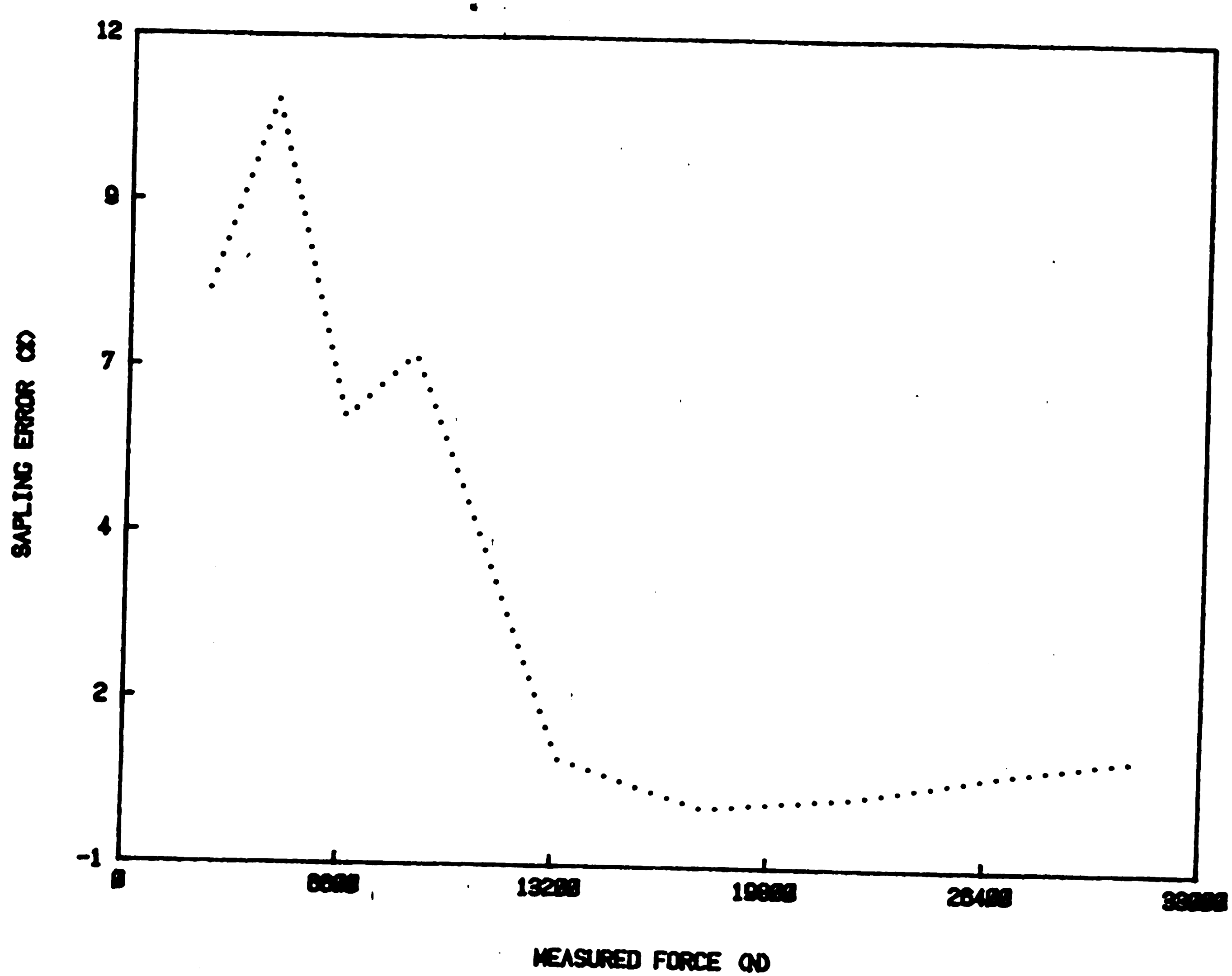


FIGURE 33(c) Verification draft force measurement error distribution graph.

non-zero. In the field test these off-zero outputs were easily removed by adjustments on the signal conditioners.

5.2 Verification Results

Figures 31 and 32 show typical verification curves that were obtained and their statistical analysis. For the final system setup used in the field tests, (the system whose field test results are reported in this study), four sets of verification data were obtained. Each set had loads varying in magnitude from 2200N to 32000N. Each load/unload process was done in sequence. The load was reduced to zero before each consecutive load was applied to a predetermined new maximum. The graph on Figure 31a shows the full loading process while that on Figure 32a shows only stable load. The difference is that data sampling for Figure 31a was initiated while the load was rising and continued after the load had stabilized. Sampling of data for Figure 32a did not start until the load had stabilized hence the horizontal linear plot of output. Also on both Figures 31a and 32a are typical data that were printed out during the verification test. Listed separately, the total horizontal and total vertical forces data are listed just as sampled. Numerical values of the forces were easy to compare with loads read off the loading system dial (corresponding to (R) on Figure 21).

Table 3(a)

Field Test Data Summary (Mold Board Plow)

		RUN1	RUN2	RUN3	RUN4	RUN5	RUN6	RUN7	RUN8	RUN9
	A	9492	14576	17120	13900	17490	17089	16275	19300	18530
C1	SD	3456	3514	2095	2958	3403	3572	1699	2589	2228
	CV	36	24	12	21	19	21	10	13	12
	A	93	-987	979	-600	93	-396	-98	-102	-943
C2	SD	1352	1366	1312	1557	1570	1877	1263	1250	1454
	CV	1449	-138	134	-260	1663	-476	-1321	-1217	155
	A	5805	8287	5004	9950	7055	7606	7246	4750	8184
C3	SD	3300	3056	2896	4012	3100	3852	2509	3247	2873
	CV	57	37	58	40	44	51	35	68	35
	A	-30	-384	-3309	-489	-538	-1245	-2580	-2255	-1530
C4	SD	1712	1446	916	1775	1646	961	694	974	1032
	CV	-5741	-377	-28	-362	-306	-77	-27	-43	-68
	A	-5978	-5022	-1721	-6823	-6503	-6805	-2077	-4381	-5827
C5	SD	4608	3434	2042	3830	3888	2153	1450	2273	2353
	CV	-77	-68	-118	-56	-60	-32	-70	-52	-140
	A	9319	17836	20399	17027	18037	17894	21444	19674	20883
TH	SD	2647	3318	2740	3447	2891	3412	2242	2704	2718
	CV	28	19	13	20	16	19	10	14	13
	A	63.6	-1374	-2331	-1090	-445	-1637	-2673	-2357	-2469
TV	SD	2438	2220	1712	2273	2749	1944	1472	1499	1730
	CV	3830	-162	-73	-209	-621	-119	-55	-64	-70
AVE. DEPTH (cm)		10	18	25	12	16	24	26	24	23
AVE. M/C (%)		20.2	21.5	25.7	23.3	19.2	18.1	21.6	19.8	22.8
BULK DENS. (g/cc)		1.46	1.43	1.25	1.34	1.49	1.51	1.44	1.46	1.49
PEN. PRES. (kPa)		461	450	429	356	604	650	459	466	526

Table 3(b)

Field Test Data Summary (Cultivator)

		RUN1	RUN2	RUN3	RUN4	RUN5	RUN6	RUN7
	A	8180	11178	7474	13474	13887	9697	7753
C1	SD	4431	6031	4662	4710	3910	4902	4955
	CV	66	54	62	35	28	51	64
	A	-3367	7673	-2571	227	-156	5129	5538
C2	SD	3892	5160	3474	4897	2833	3505	3745
	CV	-116	67	-135	2159	-1805	-68	-68
	A	4586	9483	8019	5778	6396	7063	6436
C3	SD	2856	2300	2117	2753	2868	2455	2549
	CV	62	24	26	48	45	35	40
	A	-2722	-7232	-2580	-3701	-5008	-2126	-903
C4	SD	1583	3069	1410	2598	1659	1543	1664
	CV	-58	-42	-55	-70	-33	-73	-185
	A	182	-4381	-1321	-894	-1063	187	259
C5	SD	2135	2571	2268	2002	1904	2068	2776
	CV	1179	-59	-172	-223	-179	1105	1072
	A	12944	16280	14171	18352	19220	16942	14447
TH	SD	5409	5151	5391	4684	3670	5564	4960
	CV	42	32	38	26	19	33	34
	A	-6089	440	-5155	-3474	-5164	-7255	-6441
TV	SD	2976	2731	2927	2816	2050	3314	2602
	CV	-49	620	-57	-81	-40	-46	-40

For both Tables 3 (a) and (b) :
C1 = Channel 1, C2 = Channel 2 etc.
TH = Total Horizontal force, TV = Total Vertical force
A = Average force, SD = Standard Deviation, CV = Coefficient of Variation
All forces are in Newton.

Components (HF) and (VF) also shown on Figure 21 are the ones listed on Figures 31a and 32a. In most cases (VF) was small compared to (HF) and could be used as an approximation of (R).

Figures 31b and 32b show typical statistical outputs received after each loading process and for each channel. Statistical data for sums of horizontal and vertical forces were also recorded. The average results of the four sets of verification data is shown on Table 2. Figure 33a is a plot of actual data (sampled force vs measured force). Figure 33b is a linear regression of the same verification comparison. A correlation coefficient of 1.0 and a gradient of 1.01 (sampled force/ measured force), was obtained. The system was therefore very accurate within errors of the verifying system.

The distribution of measurement error encountered is shown on Figure 33c. It is clear that in general the magnitude of measurement error is reduced at higher loads. This may be attributable to the larger hysteresis effects in the hardware and loading mechanism. At higher loads these effects are minimal hence the relatively smaller error size. A maximum 11% measurement error was encountered in the range of loads between 2500 and 8000N while for loads above 132000N error was minimal.

HORIZ FORCE	LFT FORCE
1343.7	-1093.8
1168.4	-382.54
1248.6	-642.05
1887.7	-215.25
2105.5	-516.44
1576.4	-137.83
1841.4	793.07
1520.2	444.27
2850.2	-155.44
2337.9	868.53
2973.5	-42.38
1551	538.1
2489.3	-57.27
3044.6	1366.2
2435.2	-119.51
2335.3	459.15
2133.6	566.25
374.35	-251.07
2794.2	236.62
2347.7	-167.34
2523.7	301.59
1772.5	-144.24
2038.1	499.89
2324.2	-443.16
2596.7	-59.96
2291.3	-209.97
2199.6	-15.62
3001.5	22.25
1621.1	-181.68
2221.6	157.35
2094.5	634.12
2787.5	821.71
2426.6	304.77
1364	856.53
2818.7	494.94
1581.7	-1144.8
855.86	-481.44
1387.3	-889.68
1719.2	-569.91
2206.1	-236
2522.6	19.375
3072.3	274.24
1577.1	692.19
2773.4	300.94
1014.1	-532.68
2706.6	297.97
620.7	305.66
2175.1	-249.72
1157.1	-727.56
2193.5	303.27
1822.1	-58.77
3046.4	259.33
1584.8	-165.7
2019.3	546.53
1563.7	-549.73
1537.9	-529.74
1412.3	-614.96
1332.3	-305.72
1935.6	-145.55
2112.5	-270.19
2494.5	186.78
2295.6	-357.32
1894.3	-257.19
2635.5	372.15
1904.8	-69.56
2543	954.81
2589.7	947.36

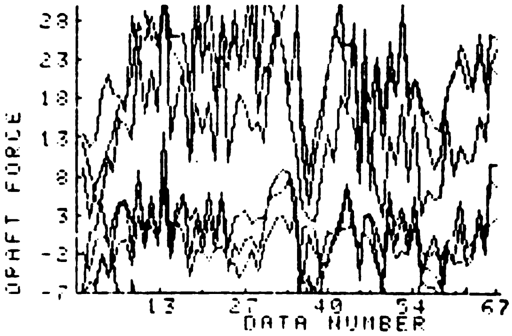
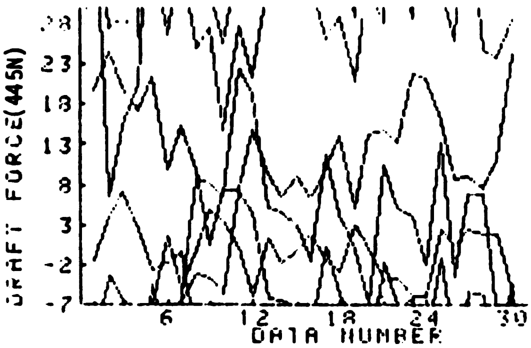


FIGURE 34(a) i) Typical output for moldboard plow tillage.
-list of total horizontal and total vertical forces sampled.
-data plot of all data and the totals.
(All forces in 445N)

```
STATISTICAL DATA FOR CHANNEL   1
--------------------------------

AVERAGE       2133.5
MINIMUM        228.4
MAXIMUM       3753.5
STD DEVN:          776.815
COEFF. OF VARTN (%):       36.41

STATISTICAL DATA FOR CHANNEL   2
--------------------------------

AVERAGE         21.0
MINIMUM       -573.0
MAXIMUM        765.7
STD DEVN:          304.402
COEFF. OF VARTN (%):    1448.83

STATISTICAL DATA FOR CHANNEL   3
--------------------------------

AVERAGE       1305.3
MINIMUM       -785.0
MAXIMUM:      3425.9
STD DEVN:          741.679
COEFF. OF VARTN (%):       56.82

STATISTICAL DATA FOR CHANNEL   4
--------------------------------

AVERAGE:        -6.7
MINIMUM:      -905.7
MAXIMUM        774.8
STD DEVN:          385.446
COEFF. OF VARTN (%):   -5740.74

STATISTICAL DATA FOR CHANNEL:  5
--------------------------------

AVERAGE     -1343.8
MINIMUM     -3563.2
MAXIMUM:      1239.7
STD DEVN:        1036.090
COEFF. OF VARTN (%):     -77.10

STAT.DATA FOR TOTAL HORIZ. FORCE
--------------------------------
--------------------------------

AVERAGE       2095.0
MINIMUM:       620.7
MAXIMUM       3073.9
STD DEVN:          595.200
COEFF. OF VARTN (%):       28.41

STAT. DATA FOR TOTAL VERT. FORCE
--------------------------------
--------------------------------

AVERAGE         14.3
MINIMUM:    -1144.8
MAXIMUM:      1360.2
STD DEVN:          547.531
COEFF. OF VARTN (%):    3830.18
```

