Development of a Three-Dimensional Tillage Force and Moment Dynamometer

by

Charles Ivor Kitson

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DEVELOPMENT OF A THREE DIMENSIONAL TILLAGE FORCE AND MOMENT DYNAMOMETER

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CHARLES IVOR KITSON

A thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

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ABSTRACT

A computer monitored three-dimensional force and moment dynamometer system was developed and evaluated. The software package developed allows the acquisition of data and determination of the three dimensional forces and moments. The unique line of action of the resultant force was then determined by means of the Wrench Theory for force and moment systems. A line representing the resultant force and a mathematical model of the surface of the tillage implement tested were then used to determine the intersection point of the resultant force and the surface of the tillage implement.

The dynamometer was calibrated using the Matrix Method to reduce the effect of interaction of the six transducer dynamometer system. This calibration method was compared to a procedure using vector analysis and individual calibration of the six transducers in tension and compression. The Matrix Method of force and moment analysis was found to improve the accuracy of the dynamometer.

Tillage trials were conducted using a field cultivator shovel and a disk blade mounted at a 30 degree angle in the University of Manitoba, Department of Agricultural Engineering Soil Bin. The resultant three dimensional forces and moments exerted on the tillage implement were measured using the dynamometer. The wrench for the resultant force and moment system measured was calculated. The intersection point of the mathematical model of the tillage tool and line describing the line of action of the resultant force, were determined.

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Chapter I

INTRODUCTION

The measurement of forces involved with tillage tool systems aids in the design of tillage equipment. If the magnitude, direction and point of application of the forces on a tillage implement are known, both over-design and under-design may be avoided. With improved measurement of the forces on tillage implements there could be a more efficient use of materials leading to cost reduction and extended life of the tillage implements.

The design and instrumentation of a tillage force and moment dynamometer are a function of the forces that the dynamometer will be expected to measure. The tillage force dynamometer presented in this thesis measures the forces and moments in three dimensions. That is the draft, lateral and vertical forces, and three moments about the three principal axes X, Y, and Z. The design of the transducer frame and location of the transducers allowed the tillage forces measured to be unaffected by the position of the tillage implement relative to the origin of the dynamometer system. The computer system used allowed for the examination of each of the three dimensional forces simultaneously.

The measurement of the forces in three dimensions allows more complete comparison of tillage implements and their associated forces. For example, a cultivator shovel and a disk blade set at an angle may have a similar total draft but quite different force components. The disk blade will generate a constant side tillage force where the side tillage force on the cultivator shovel will vary from positive to negative. The direction of the vertical force on a cultivator could be positive or negative and still give the same magnitude for the resultant force. Without the ability to determine the forces in three dimensions simultaneously important differences could not be found.

The main advantage in working in a soil bin is the ability to control factors that affect performance of a tillage implement such as type and uniformity of soil, moisture content, compaction, and accurate depth control of the tillage implement. The measurement of the forces of different implements under the same conditions, allows a direct comparison of their performance. Field studies commonly show large differences of measured forces due to soil variation. This makes it difficult to compare the performance of tillage equipment of similar design under field conditions.

The objective of this thesis was the instrumentation of the Department of Agricultural Engineering Soil Bin tool bar. This included the development of a computer monitored three dimensional force and moment dynamometer. The instrumentation and calibration of the six force transducers and the determination of the resultant force and moment equations for the dynamometer. A userfriendly software package was developed as part of this thesis to allow the collection and interpretation of three dimensional tillage forces. Finally the running of demonstration tillage trials was done with a cultivator shovel and a disk blade mounted at a 30 degree angle to the direction of travel of the soil bin carriage.

Chapter II

REVIEW OF LITERATURE

2.1 EARLY TILLAGE FORCE MEASUREMENT

One of the first sensing devices used to measure forces on tillage implements was the drawbar dynamometer. The drawbar dynamometer measured total draft of a drawn implement and was placed between the tractor and the implement. This method did not give any information on the direction of the resultant force, just the total pull of the implement. This type of dynamometer would be unsuitable for the measurement of tillage implements that generate vertical or lateral forces.

Jensen (1954) developed a strain gage drawbar dynamometer that was used in field tests to determine tractor power requirements. This dynamometer was only concerned with measurement of the total pull on the tractor. Jensen (1954) developed a dynamometer to determine the vertical component of the drawbar pull. This simplified the measurement of draft loads when using an elevated hitch in the field. The dynamometer was made of a steel ring with four gages located in such a way that two were in tension and two were in compression. This design allowed the placement of the gages in a full Wheatstone bridge for maximum sensitivity. The transducer designed to measure the vertical forces was a reduced section of the drawbar to increase the bending stress in the member. The gages were mounted symmetrically on either side of the reduced section and wired as opposite arms of a Wheatstone bridge. This allowed the tension and bending in the horizontal direction to cancel and made the transducer sensitive to bending in the vertical direction only. Work was going on attempting to measure the tillage forces on implements mounted on three-point-hitches. These forces could not be measured with a drawbar dynamometer and this constraint lead to the development of dynamometers to measure tillage forces on three-point-hitches.

2.2 THREE-POINT-HITCH TILLAGE FORCE DYNAMOMETERS

Some of the first work done on three point hitches was by Rogers and Johnston (1953). Their work was concerned with the determination of the forces in the linkages of the three point hitch. The forces measured in each of the links in the three point hitch were added algebraically to determine the drawbar pull of the implement. The data acquisition system consisted of single-acting hydraulic cylinders, Bourdon pressure gages and a 16-mm movie camera. The hydraulic cylinders were placed directly in the links of the three point hitch and connected to the Bourdon pressure gages. The Bourdon pressure gages were calibrated to read the force on the ends of the links in pounds. The gages were then clustered on a gage board and photographed simultaneously with a 16-mm movie camera.

Rogers and Johnston (1953) suggested that strain gages could be used to replace the hydraulic cylinders leading to an increase in accuracy. This was done by Reece (1961) but he took it further than just using strain gages on the links themselves.

Reece (1961) felt that the development of mounted implements had created a demand for a device capable of measurement of forces acting on these implements. He felt that the direct measurement of the forces in the links themselves was a formidable problem, with three dimensional vector analysis and simultaneous recording of at least three forces. He wanted a simpler solution that would remove the need for complex vector addition but still measure the draft force in the direction of travel. He also did not want to have to use a multi-channel recorder to monitor the system. The system he developed was made up of three strain gaged cantilever pins with ball joints at the inner end of three links. The gages were wired into a Wheatstone bridge so that the longitudinal component of the draft was measured and the effects of the lateral and vertical forces did not unbalance the bridge. The data were recorded by a battery powered single-channel oscillograph that needed no amplification.

The apparatus was calibrated by applying a horizontal load to the three-point-hitch with the tractor brakes on. The load applied was measured with a steel proving ring and a clock gauge. The accuracy of the apparatus was checked by appling measured loads to the apparatus and comparing the results. When loads were under 2224 N the maximum error was reported to be plus or minus seven percent and plus or minus three percent when over 8896 N. This force dynamometer was limited to measuring the forces on three-point-hitches with no depth control being exercised by the tractor.

The work with the type of dynamometer developed by Reece was continued by Scholtz (1964). Scholtz again worked on the development and testing of a three-point-hitch force dynamometer made of three strain-gaged beams. The three beams were initially calibrated individually in the laboratory. This system was also tested using the trace tractor method of draft measurement. This was a widely used method for determining the draft of mounted implements using a second tractor. The first tractor pulled the second tractor that had a implement mounted on it. The load was measured with a conventional drawbar dynamometer. In this method the average draft with the implement lowered minus that with the implement raised was taken to be the draft of the mounted implement. In order to compare the results obtained by towing with a hydraulic drawbar dynamometer with those from the three-point linkage dynamometer, a small experiment was run. Twenty-one tests were run each with a length of 45.72 m. Each strip was first run with the implement raised while the drawbar dynamometer readings were taken. Then the strips were run again with the implement lowered and readings were taken from both drawbar and three-point linkage dynamometers. Typical mean draft for the drawbar dynamometer was 7299.5 N compared to 7437.4 N for the three-point linkage dynamometer. This difference was not significant at the 5% level of significance.

The dynamometer developed by Scholtz did not measure the forces in the vertical direction. It only measured the draft force. The dynamometer also could not be used with the hydraulic depth control and he designed a new three-point linkage dynamometer to fulfil these requirements (Scholtz 1966). This dynamometer measured the forces acting in the vertical longitudinal plane and was able to be used with a tractor that provided both draft and position control. The dynamometer was made up of an instrumented frame that permitted the attachment of many implements without modification of the implement or dynamometer. The frame contained three transducers to measure the draft and vertical forces. There were two L-shaped and one U-shaped transducers. The U-shaped transducer was positioned so it would only be subject to draft forces and the L-shaped transducer was subject to both vertical and draft forces. The unit was calibrated in both the vertical and longitudinal direction. The vertical calibration was done by suspending weights from the ball joints on the L-shaped links and noting the meter deflection. The calibration loading for draft was applied by a hydraulic cylinder and measured by a mechanical weighing machine. The strain gage position was chosen on the L-shaped transducers so that the vertical force would not produce a signal in the Wheatstone bridge which measured draft and the draft force would not interact with the bridge that measured vertical forces. In practice this was not achieved and mutual interference was checked during calibration. It was found that the application of vertical forces caused negligible errors in draft measurement. The errors due to the application of a draft force did cause up to a 22 N force downward on the right hand L-shaped transducer while a similar draft force caused a 22 N upward force on the left L-shaped transducer. The draft force that caused these errors was one of 4448 N and the error of 22 N was not considered excessive.