FIGURE 34(a) (ii): Statistical analysis results for moldboard plow tillage forces. (All forces in 445N)

HORIZ FORCE (445N)	VERT FORCE (445N)
[illegible]	[illegible]
2760.3	-1397
3888.3	-1421
3623.3	-1536.1
5617.4	-731.64
3795.5	-1606.1
4666.7	-649.75
3432.1	-320.09
3278	-380.33
2561	-566.99
3512.9	706.6
3020.1	464
4291.6	-636.44
4510.1	-650.55
5408	-783.03
4039.2	-1045.4
3464.6	13.4
4001.7	-557.2
2892.1	-1078.4
4870.9	-1516.4
3883.4	-171.3
5606.4	-750.5
4447.6	-633.33
6172.7	-1269
5155.6	-133.5
3499.9	-1145.8
5620.9	-547.91
3415.9	-597.29
3703.5	-2099.5
4704.3	-1035.5



STATISTICAL DATA FOR CHANNEL: 1

AVERAGE: 3028.9
MINIMUM: 659.4
MAXIMUM: 5285.9
STD DEVN: 1058.531
COEFF. OF VARTN (%): 34.95

STATISTICAL DATA FOR CHANNEL: 2

AVERAGE: 51.8
MINIMUM: -2308.6
MAXIMUM: 2257.8
STD DEVN: 1101.322
COEFF. OF VARTN (%): 2158.80

STATISTICAL DATA FOR CHANNEL: 3

AVERAGE: 1298.8
MINIMUM: 52.1
MAXIMUM: 2451.3
STD DEVN: 619.160
COEFF. OF VARTN (%): 47.67

STATISTICAL DATA FOR CHANNEL: 4

AVERAGE: -831.7
MINIMUM: -1551.2
MAXIMUM: 703.1
STD DEVN: 584.266
COEFF OF VARTN (%): -70.25

STATISTICAL DATA FOR CHANNEL: 5

AVERAGE: -201.3
MINIMUM: -1379.0
MAXIMUM: 482.7
STD DEVN: 449.617
COEFF. OF VARTN (%): -223.36

STAT. DATA FOR TOTAL HORIZ. FORCE

AVERAGE: 4126.4
MINIMUM: 2561.0
MAXIMUM: 6172.7
STD DEVN: 1053.114
COEFF. OF VARTN (%): 25.52

STAT. DATA FOR TOTAL VERT. FORCE

AVERAGE: -780.7
MINIMUM: -2099.5
MAXIMUM: 706.6
STD DEVN: 632.615
COEFF. OF VARTN (%): -81.04

FIGURE 34(b) Typical output for a cultivator tillage run. (All forces 445N)

5.3 Field Test Results

Figure 34 shows typical tillage test output obtained immediately after each test run in the field. This type of output gave an 'on the spot' knowledge of ball-park magnitude and distribution of forces sampled during a specific run. Like for verification, each graph had seven separate curves, five with data from each of five channels and two of the sum of horizontal and sum of vertical forces. The x-axis of the graphs is labelled Data Number which is the data point number. Sampling rate was 5 data points a second. For example Data Number 10 is the value sampled at the end of the second second. Comparing the graph on Figure 34a(i) with that on Figure 34(b), only 30 data points per channel were obtained with the cultivator (Figure 34b) as compared to 67 with the moldboard plow. This is why data points on the cultivator graph are more spread out. As can be seen from the graphs, tillage forces varied in a very random form. Other than ball-park values and rate of variation, not much more information could be obtained from the graphs. Statistical analyses provided the basis of comparison of various test runs results. Figure 34 also shows the forces listed and statistical data also printed out immediately after each test run.

Figure 35 shows a typical plot obtained from using the penetrometer to obtain penetrating pressure data. Three plots were made by probing the selected spot repeatedly at points less than 10cm apart. On the same

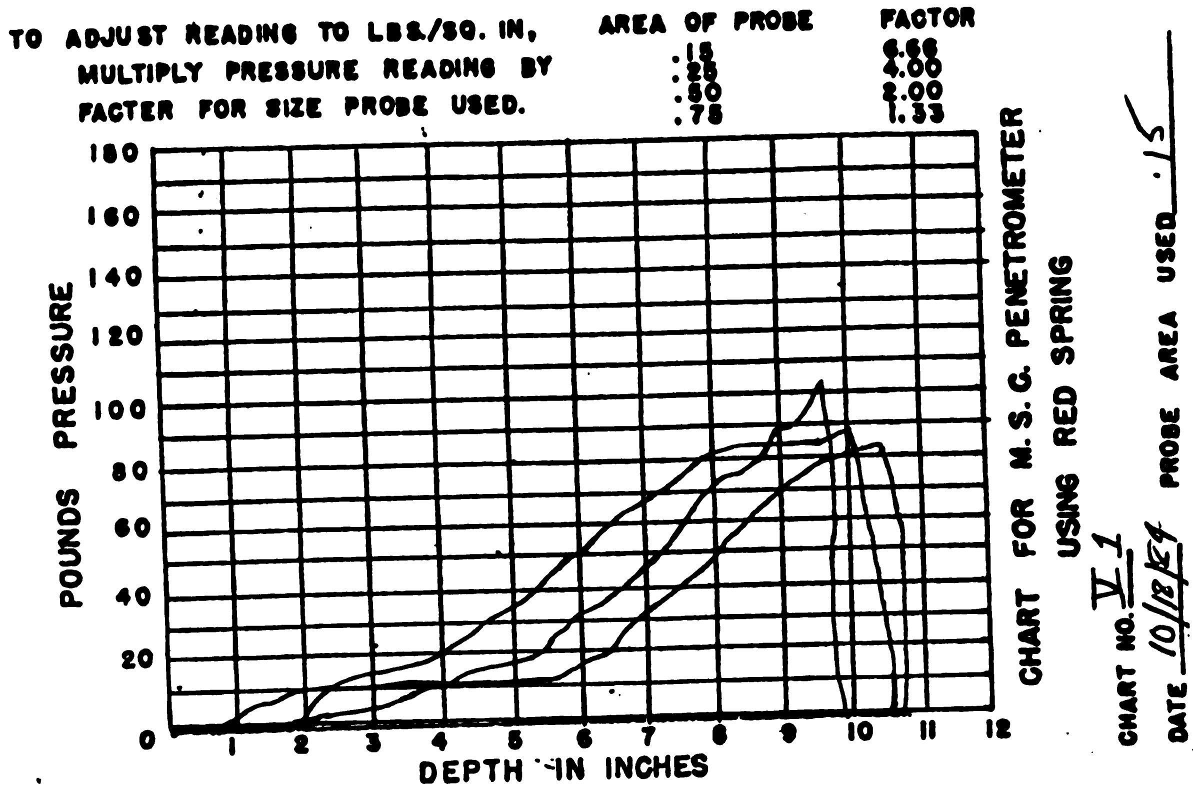


FIGURE 35: Penetrometer probe output chart showing probe area factors and typical output curves.

spot, a soil sample was also obtained for analysis. All four plots appeared on one chart as shown on Figure 35. The average of the four pressures at a depth of 15cm (6in) was computed. As can be seen on the penetrometer chart it was possible to tell where the hard pan was located (indicated by the sudden rise in penetration pressure). In most cases all three curves appeared to have the same general shape. Moisture content and dry bulk density data were obtained from the soil samples collected. Cores used had a standard volume of 347.5 cc.

Tables 3a and b show a summary of field test statistical data for moldboard plow and cultivator respectively. Initials used on these tables are defined at the bottom of Table 3(b). In total, 9 complete runs were made with the moldboard plow and a total of 7 with the cultivator. Data included is for each channel and average moisture content, bulk density, penetration resistance and tillage depth for each test run. Table 3 supplies the data used in the tillage test analysis. For analysis, averages of total vertical and total horizontal forces, as obtained from test runs for both implements were used to compare effects of moisture content, bulk density, penetrating pressure and tillage depth.

Figure 36a is a comparison plot of horizotal and vertical forces encountered in tillage with the moldboard plow. A look at Table 3 will show that the vertical forces obtained were negative in most cases. A

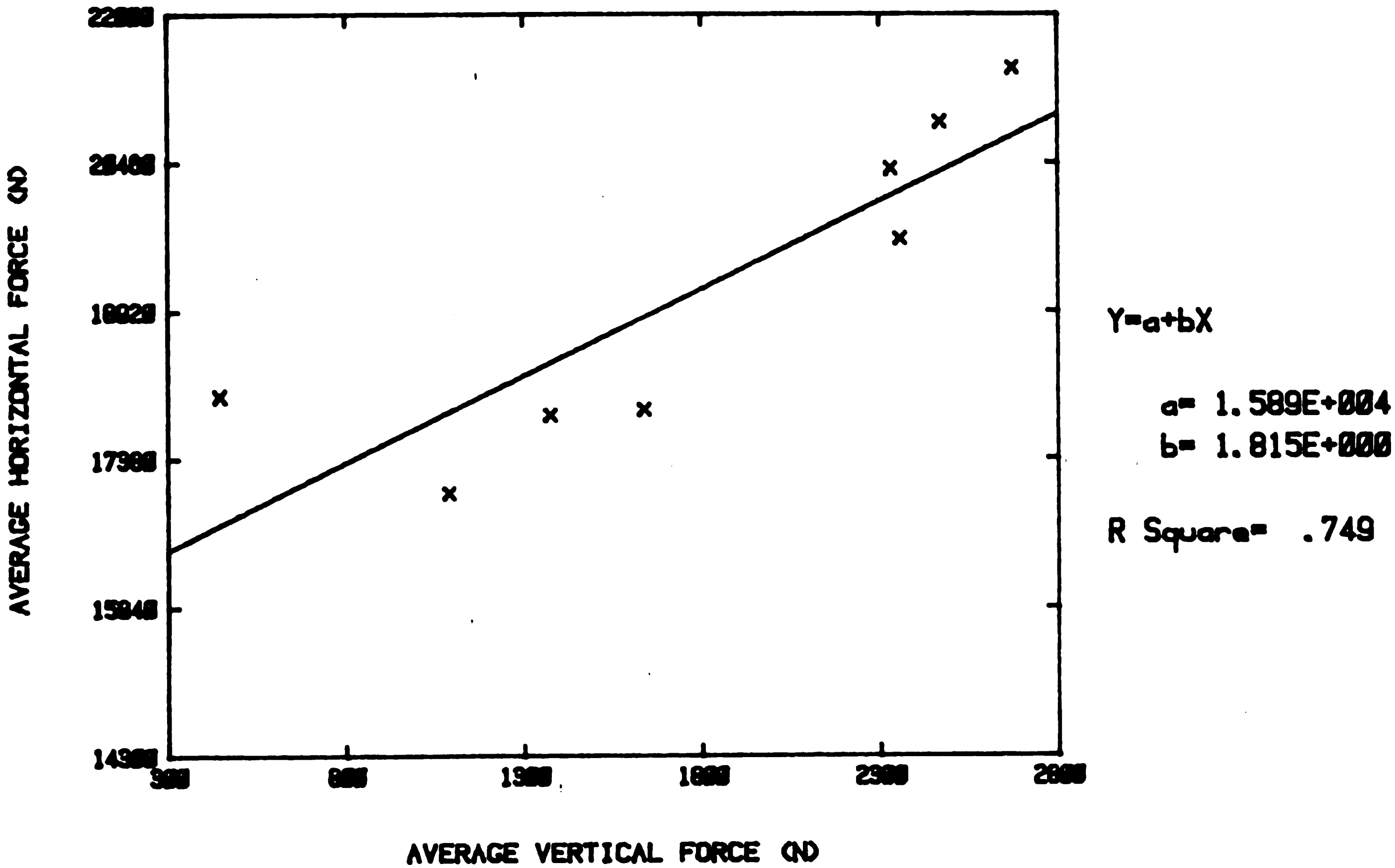


FIGURE 36a: Comparison of horizontal with vertical force for a moldboard plow.