There are some limitations on this dynamometer such as not being able to work with any mounted implement without modification. Also the dynamometer was bulky and the implement would be mounted further to the rear of the tractor. When measuring transient phenomena the extra resilience added to the hitch assembly by the dynamometer made it less suitable than other designs. Also the draft had to be determined by adding the outputs of the strain-gage circuitry from the different transducers and the torque in the vertical longitudinal plane had to be found by calculation.

An alternative technique to the multi-dynamometer system was developed by Godwin (1975). He used an extended octagonal ring transducer to simultaneously measure the two force components and the moment in the vertical longitudinal plane. The extended ring transducer had the advantage over previous dynamometers in that it alleviated the friction problems arising from dynamometer suspension bushings. The extended ring transducer also had single component construction allowing for compactness and simple mounting, which reduced the difficulties with precision alignment necessary for accurate multi-dynamometer use. The transducer consisted of a machined block of steel with strain gages mounted at strain nodes. A strain node is a position where there is a contribution to the strain from only one force component. These positions were determined using photoelastic methods. The strain gages were wired into two force bridges and one moment bridge. The two force bridges, Fx and Fz, were wired so that they were independent of the position of the load. The moment bridge My was wired so that it would be proportional to the applied moment.

The transducer was calibrated in the horizontal direction, Fx, from 0 to 2445 N and in the vertical direction, Fz, from 0 to 668 N. The calibration range for the moment about the Y-axis was from 0 to 978 Nm for an eccentric X direction force, and -103 to +103 Nm for an eccentric Z direction force. The coefficient of determination was equal to or greater than 0.9998 for all transducer outputs. The magnitude of the output from the Fz bridge was independent of the direction of loading with a reversal in polarity for a directional change. The output moment bridge was independent of the origin of the eccentric force. The hysteresis effect was also found to be small with the largest deviation from the mean of 1.4% occuring in the moment bridge. The cross sensitivity errors were also small when compared to the sensitivity of the bridges to their principal directions. Therefore the extended octagonal ring transducer met the requirements of most tillage studies with two dimensional force systems.

Work by Johnson and Voorhees (1979) resulted in the construction of a three-point-hitch accessory designed to measure draft,vertical forces, and torque simultaneously and independently in the vertical longitudinal plane of the tillage implement. This dynamometer had the special features of a dual-loading range, fast-hitching capability and was made up of three subassemblies. The tractor subassembly, was attached to the tractor, the second subassembly was the instrumented member and the third was a fast-hitch mechanism which attached to the implement. The transducer subassembly was made of aluminum alloy to increase its load sensitivity as compared to steel. Strain gages were attached to the transducer subassembly so that vertical and horizontal forces and torque in the longitudinal vertical plane could be determined separately. For calibration the force dynamometer was attached to a tractor that was anchored to the ground and loads were applied to the dynamometer through a hydraulic cylinder and a Morehouse proving ring. The three strain bridges were then monitored with a digital voltmeter to allow the determination of sensitivity to not only the principal forces for the particular bridge, but also cross sensitivity of the three bridges to other loads. Their dynamometer allowed the measurement of two dimensional forces and the moment in the vertical longitudinal plane. This allowed it to be used in tillage tool studies mainly concerned with symmetrical soil failure. If non-symmetrical soil failure in tillage tool studies is to be investigated a more complete picture of the forces involved is necessary.

2.3 THREE DIMENSIONAL TILLAGE FORCE AND MOMENT MEASUREMENT

2.3.1 Matrix Method for Force and Moment Analysis

In order to measure three-dimensional forces and moments the general method has been to use a six transducer dynamometer. The dynamometer system used by Perumpal et al. (1980) was made up of an outer passive frame, an inner active frame, and six force transducers. It was noticed in preliminary tests with the dynamometer system that a force applied in one of the three principal directions, and moments applied about one of the principal axes could cause linear outputs from all six transducers. This observation lead to the development of a transfer function. This transfer function was developed by studing the response of the dynamometer system for known inputs and relating the inputs to the outputs. A general relationship between inputs and outputs for the dynamometer system used can be shown as follows:

$(Fx, Fy, Fz, Mx, My, Mz) = f(\theta 1, \theta 2, \theta 3, \theta 4, \theta 5, \theta 6)$ .... [1]

where

Fx,Fy, and Fz = the forces in the longitudinal,lateral and vertical directions respectivly.

Mx,My, and Mz = the moments about the principal axes (x,y,z) with respect to the origin of the coordinate system.

θ1,θ2,..θ6 = the outputs from transducer 1 through 6.

The transfer function can be represented in matrix form by equations [2] and [3]:

$$\begin{bmatrix} Fx \\ FY \\ Fz \\ Mx \\ My \\ Mz \end{bmatrix} = \begin{bmatrix} K11 & K12 & K13 & K14 & K15 & K16 \\ K21 & K22 & K23 & K24 & K25 & K26 \\ K31 & K32 & K33 & K34 & K35 & K36 \\ K41 & K42 & K43 & K44 & K45 & K46 \\ K51 & K52 & K53 & K54 & K55 & K56 \\ K61 & K62 & K63 & K64 & K65 & K66 \end{bmatrix} \begin{bmatrix} \theta 1 \\ \theta 2 \\ \theta 3 \\ \theta 4 \\ \theta 5 \\ \theta 6 \end{bmatrix} \quad ....[2]$$

or

$(F) = [K]\ (\theta)$ .... [3]

In the work by Perumpal et al. (1980) the [K] matrix was developed and referred to as the coefficient matrix. The units of the elements of the matrix are not uniform across the matrix since different rows relate to forces and others to moments. The units of the first three rows are in N/transducer output unit. The units of the last three rows are in Nm/transducer output unit. If the coefficient matrix [K] is known and the outputs of the six transducers are known then the three dimensional forces and moments can be determined. This system was developed by first determining the inverse coefficient matrix. A coordinate system was established that was convenient for force and moment application. Then a force of desired magnitude was applied in the X direction and the output of the six transducers was recorded. This was repeated for the forces in the Y and Z directions and the average transducer outputs per unit force in the X, Y, and Z direction were obtained. The loading condition for a unit force in the X direction can be expressed in matrix form as follows:

$$\begin{bmatrix} \theta 1 \\ \theta 2 \\ \theta 3 \\ \theta 4 \\ \theta 5 \\ \theta 6 \end{bmatrix} = \begin{bmatrix} K11' & K12' & K13' & K14' & K15' & K16' \\ K21' & K22' & K23' & K24' & K25' & K26' \\ K31' & K32' & K33' & K34' & K35' & K36' \\ K41' & K42' & K43' & K44' & K45' & K46' \\ K51' & K52' & K53' & K54' & K55' & K56' \\ K61' & K62' & K63' & K64' & K65' & K66' \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad \text{..........} [4]$$

When the matrix is multiplied out it becomes more clear how to determine the K11', K21',..K61' coefficients. Multiplication and solving for the K11' value gives:

$$\theta 1 = K11'\ Fx + K12'\ Fy + K13'\ Fz + K14'\ Mx + K15'\ My + K16'\ Mz \ .[5]$$

since Fx=1 and Fy=Fz=Mx=My=Mz=0 equation [5] simplifies to:

θ1 = K11'   or K11'=θ1/unit load in x direction ....[6]

Similarly K21' to K61' can be determined from the matrix by the same simplifying statement, Fx=1 and Fy=Fz=Mx=My=Mz=0. The results of the multiplication of the matrix and the simplifying statement are:

θ2=K21' or K21'=θ2/unit load in x direction .... [7]

θ3=K31' or K31'=θ3/unit load in x direction .... [8]

θ4=K41' or K41'=θ4/unit load in x direction .... [9]

θ5=k51' or K51'=θ5/unit load in x direction .... [10]

θ6=K61' or K61'=θ6/unit load in x direction .... [11]

Similarly the coefficients for the other columns can be defined as the the average transducer output per unit load or moment for the corresponding transducers, forces and moments. If we look at the matrix represented in equation [4] the units of the inverse coefficient matrix are not uniform across the matrix. The units of the first three columns are transducer output per unit force and transducer output per unit moment. After Perumpal et al. (1980) developed the inverse coefficient matrix for their dynamometer and coordinate system they performed 33 verification tests.

When standard vector analysis was used to predict the forces and moments applied to the frame during the verification tests considerable discrepancy between the known applied load and the predicted was found. They felt this could be due to the load cells not being parallel to the principal axes of the coordinate system. This interaction due to the misalignment was accounted for by the matrix method since the coefficient matrix was developed by observing the response of the system to actual applied loads or moments. The results of the verification tests showed excellent agreement among the applied tests when the forces and moments were computed using the matrix method. To determine whether or not the differences from the applied load were significant three statistical tests were conducted. These included the t-test, Sign Test, and Wilcoxen Signed rank test. The results of these tests at the 5 percent significance level indicated that there was no significant difference between applied and computed loads when using the matrix method to compute the loads. The largest error in force and moment prediction represented in the work by Perumpal et al. (1980) was 13.8 N when the load was actually zero. There is no value given for average error over the tests or the maximum error recorded during testing. It was concluded from this work that the coefficient matrix procedure can be effectively used to determine the three-dimensional force and moment components on a tillage tool during soil tillage tool interaction studies.

2.3.2 The Wrench Theory

The outputs of a three-dimensional force and moment dynamometer are the forces and moments in the X, Y, and Z directions. This is independent of the manner the forces and moments are determined, matrix method or force vector analysis. If the three-dimensional moments and forces are known then according to Beer and Johnson (1977) the "Wrench" for a system of forces can be determined. A wrench can be defined as a force and moment system with the force vector being normal to the plane that contains the couple that produces the moment, or the moment and the force are considered to be parallel vectors. This force, moment system resembles the force moment combination developed when tighting a bolt; the moment applied to the bolt is parallel to the force due to the turning threads pulling on the bolt.