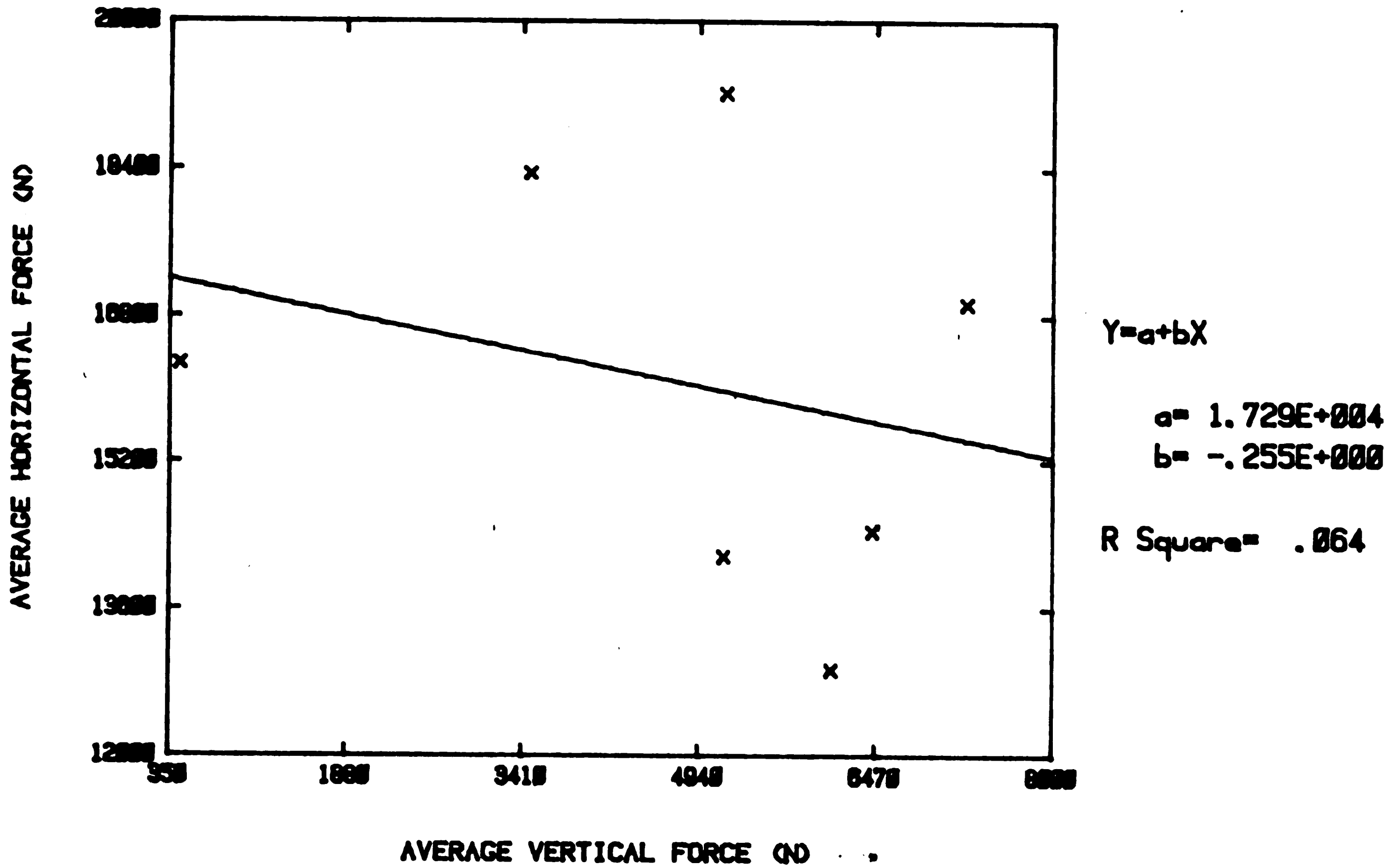


FIGURE 36b: Comparison of horizontal with vertical force for a cultivator.

negative vertical force implies a vertically downward directed force. For analysis and comparison purposes absolute values of the vertical forces were used.A rise on the negative scale is actually a reduction in magnitude of the vertical force.

Figures 36 a and b and 37 a(i) through d(ii) are graphs of the data on Table 3. The plots are for comparison purposes and they show variation between horizontal and vertical components of draft force and the influence on these forces of some soil physical properties. Only very general tendencies were sought in the analysis because farm soil is a complex medium to work with and much more data than was collected in this study would be necessary if conclusive remarks were to be made. Data collected in this study is therefore only illustrative and not conclusive. For conclusive studies it would also be necessary to measure effecct of other physical properties like cohesion, friction shear strength etc. It would also be necessary to measure side draft especially for a complete comparison of draft force distribution. To make the general comparisons and using the data on Table 3, linear regressions were made as a means of checking the general tendencies of various parameters to influence the horizontal and vertical components of draft. Logarithmic ($y= a+LogX$, exponential ($y=ae^{x}$) and power ($y=ax^{b}$) regression curves were also tried for a comparison of correlation coefficients between the various regressions. Compairing correlation

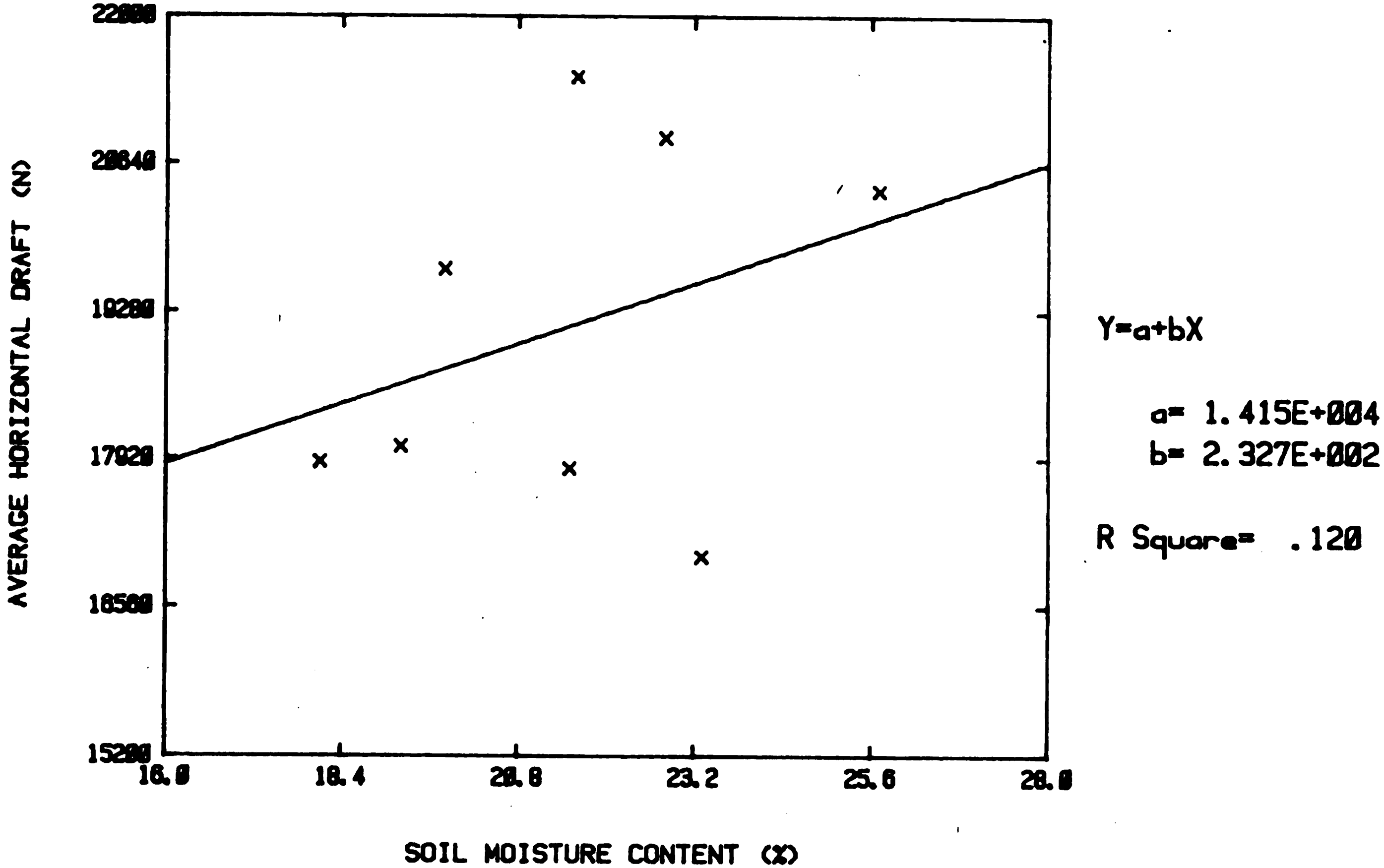


FIGURE 37a (i) : Variation of horizontal force with moisture content when working with a moldboard plow.

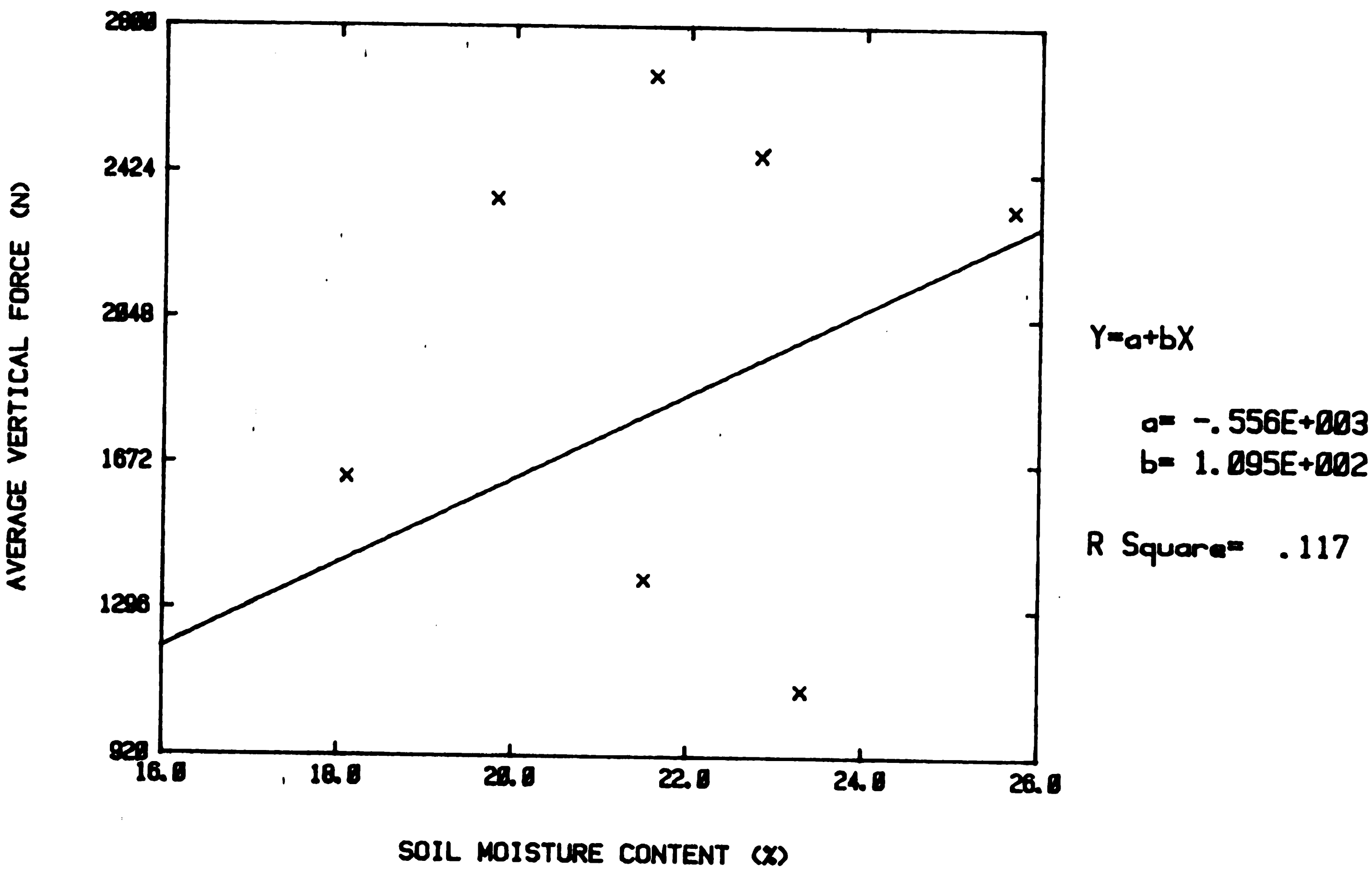


FIGURE 37a (ii) : Variation of vertical force with moisture content when working with a moldboard plow.

coefficients they varied in difference from that of linear regression by 2% (for Horizontal draft versus Moisture Content) to 54% (for vertical draft versus moisture content). Although 54% might seem a large difference graphical appearances were visually very similar. The linear regression was therefore selected as a representative basis of general comparisons.Correlation coefficients (R Square - see Figures 36 and 37) for linear regression varied between.006 and .749.

Figure 36a (Average Horizontal Force versus Average Vertical Force) shows a tendency for horizontal force to increase as vertical force increased when working with the moldboard plow. The corresponding graph (Figure 36b) for a cultivator shows a decreasing tendency of horizontal force as vertical force increased.