The wrench for a system of forces represents what is known as the Central Axis of the Wrench which is along the line of action of the resultant force. This central axis of the wrench uniquely positions the line of action of the resultant force in space. Therefore, to determine the magnitude, direction and position in space of the resultant force for a six transducer tillage force moment dynamometer we may determine the wrench for the dynamometer force moment system.

If the analysis of the tillage forces and moments was done in two dimensions rather than three dimensions the determination of the position of the resultant force would be quite simple. The position of the resultant force in two dimensions is at the point where the torque would be equal to zero. When working in three dimensions we are not finding positions of zero torque, we are finding position of minimum torque for a system of forces. The wrench represents this position of minimum torque for a three-dimensional system of forces and moments.

2.3.3 Determination of the Wrench for a System of Forces and Moments

The Wrench Theory described by Beer and Johnston is quite old but is generally only used in text books or for theoretical mechanics. In the general case a system of forces in space can be represented by a resultant force vector R and a couple vector Mo which are not parallel, and neither of which is zero as shown in Fig. 2.1. The couple vector can be replaced by two other couples by resolving the vector Mo into component vectors M_1 parallel to the force vector R, and M_2 perpendicular to force vector R as shown in Fig. 2.2. The couple vector M_2 may then be replaced by a single acting force, vector R, acting along a new line of action, much like in two dimensional analysis. The original system now is reduced to a force vector R and a moment vector M_1 acting parallel to the line of action of the force vector as shown in Fig. 2.3.

Following these steps would allow the determination of the wrench for the system of forces and moments, and the line of action of the resultant force. This method has been used by Orlandea, Chen and Bereyl