As mentioned earlier the hook-up of the moldboard plow on the quick-hitch needed cross-shaft modification. Moldboard adjustments therefore might not have allowed for a uniform force distribution. However as the resultant draft force increased, the components (measured) were expected to increase. This was the tendency observed on Figure 36a. Adjustments for the cultivator were non-problematic although at times it would tend to clog-up. Distribution and magnitude of force components when working with the cultivator were expected to be more random (than with moldboard plow)

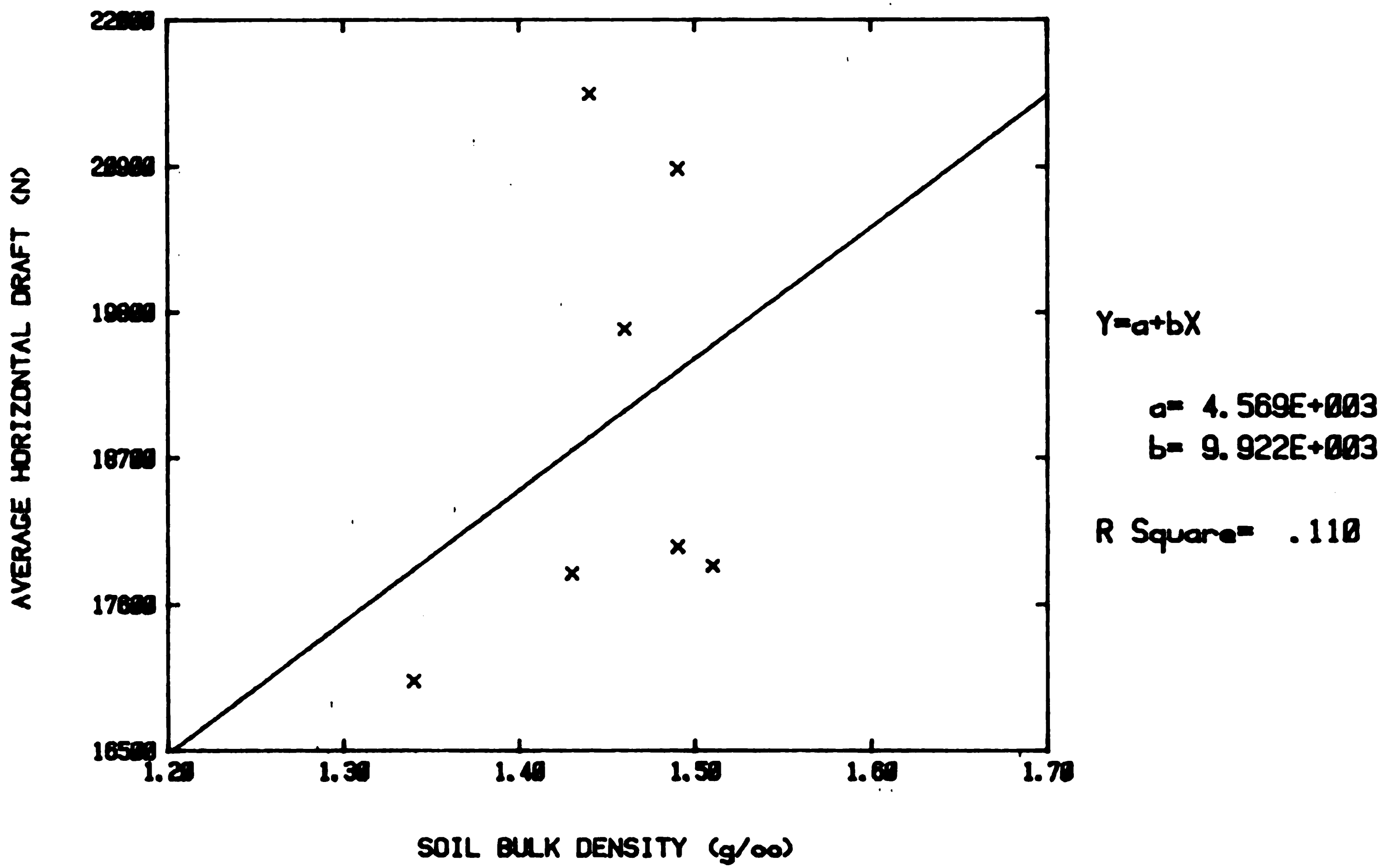


FIGURE 37b (i) : Variation of horizontal force with bulk density when working with a mold board plow.

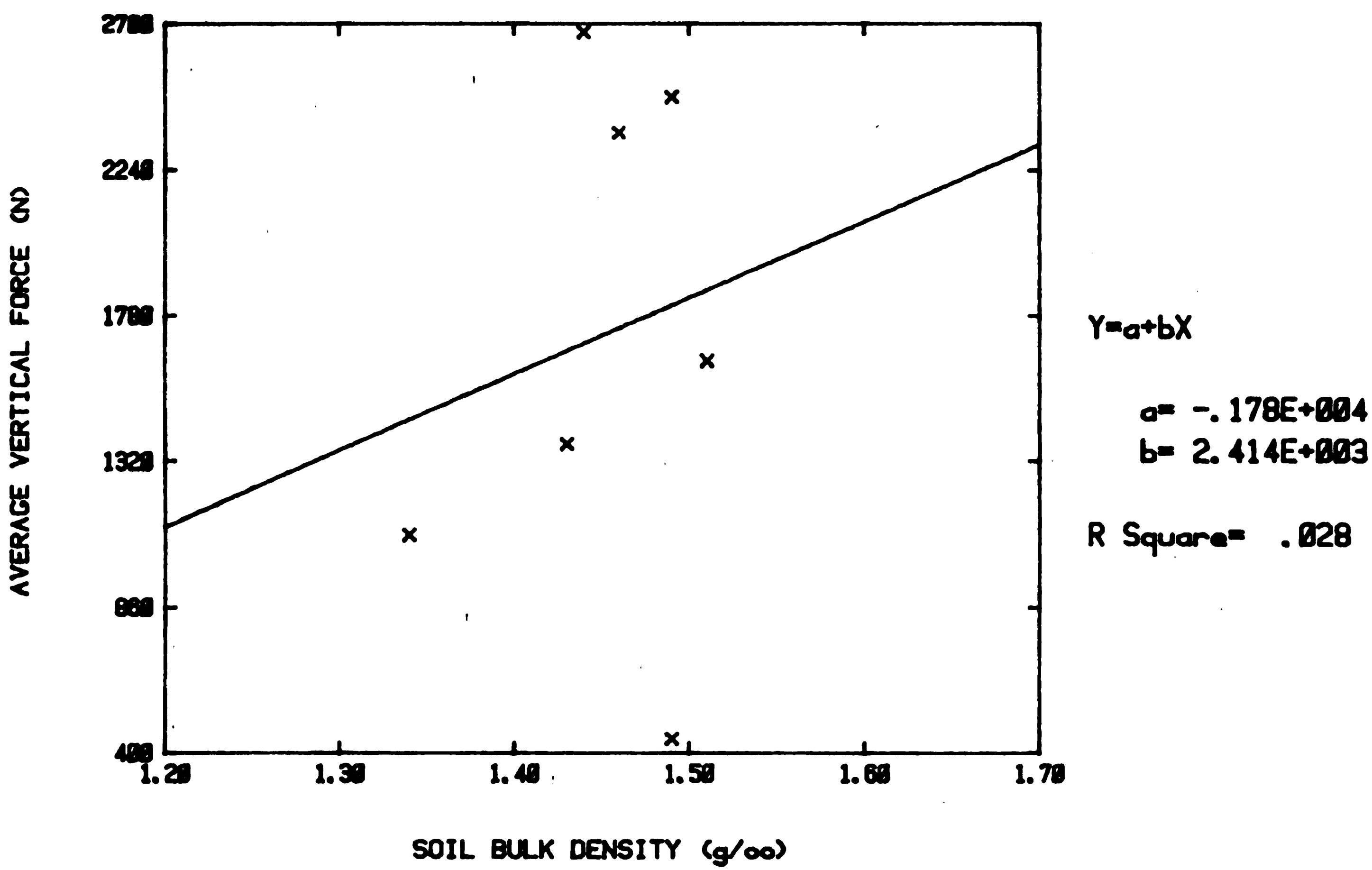


Figure 37b (ii) : Variation of vertical force with bulk density when working with a mold board plow.

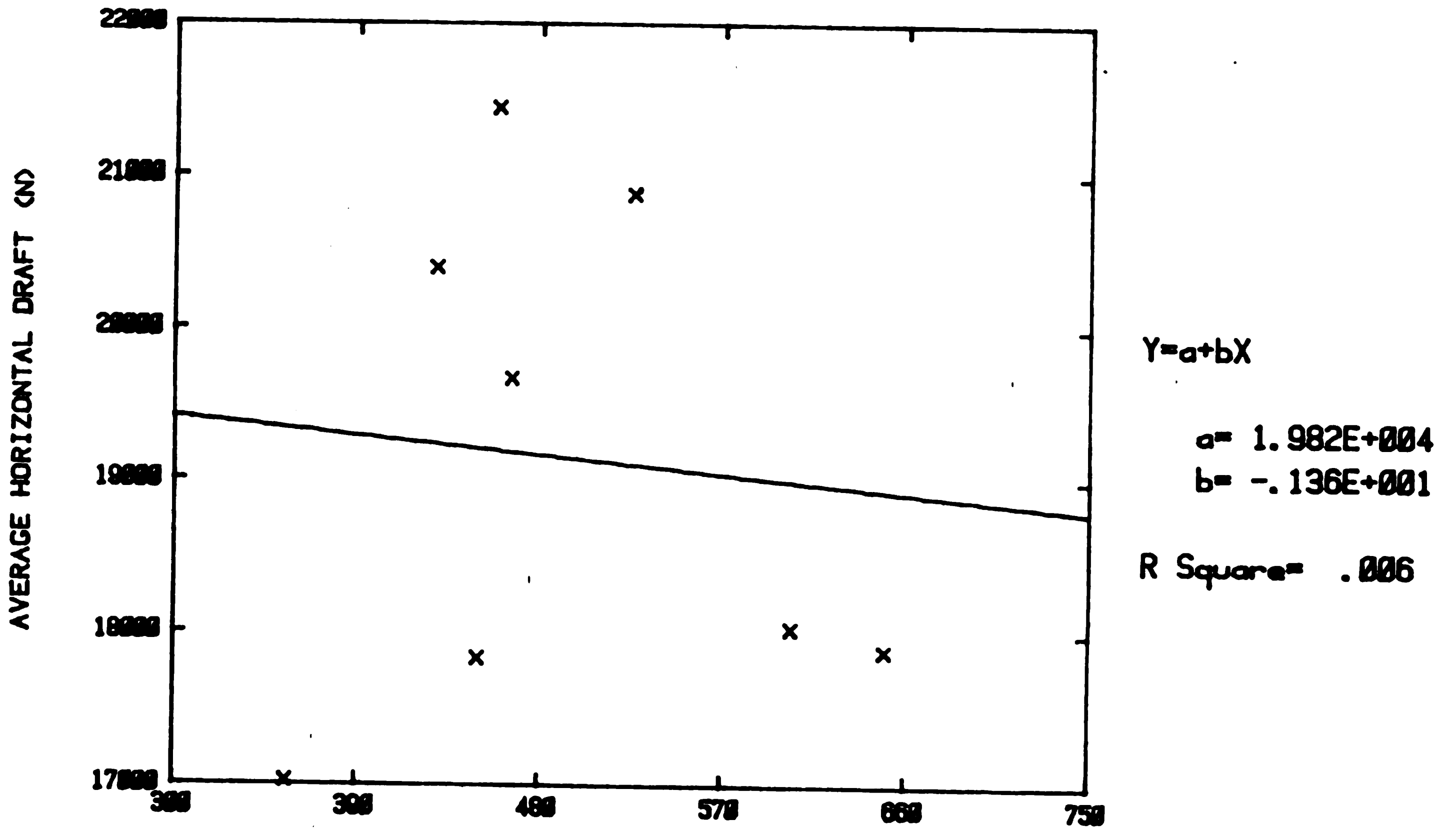


FIGURE 37c (i) : Variation of horizontal force with penetration resistance when working with a moldboard plow.

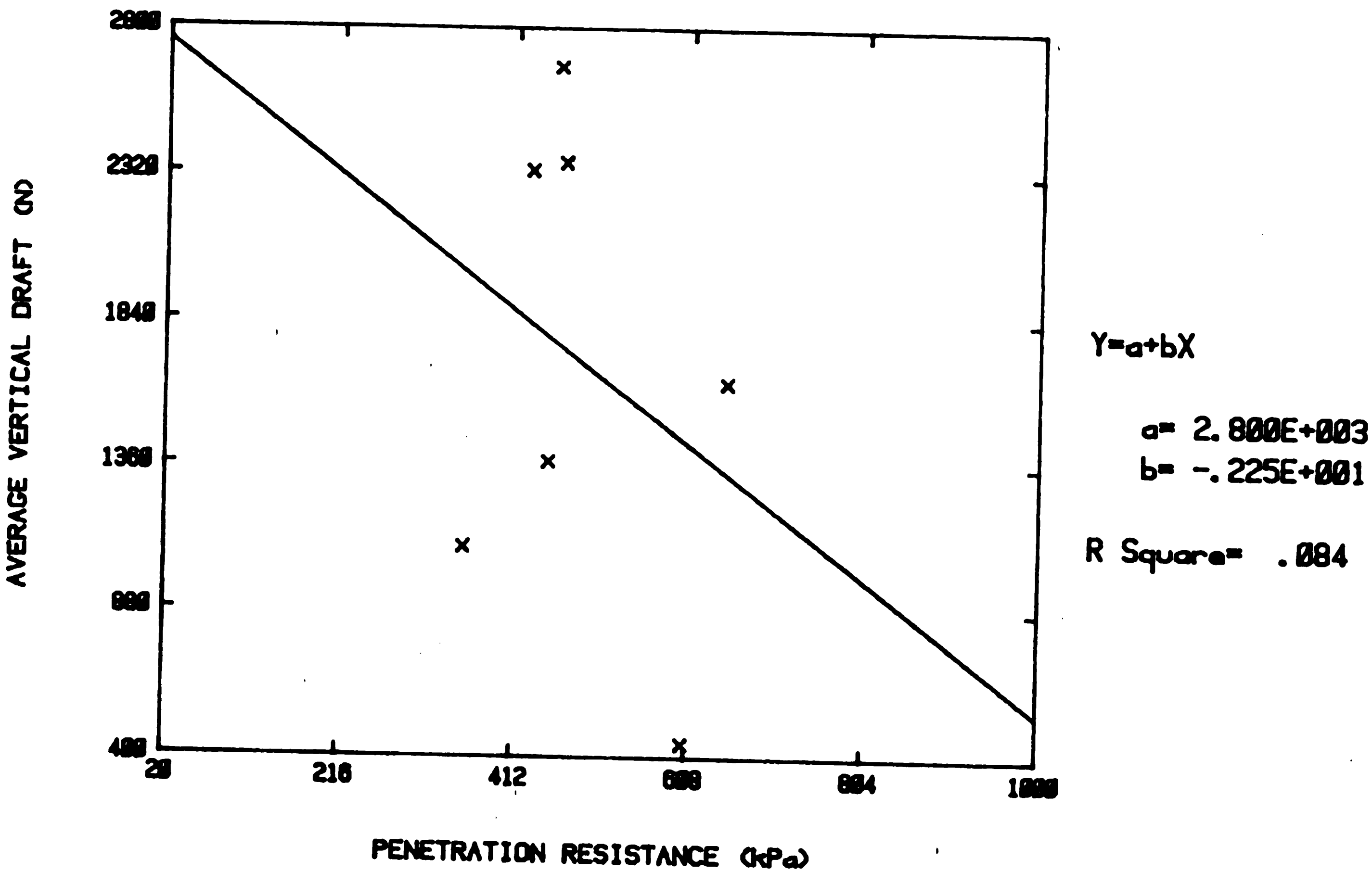


FIGURE 37c (ii) : Variation of vertical force with penetration resistance when working with a moldboard plow.

and that seems evident when Figures 36a and b are compared. The slightly negative (linear regression) slope of Figure 36b may be only a coincidence. The data is relatively randomly distributed.