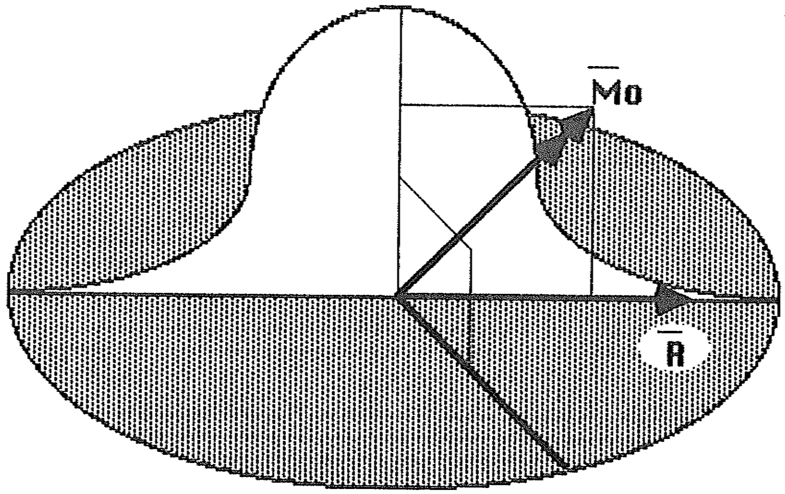

Figure 2.1: General Force Moment System

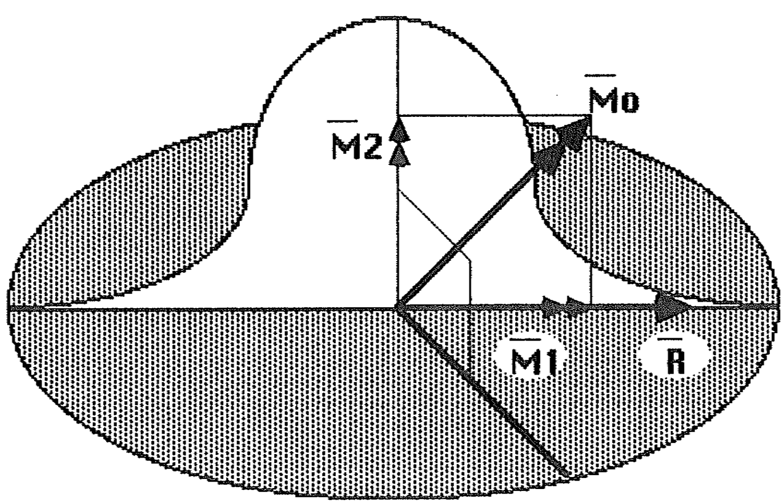

Figure 2.2: Component Moment System

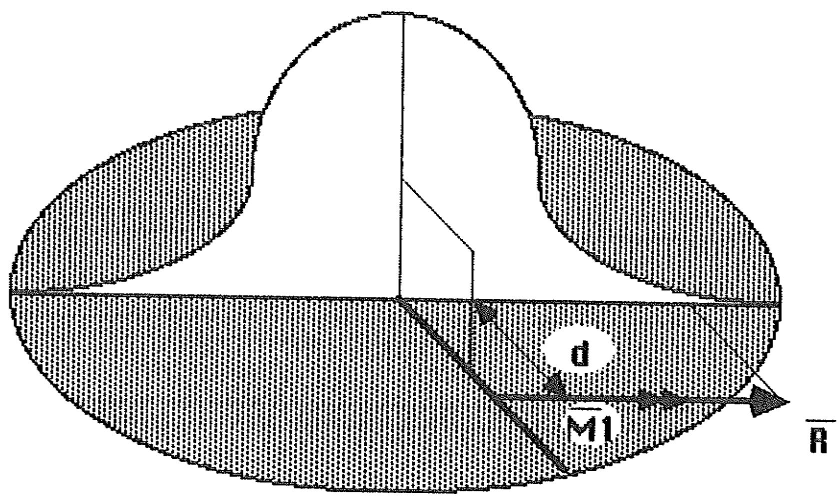

Figure 2.3: Reduction of Perpendicular Component Moment

(1982) in their paper on Soil-Tool Interactions, Determinations and Interpretations. In their work they used a six transducer dynamometer to measure the three dimensional forces and moments on different tillage equipment. They then used the Wrench method to determine the unique line of action of the resultant tillage tool force.

A more complete analysis of the application of the Wrench method as used in this thesis will be presented in later chapters.

Chapter III

DESIGN AND CALIBRATION PROCEDURE

3.1 INTRODUCTION

The three-dimensional force and moment tillage tool dynamometer used in this thesis was based on the design used by the Agricultural Engineering Department at the University of Saskatchewan. This design has been commonly used for the measurement of three-dimensional forces and moments on tillage equipment. Similar designs have been used by Perumpal et al. (1980) and Orlandea, Chen and Breylenyl (1982) to measure three dimensional forces and moments on tillage tool systems. The three-dimensional tillage tool dynamometer used in this thesis was made up of three subassemblies. These subassemblies were comprised of the active frame, passive frame, and the six transducer subassembly.

The basis of the design was that the active frame was attached to a tillage implement and held solidly in place by six force transducers. The force transducer subassembly was held secure by the passive frame which was mounted to the tool carriage on the University of Manitoba Tillage Tool Soil Bin. The tillage tool soil forces and moments were measured as they acted upon the six force transducers. Fig. 3.1 represents a conceptual drawing of the active transducer frame with the tillage implement and transducer locations shown.

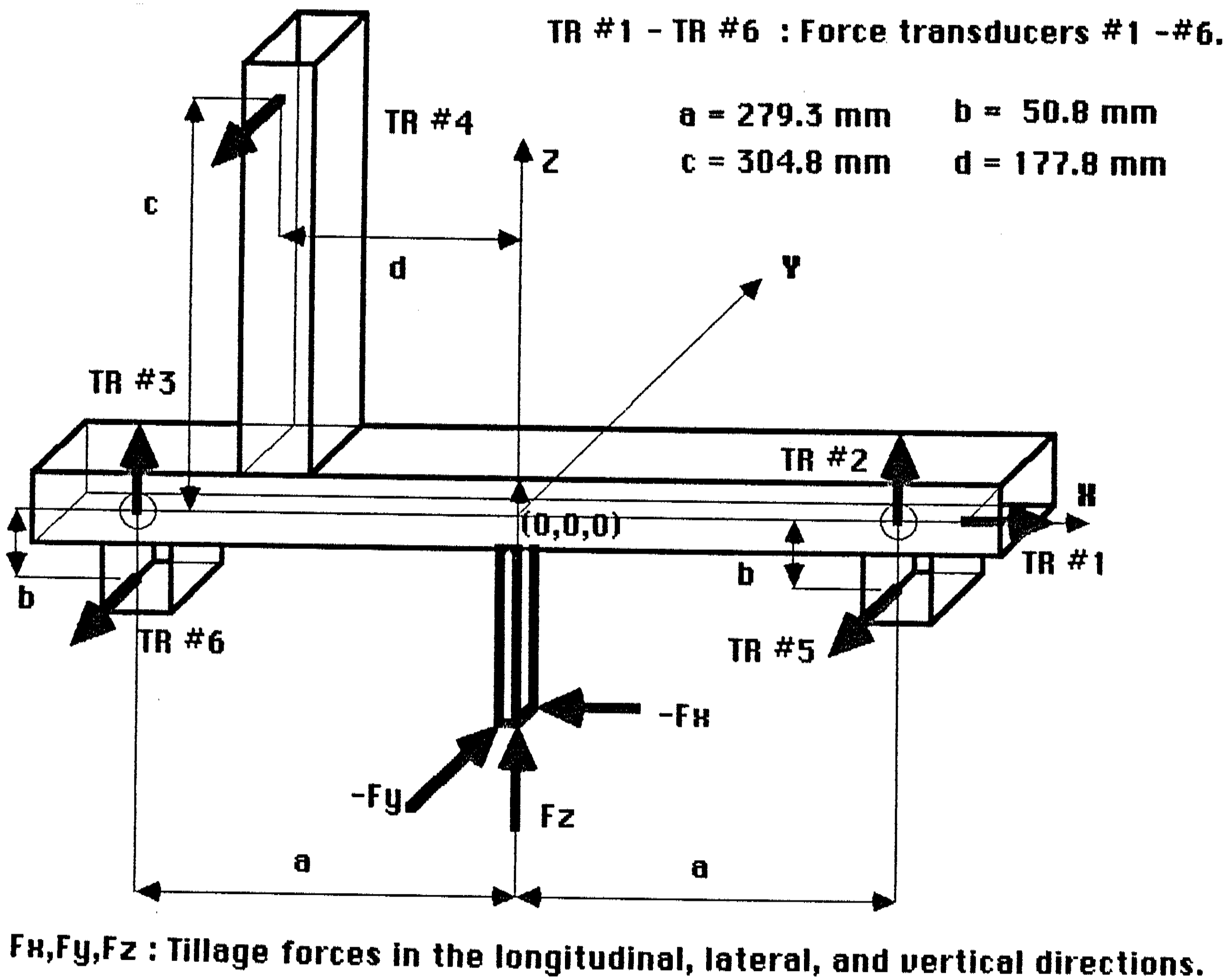

Figure 3.1: Three Dimensional Force and Moment Dynamometer

3.2 THREE DIMENSIONAL FORCE AND MOMENT DYNAMOMETER ASSEMBLY

3.2.1 Passive Frame Subassembly

The passive frame subassembly shown in Fig. 3.2 through Fig. 3.3 was made of 50.8 mm by 50.8 mm by 6.0 mm thick steel tubing with a 355.6 mm by 101.6 mm by 9.0 mm thick plate attached to it. The plate was used to attach the passive frame to the soil bin carriage tool bar. The carriage had a similar plate mounted on it to allow fast attachment of the force and moment dynamometer.

The transducers were mounted to the passive frame at six mounting positions. At these positions there were mounting brackets that allowed the insertion of a 12.7 mm bolt and bushings to hold the transducer in place.