Again much more data would be required to be able to make conclusive remarks. Too many variables associated with the tractor, terrain and soil physical properties determine this distribution. Figures 37a (i) through 37d (ii) show plots of variation of both horizontal and vertical forces compared to variation of other parameters mentioned above.

Figures 37a (i) and (ii) shows that moisture content of the soil has an effect upon both the horizontal and vertical draft components. The magnitude of horizontal draft component depends upon the coefficient of friction between the plow material (steel) and the particular type of soil. The magnitude of the coefficient rises to a peak and falls as moisture content is increased from a relatively low percentage value. Between moisture contents of 12 to 25%, soil goes through an adhesion phase. It reaches a peak coefficient of friction and then begins to decline as the higher moisture begins a lubricating phase. Regarding the vertical force variation with moisture content, several investigators have found that soil-metal coefficients of friction decrease as normal loads become larger, particularly in moist clays and clay loams (Kepner et al., 1980 pp121).

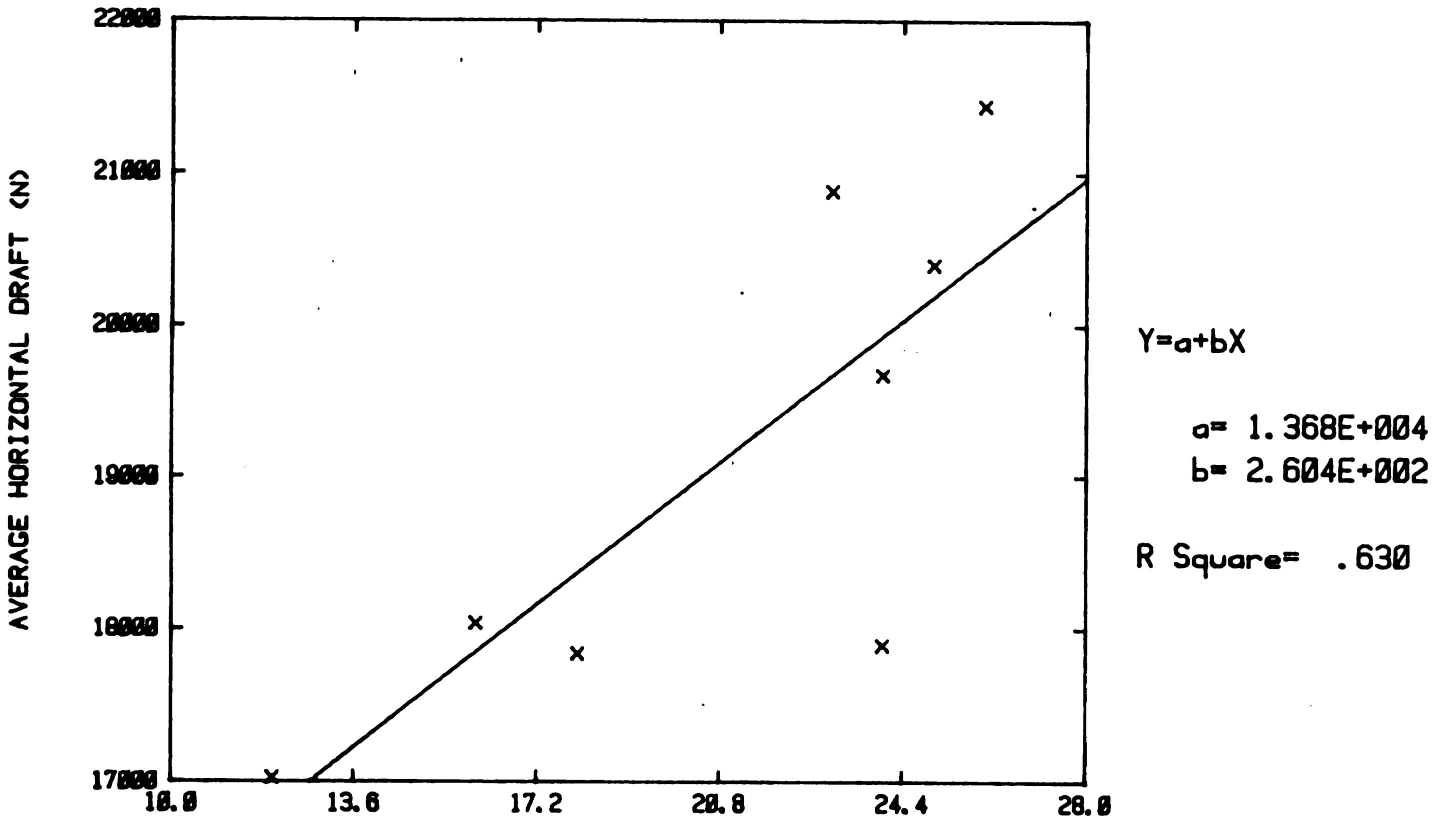


FIGURE 37d (i) : Variation of horizontal force with tillage depth when working with a moldboard plow.

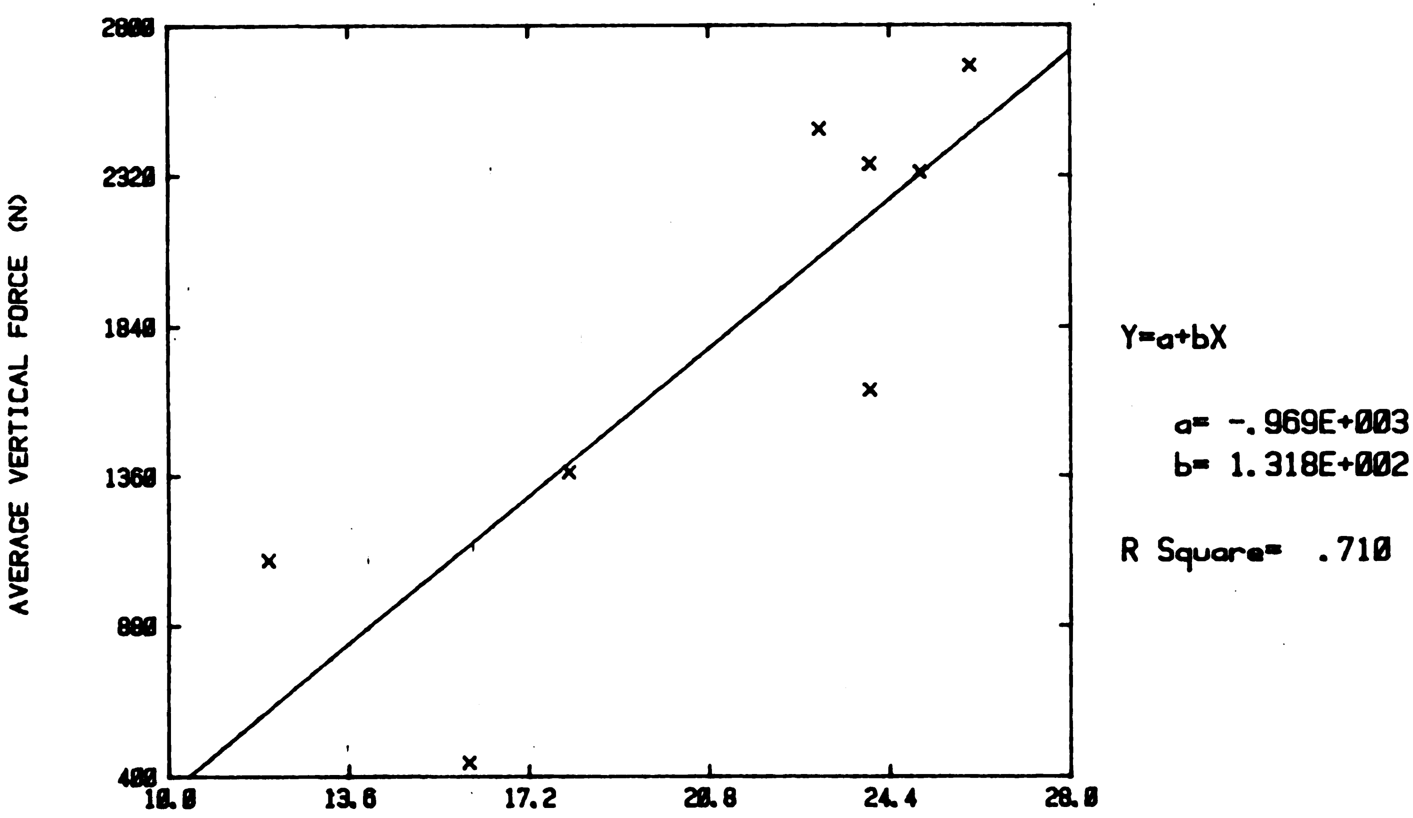


FIGURE 37d (ii) : Variation of vertical force with tillage depth when working with a moldboard plow.

HORIZ. FORCE (445N)	VERT. FORCE (445N)
2142.2	-637.31
2255	-620.52
2560.2	-740.64
2275.7	-732.62
2679.2	-784.29
2116.3	-768.47
2455	-751.08
2502.4	-776.21
2937.2	-588.71
2768.4	-979.3
2637.2	-735.82
3206.5	-633.27
2561.9	-814.64
2793.8	-556.05
2652.6	-1016.7
2299.3	-810.98
3869.7	-777.31
3148.2	-1120.8
2756.2	-1133.7
2972.1	-543.88
2605	-963.51
3038.6	-912.67
2967.3	-920.86
3199.9	-790.37
2605.8	-1001.6
2718.2	-916.27
3386.3	-1007.6
2886.1	-839.53
3423.1	-865.83
3558.4	-931.07
3328.2	-849.11
3365.9	-917.6
3377.9	-454.9
3322.1	-754.75
2711.1	-804.01
2707.1	-891.63
2985.3	-527.77
2610.2	-682.56
3109.7	-812.83
3067.3	-1005.1
3340.1	-886.76
2922.9	-787.12
2908.2	-776.47
2329	-935.84

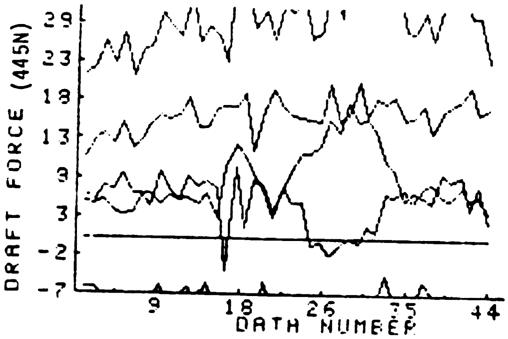


FIGURE 38(a) Typical tillage force output showing evidence of hardware failure. (Allforces in 445N)

STATISTICAL DATA FOR CHANNEL: 1

AVERAGE:	818.4
MINIMUM:	235.3
MAXIMUM:	1793.4
STD DEVN:	381.364
COEFF. OF VARTN (%):	46.60

STATISTICAL DATA FOR CHANNEL: 2

AVERAGE:	.0
MINIMUM:	-.1
MAXIMUM:	.2
STD DEVN:	.077
COEFF. OF VARTN (%):	444.70

STATISTICAL DATA FOR CHANNEL: 3

AVERAGE:	431.6
MINIMUM:	-396.2
MAXIMUM:	926.2
STD DEVN:	295.631
COEFF. OF VARTN (%):	68.49

STATISTICAL DATA FOR CHANNEL: 4

AVERAGE:	-812.7
MINIMUM:	-1133.6
MAXIMUM:	-454.9
STD DEVN:	155.274
COEFF. OF VARTN (%):	-19.11

STATISTICAL DATA FOR CHANNEL: 5

AVERAGE:	1615.0
MINIMUM:	1061.5
MAXIMUM:	2052.0
STD DEVN:	233.227
COEFF. OF VARTN (%):	14.44

STAT.DATA FOR TOTAL HORIZ. FORCE

AVERAGE:	2865.1
MINIMUM:	2116.3
MAXIMUM:	3869.7
STD DEVN:	404.761
COEFF. OF VARTN (%):	14.13

STAT. DATA FOR TOTAL VERT. FORCE

AVERAGE:	-812.7
MINIMUM:	-1133.7
MAXIMUM:	-454.9
STD DEVN:	155.293
COEFF. OF VARTN (%):	-19.11

FIGURE 38(b): Statistical analysis results for output with evidence of hardware failure. (All forces in 445N)

HORIZ FORCE (445N)	VERT FORCE (445N)
3.762E12	32.36
3.762E12	31.24
3.762E12	32.06
3.762E12	32.5
-3.762E12	31.3
3.762E12	31.62
3.762E12	31.89
3.762E12	30.93
-3.762E12	30.6
3.762E12	48.92
3.762E12	46.01
3.762E12	54.57
3.762E12	54.06
3.762E12	51.14
3.762E12	51.21
3.762E12	51.75
3.762E12	51.14
3.762E12	52.9
-3.762E12	50.89
3.762E12	49.35
-3.762E12	49.48
3.762E12	49.05
3.762E12	49.8
3.762E12	49.88
3.762E12	48.16
3.762E12	50.48
-3.762E12	48.67
3.762E12	48.12
3.762E12	47.16
-3.762E12	45.33
-3.762E12	46.4
3.762E12	47.89
3.762E12	47.34
3.762E12	50.5
3.762E12	48.48
3.762E12	48.38
3.762E12	47.3
3.762E12	47.17
3.762E12	47.14

STATISTICAL DATA FOR CHANNEL 1

AVERAGE: -166870.5E-003
MINIMUM: -165750.0E-003
MAXIMUM: -124660.0E-003
STD DEVN: 22946321.63E-006
COEFF. OF VARTN (%): -13.75

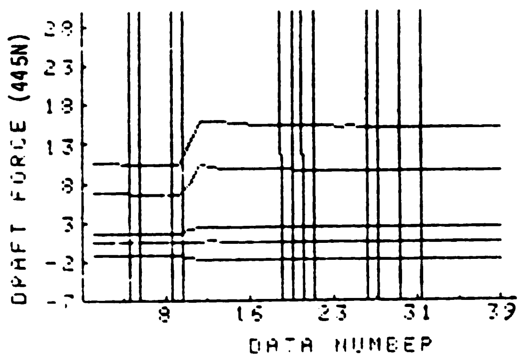


FIGURE 38(c) Typical output showing evidence of short-circuiting problem in the wiring of channel 1.

While no coefficient of friction data were obtained in this test, no conclusive discussion can be made from plots of Figure 37a (i) and (ii). A look at variation on Figure 37a (i), however would imply an adhesion phase as horizontal draft seems to increase with increased moisture content.

Figures 37b (i) and (ii) show that as penetration pressure increases both horizontal and vertical force components decrease. It would seem reasonable to expect that there is reduced implement penetration and hence lower horizontal resistance at the implement/soil interface as penetration pressure (resistance) increases. This also results in a lower vertical force. In the most part this is supported by the graphs obtained.

It would also seem reasonable to expect that penetrating pressure should vary in an equivalent manner as the bulk density. The same argument would then hold for variation in vertical and horizontal draft. However soil of a large bulk density is necessarily heavier and more difficult to not only turn over but also pass an implement through (due to large cohesive forces). The tendency observed of both horizontal and vertical draft components to increase with increasing bulk density supports this theoretical argument.

Figures 37d (i) and (ii) both show a general increase in force with increase in tillage depth. From theory it would be expected that increased depth should

FORCE(445N)
-238 52
-238 52
- 03042
-.08112
02028
-.03042
-.13182
.02028
-.08112
-.08112
-.08112
-.08112
-.08112
-.03042
.02028
-.08112
-.13182
-.08112
-.08112
-.08112
-.03042
-.03042
.02028
-.03042
.02028
-.03042
-.03042
.02028
-.03042
-.03042
-.08112
-.08112
-.03042
.02028
-.03042
-.03042
.07098
.07098
.07098
.02028
-.03042
-.08112
-.03042
.02028
-.03042
.07098
-.08112
-.08112
.02028
.07098
02028
.02028
-.03042
.02028

STATISTICAL DATA FOR CHANNEL 1

AVERAGE	-4.5
MINIMUM	-238.5
MAXIMUM	.1
STD DEVN	32.760
COEFF. OF VARTN (%):	-723.75

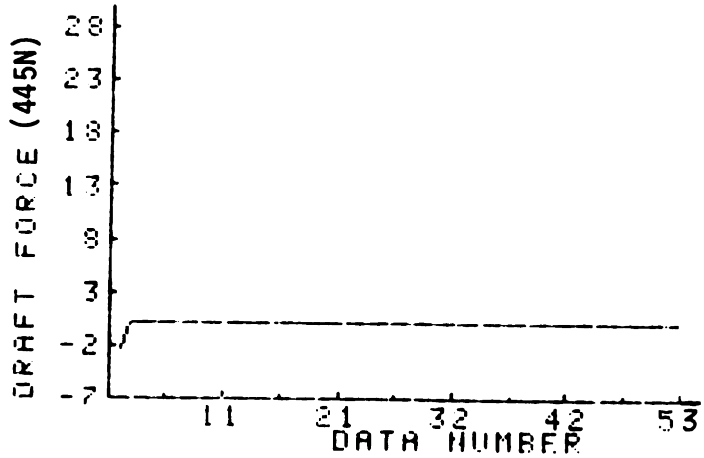


FIGURE 39: **Noise-error test without strain gage excitation.**

FORCE(445N)
163.91
8.5645
-2.7923
-.71355
-5.9357
-11.969
-13.845
7.1449
.65535
-24.086
-4.2119
-27.331
4.762
-7.7609
1.72
8.0068
-26.418
-6.4427
-12.324
-3.6542
4.5592
-6.4934
-24.492
-7.1525
2.0242
8.0068
-9.5354
-3.9077
-20.436
-4.0598
-4.7696
-13.743
-7.2032
-16.177
-25.05
-16.735
.19905
-4.4654
-4.1105
-16.785
-1.0178
-5.1752
-6.7976
-51.819
-18.154

STATISTICAL DATA FOR CHANNEL: 1

AVERAGE:	-4.6
MINIMUM:	-51.8
MAXIMUM:	163.9
STD DEVN:	28.199
COEFF. OF VARTN (%):	-615.97

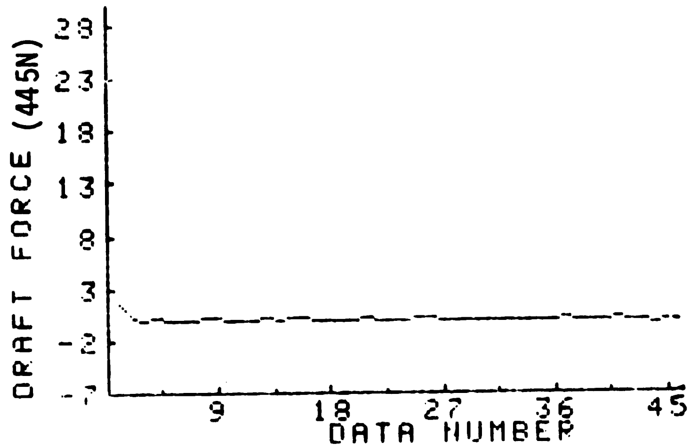


FIGURE 40: **Noise-error test with strain gage excitation.**

tend to increase draft. Consequently therefore both horizontal and vertical components of force should increase with increased tillage depth. At larger depths there's more soil/tool interaction hence more frictional resistance and soil weight. The resultant force angle also increases (see Figure 21) as depth increases.

Figure 38 demonstrates how easily evidence of hardware failure was detected in the output. Output graphs with excessive readings, (shown by vertical curves - Figure 38c), or very close to perfectly horizontal line graphs (zero - reading) Figure 38b, implied system misfunction. Excessive unexpected outputs, were evidence of short-circuiting in the bridge wiring. Non-varying zero voltage implied discontinuity in the wiring. This was also evidenced in the statistical output (see channel 2 statistical output, Figure 38b). A distinctly different coefficient of variation is also recorded for this channel.

5.3.1 Noise-Error Sources Test Results

Figures 39 and 40 show results of test for error due to electrical noise. Figure 39 is a typical output of data sampled in the field with the bridge circuit power cut off. The corresponding single channel statistical output data is shown.

Figure 40 shows the output for the noise test in the field with bridge excitation switched on. The test with gages excited is a little more irregular, a response by the transducers to the tractor vibration during travel over the rough ground.

At the beginning of the test there appeared to be a trauma in the system which resulted in a noise signal. This signal is recorded at the beginning of the graph of Figure 40. A look at the list of forces sampled, on this same figure shows a relatively large first value which makes the mean appear to be relatively large. The averages with and without gage excitation seem close and approximately zero except for the noise error due to starting trauma. While several sampling speeds were tried, no significant difference was evident between the outputs. Thus the error due to noise, except at the beginning of a particular test, was considered to be absent. At higher sampling speeds some noise from the surrounding engine electrical systems and hardware vibration, may affect the data.

5.3.2 Hardware Performance

At the end of the field test, the dynamometer and its related hardware had been exposed to vigorous shock loads and vibration. The transducers stood up to the torture quite effectively. The only weakness was the top transducer support. While this beam performed well in tillage it showed weakness in the implement transport position. There was excessive load arising from the implement overhang. This load was more severe to the support than to the pin itself. The transducer stayed relatively straight and maintained calibration, but the support was deformed.

At the end of the field test, a check was made to determine how much the transducer outputs had changed from those at calibration time - a test for the amount of permanent strain acquired. This was done by rebalancing all channels, switching the calibration resistors into the circuits and comparing outputs with those obtained at calibration time. Table 4 shows the resulting percentage differences for the various channels. The values indicate the amount of permanent strain acquired during the tillage process.

Table 4

Permanent Strain Test Results.

Channel	Force component measured	Calibration change (%)
1	LRH	6.3
2	LRV	2.2
3	LLH	5.4
4	LLV	1.8
5	UH	14.0

LRH = lower right horizontal force

LRV = lower right vertical force

LLH = lower left horizontal force

LLV = lower left vertical force

A count was made of number of times sampled loads exceeded the maximum calibration loads. The load that exceeded the calibration by the greatest amount was that of lower right horizontal component when working with the moldboard plow. These loads exceeded maximum calibration loads 27% of the time. There was no detrimental effect of these excess loads on the dynamometer.

6. SUMMARY AND OBSERVATIONS

6.1 Summary

Tillage consumes a major part of the energy input in the farm system. To increase knowledge of energy required by the tillage operation, forces between the implement and tractor need to be measured. As fully mounted and semimounted implements have increased over the years, the three point hitch dynamometer has become necessary. In development of strain gage transducer measurement systems, placement of the strain gage transducers has varied. Of the various alternatives, a frame to carry the transducers between the tractor and implement has become the most convenient.

A three point hitch dynamometer was developed, which used a quick coupler to support the strain gage transducers. This dynamometer was calibrated, verified and field tested for capabilities and limitations as a future tillage energy research tool. A micro-computer based data acquisition system was utilized for obtaining data at all stages of the development and testing process. A computer program was written to control data collection. The same program was capable of doing a statistical analysis of the data making the whole process capable of giving real time performance feedback.

Two implements were used in the on-farm tillage test. Data for tillage forces, tillage depth and soil physical properties were obtained. Results were analyzed to see if relationships between variation of the forces and variation in soil physical properties were as expected. This test confirmed quality of performance of the dynamometer. Presence of electrical noise in the measurement system was also examined.

A reasonably good demonstration of the system's performance capabilities and limitations was accomplished. With the integration of other energy-related parameters of the tillage systems, into the data acquisition system, a full input/output energy utilization study is possible.

6.2 Observations

The dynamometer developed, proved to be relatively simple and economically feasible to build. After the weaker points were corrected, the dynamometer's performance was excellent. The data acquisition system and power supply proved very satisfactory and convenient. The cantilever type force transducer support will require strengthening because this is currently a weak point. The following are general observations about the dynamometer performance:

a) The transducers maintained calibration effectively with the exception of a maximum permanent strain of 14% for the upper transducer.

b) The dynamometer is a useful tool for a detailed measure of draft force magnitude, distribution and direction among the three linkage arms. The effect on this distribution as influenced by type of implement, tillage depth and soil physical properties suggests many possible and interesting studies.

c) At the signal sampling speeds used, no significant amount of electrical noise appeared to affect the force-initiated off-balance signal. Much higher sampling speeds would be required to detect any such signal, if it existed.

d) The ability of the data acquisition system to measure, store and make real-time plots and analysis of data provided great time saving and convenience. It was possible to enter tillage test data before each test.

e) Errors and hardware failures were easily detected from the observation of the output. Software errors could be quickly corrected while still in the field.

f) Performance accuracy of the dynamometer was better at higher loads. Transducer sensitivity was adequate for all data sampling speeds used and for the resolution required. Hysteresis on the transducers was insignificant.

g) Total force on the tractor due to the implement soil interaction was not a function of soil alone. While hitch geometry and terrain may determine the distribution and magnitude of the force, there may be a dynamic load reaching the dynamometer and therefore getting measured as if it was part of the draft force. This load depends on parameters like type of field, length of plots tire pressure etc. It was not separable from the load due to soil alone.

6.3 Future Work

The development and testing of this tillage force measuring system was part of an on-going effort to develop a fully instrumented tractor for complete input/output energy analysis. Although the tractor instrumentation system has experienced various tradeoffs among time, cost, accuracy and availability of equipment; (as it has undergone development), the three-point-hitch dynamometer was the part of tractor system that required major effort. Other parts needed for the instrumentation package will be required to measure side draft, drive wheel axle torque and rotating speed, fuel consumption, PTO torque and speed, ground and engine speeds.

While the three-point-hitch dynamometer performed well, its main weakness was physical strength. To correct this the following should be done before more tillage work is conducted:

a) Heat treat the transducer support beams and make them from a completely solid steel beam, with necessary framework to reinforce them.

b) Locally manufacture sensing pins which will in turn be made long enough on the threaded side, hence enough room for more grip by the nut. The inner locking half-nut will be replaced with a collar hence supplying enough locking strength. This may need a minor modification of tractor links if the diameter of the pins is increased.

c) A cross-bar should be made, for use across the two lower hitching points, for one and two point semi-mounted implements.

d) A more convenient calibration loading mechanism should be developed. A system that utilized static loading units (weights) would be excellent. This would eliminate the dynamics of the load, encountered in the system used.

e) A more moisture resistant strain gage cover (other than the unreliable silicon rubber) should be used. This will prevent spurious strain, swelling or contraction of cement, loss of insulation resistance within the wire grid plus electrolytic polarization that was possibly caused by moisture that leaked into the bonding area.

f) An instrument with an analog electrical signal output to measure tillage depth would be a useful part of the instrumentation package.

g) A study on a means to separate the dynamic load on the tractor from loads due to soil/implement interaction alone is suggested (see Section 6.2)

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A P E N D I X

LISTINGS OF THE DATA ACQUISITION PROGRAMS. INCLUDED ARE THE TWO COMPUTER PROGRAMS USED. THE FIRST ONE IS FOR FIVE CHANNEL (SIMULTANEOUS SAMPLING) AND THE SECOND ONE IS THE MODIFIED VERSION USED TO SAMPLE ONE CHANNEL AT ELEVATED SAMPLING SPEEDS WHICH THE THE FIRST ONE COULD NOT HANDLE. SEE SECTION 4.5 OF THE TEXT.

MULTICHANNEL SAMPLING DATA COLLECTION CONROL AND ANALYSIS PROGRAM

```
 10 CLEAR
 20 OPTION BASE 1
 30 COM J,T1,S2,W,M1,M2
 40 REAL H(7,5)
 50 ! ENABLE KBD 1+8+32+128
 60 SHORT A(554),B(554),C(554),D
    (554),E(554),P(554),Q(554)
 70 DIM A$[32]
 80 DISP "ENTER TEST DATA e g M/
    BOARD/PASS1/JUNE6"
 90 INPUT B$
100 A$="READY TO TAKE DATA"
110 K=0 @ N=0
120 REM THE F'S ARE CALIBRATION
    FACTORS
130 F(1)=887 @ F(2)=848 @ F(3)=8
    13 @ F(4)=632 @ F(5)=799
140 GOTO 2580
150 ON KEY# 1,"DATA" GOTO 480
160 ON KEY# 2,"STOP" GOTO 240
170 ON KEY# 3,"PLOT" GOTO 370
180 ON KEY# 4,"STORE" GOTO 2340
190 ON KEY# 5," Z/C " GOTO 2580
200 OFF KEY# 6
210 OFF KEY# 7
220 OFF KEY# 8
230 GOTO 350
240 OUTPUT 709 ;"T00"
250 N=N-1
260 CLEAR
270 DISP "I AM SUMMING FORCES"
280 PRINT "HORIZ FORCE",TAB(16);
    "VERT  FORCE"
290 PRINT
300 FOR I=1 TO N
310 P(I)=A(I)+C(I)+E(I)
320 Q(I)=B(I)+D(I)
330 PRINT P(I);TAB(16);Q(I)
340 NEXT I
350 CLEAR
360 BEEP
370 KEY LABEL
380 DISP
390 DISP "DATA COLLECTED AND STO
    RED BY PRESSING USER DEFINED
     KEYS"
400 DISP
410 DISP "KEY# 1 START DATA COLL
    ECTION"
420 DISP "KEY# 2 STOP DATA INPUT
    "
430 DISP "KEY# 3 PLOT  LATEST DA
    TA SAMPLED"
440 DISP "KEY# 4 STORE DATA"
450 DISP
460 DISP A$
470 GOTO 470
480 ! ------------------------
490 ! Data sampling Subroutine
500 ! ------------------------
```

```
510 CLEAR
520 DISP USING "8/6X,20A" ; "DAT
    A BEING COLLECTED"
530 KEY LABEL
540 A$="READY TO PLOT & STORE DA
    TA"
550 CLEAR 709
560 OUTPUT 709 ;"TO200AE1AF1AL5V
    R3"
570 OUTPUT 709 ;"VS1VF1VN5VO5VA1
    "
580 N=0
590 WAIT 1000
600 N=N+1
610 OUTPUT 709 ;"AC1VT2SO1"
620 OUTPUT 709 ;"VS"
630 ENTER 709 ; A(N),B(N),C(N),D
    (N),E(N)
640 A(N)=(A(N)-Z(1))*F(1)
650 B(N)=(B(N)-Z(2))*F(2)
660 C(N)=(C(N)-Z(3))*F(3)
670 D(N)=(D(N)-Z(4))*F(4)
680 E(N)=(E(N)-Z(5))*F(5)
690 IF N>399 THEN 240
700 GOTO 600
710 ! ---------------------
720 ! Sampling Explained
730 ! ---------------------
740 ! TO200-TTL pulse output eve
    ry .2 seconds
750 ! AE1-External channel incre
    ament
760 ! AF1-Let first channel be 1
770 ! AL5-Let last channel be 5
780 ! VR3-Data signals are in 10
    volt range
790 ! VF1-Format is ASCII
800 ! VN5-Five readings per trig
    ger
810 ! VO5-# of digits Note:MORE
    DIGITS IMPLIES LOWER CONVERS
    ION SPEED
820 ! VA1-Auto Zero VA is"ON" No
    te READING RATE IS HALVED BU
    T ACCURACY IMPROVED"
830 ! VS1-Storage in ASCII
840 ! AC1-Close channel 1-(Start
     sampling all channels)
850 ! VT2-Trigger externally
860 ! SO1-System wait for output
    -ON
870 ! --------------------
880 !  Plot data subroutine
890 ! --------------------
900 PRINT @ PRINT
910 PRINT B$
920 PRINT
930 GRAPH
940 PEN 1 @ GCLEAR
950 PLOTTER IS 1
```

```
960 LOCATE 25,130,20,90
970 SCALE 0,N+1,-7,30
980 FXD 0,0
990 REM **LABEL AND DRAW AXES***
1000 LAXES -(N/10),5,0,-7,2,1
1010 FOR J=1 TO 7
1020 MOVE 0,0
1030 K=0 @ T1=0 @ S2=0
1040 FOR I=1 TO N
1050 CLEAR
1060 GRAPH
1070 K=K+1
1080 ON J GOTO 1090,1160,1230,13
     00,1370,1440,1510
1090 LINETYPE 1
1100 W=A(I)
1110 A(I)=A(I)/100
1120 PLOT K,A(I)
1130 A(I)=A(I)*100
1140 GOSUB 2920
1150 GOTO 1570
1160 LINETYPE 5
1170 W=B(I)
1180 B(I)=B(I)/100
1190 PLOT K,B(I)
1200 B(I)=B(I)*100
1210 GOSUB 2920
1220 GOTO 1570
1230 LINETYPE 6
1240 W=C(I)
1250 C(I)=C(I)/100
1260 PLOT K,C(I)
1270 C(I)=C(I)*100
1280 GOSUB 2920
1290 GOTO 1570
1300 LINETYPE 7
1310 W=D(I)
1320 D(I)=D(I)/100
1330 PLOT K,D(I)
1340 D(I)=D(I)*100
1350 GOSUB 2920
1360 GOTO 1570
1370 LINETYPE 8
1380 W=E(I)
1390 E(I)=E(I)/100
1400 PLOT K,E(I)
1410 E(I)=E(I)*100
1420 GOSUB 2920
1430 GOTO 1570
1440 LINETYPE 8
1450 W=P(I)
1460 P(I)=P(I)/100
1470 PLOT K,P(I)
1480 P(I)=P(I)*100
1490 GOSUB 2920
1500 GOTO 1570
1510 LINETYPE 8
1520 W=Q(I)
1530 Q(I)=Q(I)/100
1540 PLOT K,Q(I)
```

```
1550 Q(I)=Q(I)*100
1560 GOSUB 2920
1570 NEXT I
1580 ALPHA
1590 T2=T1^2
1600 S=((S2-T2/N)/(N-1))^.5
1610 V1=T1/N
1620 C3=S*100/V1
1630 GOSUB 3010
1640 ON J GOTO 1650,1670,1690,17
     10,1730,1750,1770
1650 P=1
1660 GOTO 1780
1670 P=2
1680 GOTO 1780
1690 P=3
1700 GOTO 1780
1710 P=4
1720 GOTO 1780
1730 P=5
1740 GOTO 1780
1750 P=6
1760 GOTO 1780
1770 P=7
1780 FOR L=1 TO 5
1790 ON L GOTO 1800,1820,1840,18
     60,1880
1800 H(P,L)=V1
1810 GOTO 1890
1820 H(P,L)=M1
1830 GOTO 1890
1840 H(P,L)=M2
1850 GOTO 1890
1860 H(P,L)=S
1870 GOTO 1890
1880 H(P,L)=C3
1890 NEXT L
1900 GRAPH
1910 REM V1=AVERAGE @ M1=MINIMUM
      @ M2=MAXIMUM
1920 REM S=STD DEVIATION @ C3=CO
     EFF. OF VARIATION
1930 NEXT J
1940 MOVE N/2 5,-12
1950 LDIR 0
1960 LABEL "DATA NUMBER"
1970 MOVE -(N/8),-7
1980 LDIR 90
1990 LABEL "DRAFT FORCE 100LB"
2000 COPY
2010 !
2020 REM ** END OF PLOT **
2030 ALPHA
2040 FOR U=1 TO 7
2050 IF U=6 THEN GOTO 2080
2060 IF U=7 THEN GOTO 2100
2070 PRINT USING 2230 ; U @ GOTO
      2120
2080 PRINT USING 2240 @ PRINT US
     ING 2260 @ PRINT USING 2260
```

```
2090 GOTO 2130
2100 PRINT USING 2250 @ PRINT US
     ING 2260 @ PRINT USING 2260
2110 GOTO 2130
2120 PRINT USING 2260
2130 PRINT
2140 FOR V=1 TO 5
2150 IF V=1 THEN PRINT USING 227
     0 ; H(U,V)
2160 IF V=2 THEN PRINT USING 228
     0 ; H(U,V)
2170 IF V=3 THEN PRINT USING 229
     0 ; H(U,V)
2180 IF V=4 THEN PRINT USING 230
     0 ; H(U,V)
2190 IF V=5 THEN PRINT USING 231
     0 ; H(U,V)
2200 NEXT V
2210 PRINT @ PRINT
2220 NEXT U
2230 IMAGE "STATISTICAL DATA FOR
      CHANNEL:",1X,DD
2240 IMAGE "STAT DATA FOR TOTAL
     HORIZ. FORCE"
2250 IMAGE "STAT. DATA FOR TOTAL
      VERT  FORCE"
2260 IMAGE "------------------------
     ------------"
2270 IMAGE "AVERAGE:",1X,DDDDDDD
     .D
2280 IMAGE "MINIMUM:",1X,DDDDDDD
     .D
2290 IMAGE "MAXIMUM:",1X,DDDDDDD
     .D
2300 IMAGE "STD DEVN:",1X,DDDDDD
     DDD.DDD
2310 IMAGE "COEFF. OF VARTN (%):
     ",1X,DDDDDD.DD
2320 DISP USING "8/6X,28A" ; "WI
     SH TO STORE DATA?-Key #4"
2330 GOTO 470
2340 ! ------------------
2350 ! Storing Subroutine
2360 ! ------------------
2370 A$="READY FOR NEXT IMPLEMEN
     T"
2380 CLEAR
2390 DISP "ENTER FILE NAME FOR P
     RESENT STORAGE"
2400 INPUT D$
2410 KEY LABEL
2420 CREATE D$,1,63*N
2430 ASSIGN# 1 TO D$
2440 PRINT# 1 ; N
2450 FOR I=1 TO N
2460 ! A(I)=A(I)*100
2470 ! B(I)=B(I)*100
2480 ! C(I)=C(I)*100
2490 ! D(I)=D(I)*100
2500 ! E(I)=E(I)*100
```

```
2510 ! P(I)=P(I)*100
2520 ! Q(I)=Q(I)*100
2530 PRINT# 1 ; A(I),B(I),C(I),D
     (I),E(I),P(I),Q(I)
2540 NEXT I
2550 ASSIGN# 1 TO *
2560 GOTO 350
2570 END
2580 !
2590 ! ------------------------
2600 ! Zero and Calibration sub
2610 ! ------------------------
2620 CLEAR 709
2630 OUTPUT 709 ;"SI" ! Initiali
     ze scanner.  See Mainframe
     instr631 A(I)=A(I)*100
2640 CLEAR
2650 FOR I=1 TO 5
2660 C(I)=0 @ Z(I)=0
2670 NEXT I
2680 ! DISP "PRESS <CONT> WHEN R
     EADY TO SAMPLE CAL. READING
     S"
2690 ! BEEP
2700 ! PAUSE
2710 ! FOR I=1 TO 5
2720 ! FOR J=1 TO 10
2730 ! OUTPUT 709 USING "AA,D" ;
      "AI",I
2740 ! ENTER 709 ; C
2750 ! C(I)=C(I)+C
2760 ! NEXT J
2770 ! C(I)=C(I)/10
2780 ! NEXT I
2790 ! CLEAR
2800 DISP "PRESS <CONT> WHEN REA
     DY TO SAMPLE ZERO READINGS"
2810 BEEP
2820 PAUSE
2830 FOR I=1 TO 5
2840 FOR J=1 TO 10
2850 OUTPUT 709 USING "AA,D" ; "
     AI",I
2860 ENTER 709 ; Z
2870 Z(I)=Z(I)+Z
2880 NEXT J
2890 Z(I)=Z(I)/10
2900 NEXT I
2910 GOTO 150
2920 ! -------------------------
2930 ! Sum @ Sum of Squares Subr
     outine
2940 ! -------------------------

2950 ALPHA
2960 T1=T1+W
2970 S1=W^2
2980 S2=S2+S1
2990 RETURN
3000 !
```

```
3010 ! ------------------
3020 ! Min/Max Subroutine
3030 ! ------------------
3040 FOR I=1 TO N-1
3050 FOR M=I+1 TO N
3060 ON J GOTO 3070,3120,3170,32
     20,3270,3320,3370
3070 IF A(I)<=A(M) THEN 3410
3080 R=A(I)
3090 A(I)=A(M)
3100 A(M)=R
3110 GOTO 3410
3120 IF B(I)<=B(M) THEN 3410
3130 R=B(I)
3140 B(I)=B(M)
3150 B(M)=R
3160 GOTO 3410
3170 IF C(I)<=C(M) THEN 3410
3180 R=C(I)
3190 C(I)=C(M)
3200 C(M)=R
3210 GOTO 3410
3220 IF D(I)<=D(M) THEN 3410
3230 R=D(I)
3240 D(I)=D(M)
3250 D(M)=R
3260 GOTO 3410
3270 IF E(I)<=E(M) THEN 3410
3280 R=E(I)
3290 E(I)=E(M)
3300 E(M)=R
3310 GOTO 3410
3320 IF P(I)<=P(M) THEN 3410
3330 R=P(I)
3340 P(I)=P(M)
3350 P(M)=R
3360 GOTO 3410
3370 IF Q(I)<=Q(M) THEN 3410
3380 R=Q(I)
3390 Q(I)=Q(M)
3400 Q(M)=R
3410 NEXT M
3420 ON J GOTO 3430,3460,3490,35
     20,3550,3580,3610
3430 M1=A(1)
3440 M2=A(N)
3450 GOTO 3630
3460 M1=B(1)
3470 M2=B(N)
3480 GOTO 3630
3490 M1=C(1)
3500 M2=C(N)
3510 GOTO 3630
3520 M1=D(1)
3530 M2=D(N)
3540 GOTO 3630
3550 M1=E(1)
3560 M2=E(N)
3570 GOTO 3630
3580 M1=P(1)
3590 M2=P(N)
3600 GOTO 3630
3610 M1=Q(1)
3620 M2=Q(N)
3630 NEXT I
3640 RETURN
```

SINGLE CHANNEL SAMPLING DATA COLLECTION

CONTROL AND ANALYSIS PROGRAM

```
 10 CLEAR
 20 OPTION BASE 1
 30 COM J,T1,S2,W,M1,M2
 35 REAL H(5)
 40 ! ENABLE KBD 1+8+32+128
 50 SHORT A(4000)
 60 DIM A$[32]
 70 DISP "ENTER TEST DATA e.g M/
    BOARD/PASS1/JUNE"
 80 INPUT B$
 90 A$="READY TO TAKE DATA"
100 K=0 @ N=0
110 REM F IS THE CHANNEL'S CALIB
    RATION FACTOR
111 DISP "WHAT CHANNEL ARE YOU S
    AMPLING"
112 BEEP
113 INPUT C
114 IF C=1 THEN F=507
115 IF C=2 THEN F=462
116 IF C=3 THEN F=438
117 IF C=4 THEN F=561
118 IF C=5 THEN F=418
120 ! F(1)=588 @ F(2)=497 @ F(3)
    =481 @ F(4)=416 @ F(5)=418
130 GOTO 2500
140 ON KEY# 1,"DATA" GOTO 470
150 ON KEY# 2,"STOP" GOTO 230
160 ON KEY# 3,"PLOT" GOTO 860
170 ON KEY# 4,"STORE" GOTO 2260
180 ON KEY# 5," Z/C " GOTO 2500
190 OFF KEY# 6
200 OFF KEY# 7
210 OFF KEY# 8
220 GOTO 340
230 OUTPUT 709 ;"T00"
240 N=N-1
290 FOR I=1 TO N
300 PRINT A(I)
310 NEXT I
340 CLEAR
350 BEEP
360 KEY LABEL
370 DISP
380 DISP "DATA COLLECTED AND STO
    RED BY PRESSING USER DEFINED
     KEYS"
390 DISP
400 DISP "KEY# 1:START DATA COLL
    ECTION"
410 DISP "KEY# 2:STOP DATA INPUT
    "
420 DISP "KEY# 3:PLOT  LATEST DA
    TA SAMPLED"
430 DISP "KEY# 4:STORE DATA"
440 DISP
450 DISP A$
460 GOTO 460
470 ! ------------------------
480 ! Data sampling Subroutine
```

```
490 ! -----------------------
500 CLEAR
520 KF  LABEL
530 ...   EADY TO PLOT & STORE DA
    T...
540 CLEAR 709
541 DISP "WHAT SAMPLING RATE? (2
    00,100 OR 010 mS)"
542 REM 200 => (TO200)-FIVE SAMP
    LES A SECOND
543 REM 10 => (TO10)-HUNDRED SAM
    PLES A SECOND
544 BEEP
545 INPUT T
547 DISP USING "5/6X,20A" ; "DAT
    A BEING COLLECTED"
549 OUTPUT 709 USING "AA,DDD" ;
    "TO",T
550 OUTPUT 709 ;"AE1VR3"
560 OUTPUT 709 ;"VS1VF1VN1VD5VA1
    "
570 N=0
580 WAIT 1000
590 N=N+1
595 OUTPUT 709 USING "AA,D" ; "A
    C",C
600 OUTPUT 709 ;"VT2SO1"
610 OUTPUT 709 ;"VS"
620 ENTER 709 ; A(N)
630 A(N)=(A(N)-Z)*F
640 ! B(N)=(B(N)-Z(2))*F(2)
650 ! C(N)=(C(N)-Z(3))*F(3)
660 ! D(N)=(D(N)-Z(4))*F(4)
670 ! E(N)=(E(N)-Z(5))*F(5)
680 IF N>4000 THEN 230
690 GOTO 590
700 ! ______________________
710 ! Sampling Explained
720 ! ----------------------
730 ! TO200-TTL pulse output eve
    ry .2 seconds
740 ! AE1-External channel incre
    ament
750 ! AF1-Let first channel be 1
760 ! AL5-Let last channel be 5
770 ! VR3-Data signals are in 10
    volt range
780 ! VF1-Format is ASCII
790 ! VN1-One readings per trigg
    er
800 ! VD5-# of digits Note:MORE
    DIGITS IMPLIES LOWER CONVERS
    ION SPEED
810 ! VA1-Auto Zero VA is"ON" No
    te:READING RATE IS HALVED BU
    T ACCURACY IMPROVED"
820 ! VS1-Storage in ASCII
830 ! AC1-Close channel 1-(Start
     sampling all channels)
840 ! VT2-Trigger externally
```

```
850 ! 301-System wait for output
    -ON
860 ! --------------------
870 !  Plot data subroutine
880 ! --------------------
890 PRINT @ PRINT
900 PRINT B$
910 PRINT
920 GRAPH
930 PEN 1 @ GCLEAR
940 PLOTTER IS 1
950 LOCATE 25,130,20,90
960 SCALE 0,N+1,-7,30
970 FXD 0,0
980 REM **LABEL AND DRAW AXES***
990 LAXES -(N/10),5,0,-7,2,1
1000 ! FOR J=1 TO 7
1010 MOVE 0,0
1020 K=0 @ T1=0 @ S2=0
1030 FOR I=1 TO N
1040 CLEAR
1050 GRAPH
1060 K=K+1
1070 ! ON J GOTO 1080,1140,1200,
     1260,1320,1380,1440
1080 LINETYPE 1
1090 W=A(I)
1100 A(I)=A(I)/100
1110 PLOT K,A(I)
1115 A(I)=A(I)*100
1120 GOSUB 2840
1130 GOTO 1490
1490 NEXT I
1500 ALPHA
1510 T2=T1^2
1520 S=((S2-T2/N)/(N-1))^.5
1530 V1=T1/N
1540 C3=S*100/V1
1550 GOSUB 2930
1700 FOR L=1 TO 5
1710 ON L GOTO 1720,1740,1760,17
     80,1800
1720 H(L)=V1
1730 GOTO 1810
1740 H(L)=M1
1750 GOTO 1810
1760 H(L)=M2
1770 GOTO 1810
1780 H(L)=S
1790 GOTO 1810
1800 H(L)=C3
1810 NEXT L
1820 GRAPH
1830 REM V1=AVERAGE @ M1=MINIMUM
      @ M2=MAXIMUM
1840 REM S=STD DEVIATION @ C3=CO
     EFF. OF VARIATION
1860 MOVE N/2.5,-12
1870 LDIR 0
1880 LABEL "DATA NUMBER"
```

```
1890 MOVE -(N/8),-7
1900 LDIR 90
1910 LABEL "DRAFT FORCE 100LB"
1920 COPY
1930 !
1940 REM ** END OF PLOT **
1950 ALPHA
1990 PRINT USING 2150 ; C
2040 PRINT USING 2180
2060 FOR V=1 TO 5
2070 IF V=1 THEN PRINT USING 219
     0 ; H(V)
2080 IF V=2 THEN PRINT USING 220
     0 ; H(V)
2090 IF V=3 THEN PRINT USING 221
     0 ; H(V)
2100 IF V=4 THEN PRINT USING 222
     0 ; H(V)
2110 IF V=5 THEN PRINT USING 223
     0 ; H(V)
2120 NEXT V
2130 PRINT @ PRINT
2150 IMAGE "STATISTICAL DATA FOR
      CHANNEL:",1X,DD
2180 IMAGE "--------------------
     ------------"
2190 IMAGE "AVERAGE:",1X,DDDDDDD
     .D
2200 IMAGE "MINIMUM:",1X,DDDDDDD
     .D
2210 IMAGE "MAXIMUM:",1X,DDDDDDD
     .D
2220 IMAGE "STD DEVN:",1X,DDDDDD
     DDD.DDD
2230 IMAGE "COEFF. OF VARTN (%):
     ",1X,DDDDDD.DD
2240 DISP USING "8/6X,28A" ; "WI
     SH TO STORE DATA?-Key #4"
2250 GOTO 460
2260 ! -----------------
2270 ! Storing Subroutine
2280 ! -----------------
2290 A$="READY FOR NEXT IMPLEMEN
     T"
2300 CLEAR
2310 DISP "ENTER FILE NAME FOR P
     RESENT STORAGE"
2320 INPUT D$
2330 KEY LABEL
2340 CREATE D$,1,9*N
2350 ASSIGN# 1 TO D$
2360 PRINT# 1 ; N
2370 FOR I=1 TO N
2380 ! A(I)=A(I)*100
2390 ! B(I)=B(I)*100
2400 ! C(I)=C(I)*100
2410 ! D(I)=D(I)*100
2420 ! E(I)=E(I)*100
2430 ! P(I)=P(I)*100
2440 ! Q(I)=Q(I)*100
```

```
2450 PRINT# 1 ; A(I)
2460 NEXT I
2470 ASSIGN# 1 TO *
2480 GOTO 340
2490 END
2500 !
2510 ! ------------------------
2520 ! Zero and Calibration sub
2530 ! ------------------------
2540 CLEAR 709
2550 OUTPUT 709 ;"SI" ! Initiali
     ze scanner.  See Mainframe
     instr

2560 CLEAR
2570 ! FOR I=1 TO 5
2580 Z=0
2590 ! NEXT I
2600 ! DISP "PRESS <CONT> WHEN R
     EADY TO SAMPLE CAL. READING
     S"
2610 ! BEEP
2620 ! PAUSE
2630 ! FOR I=1 TO 5
2640 ! FOR J=1 TO 10
2650 ! OUTPUT 709 USING "AA,D" ;
      "AI",I
2660 ! ENTER 709 ; C
2670 ! C(I)=C(I)+C
2680 ! NEXT J
2690 ! C(I)=C(I)/10
2700 ! NEXT I
2710 ! CLEAR
2720 DISP "PRESS <CONT> WHEN REA
     DY TO SAMPLE ZERO READINGS"
2730 BEEP
2740 PAUSE
2760 FOR J=1 TO 10
2765 ON C GOTO 2770,2772,2774,27
     76,2778
2770 OUTPUT 709 USING "AA,D" ; "
     AI",1
2771 GOTO 2780
2772 OUTPUT 709 USING "AA,D" ; "
     AI",2
2773 GOTO 2780
2774 OUTPUT 709 USING "AA,D" ; "
     AI",3
2775 GOTO 2780
2776 OUTPUT 709 USING "AA,D" , "
     AI",4
2777 GOTO 2780
2778 OUTPUT 709 USING "AA,D" , "
     AI",5
2780 ENTER 709 ; Z1
2790 Z=Z+Z1
2800 NEXT J
2810 Z=Z/10
2830 GOTO 140
2840 ! ------------------------
```

```
2850 ! Sum & Sum of Squares Subr
     outine
2860 ! -------------------------

2870 ALPHA
2880 T1=T1+W
2890 S1=W^2
2900 S2=S2+S1
2910 RETURN
2920 !
2930 ! ------------------
2940 ! Min/Max Subroutine
2950 ! ------------------
2960 FOR I=1 TO N-1
2970 FOR M=I+1 TO N
2990 IF A(I)<=A(M) THEN 3330
3000 R=A(I)
3010 A(I)=A(M)
3020 A(M)=R
3330 NEXT M
3350 M1=A(1)
3360 M2=A(N)
3550 NEXT I
3560 RETURN
```