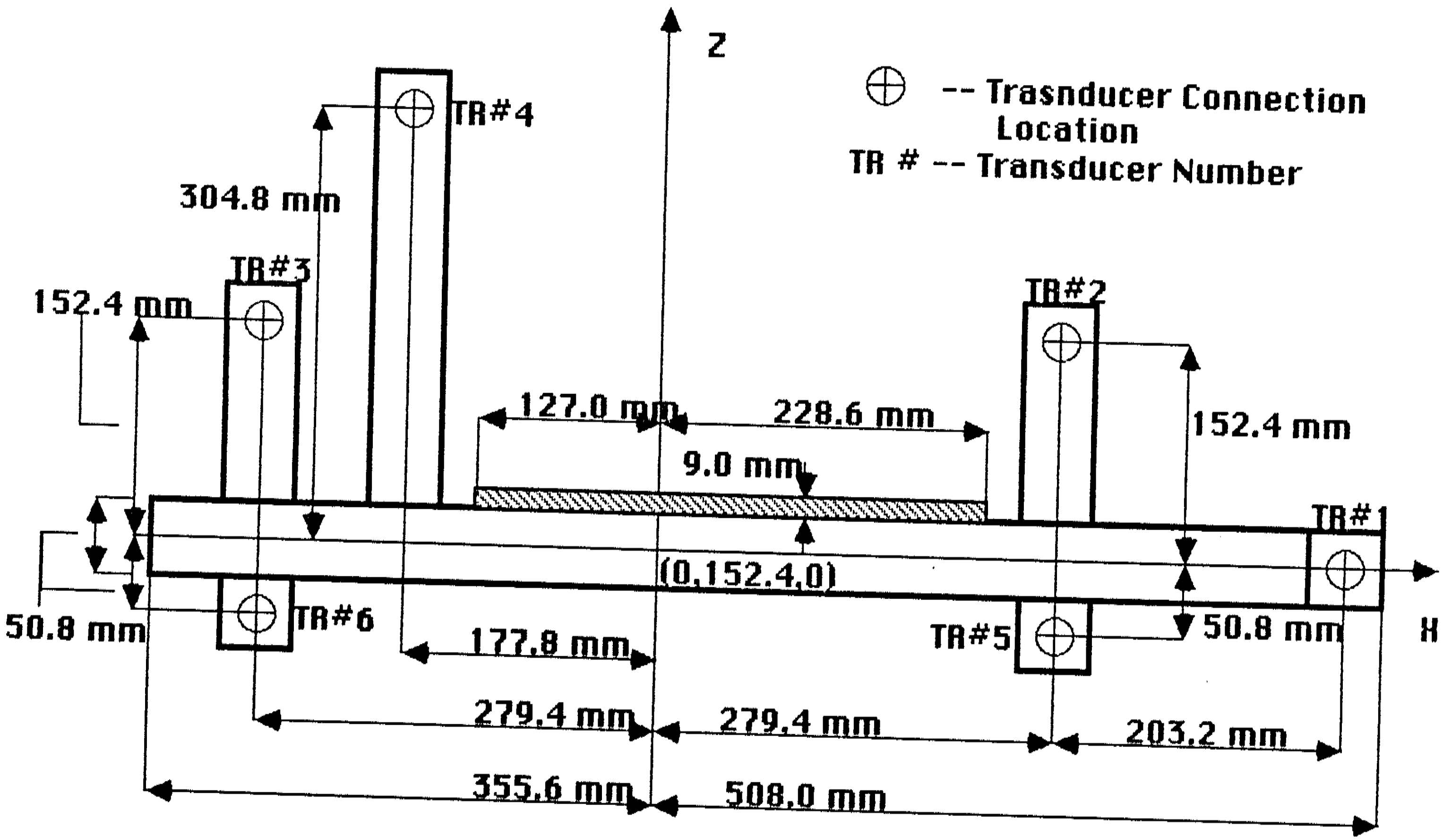

Figure 3.2: Passive Transducer Frame XZ Plane

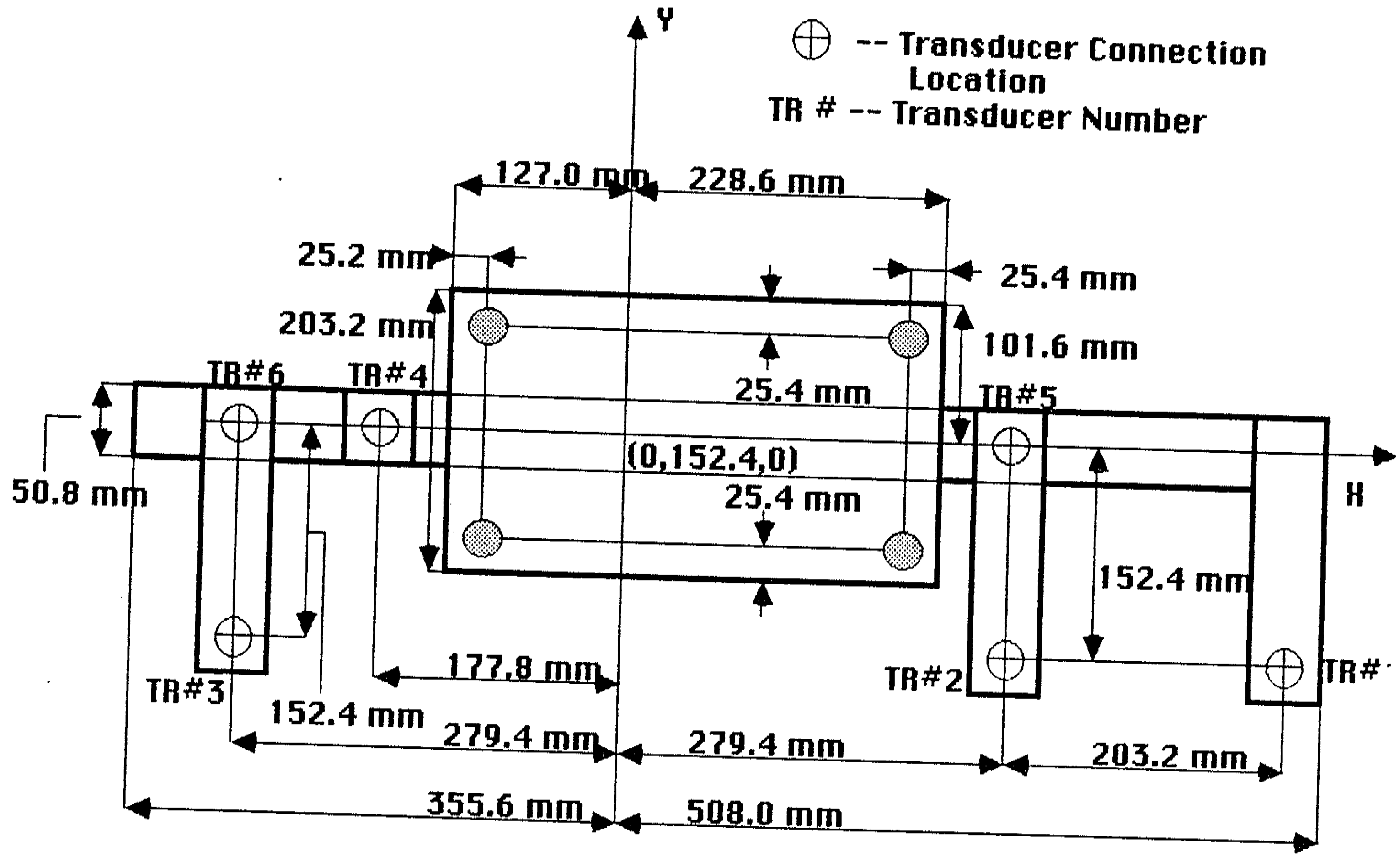

Figure 3.3: Passive Transducer Frame XY Plane

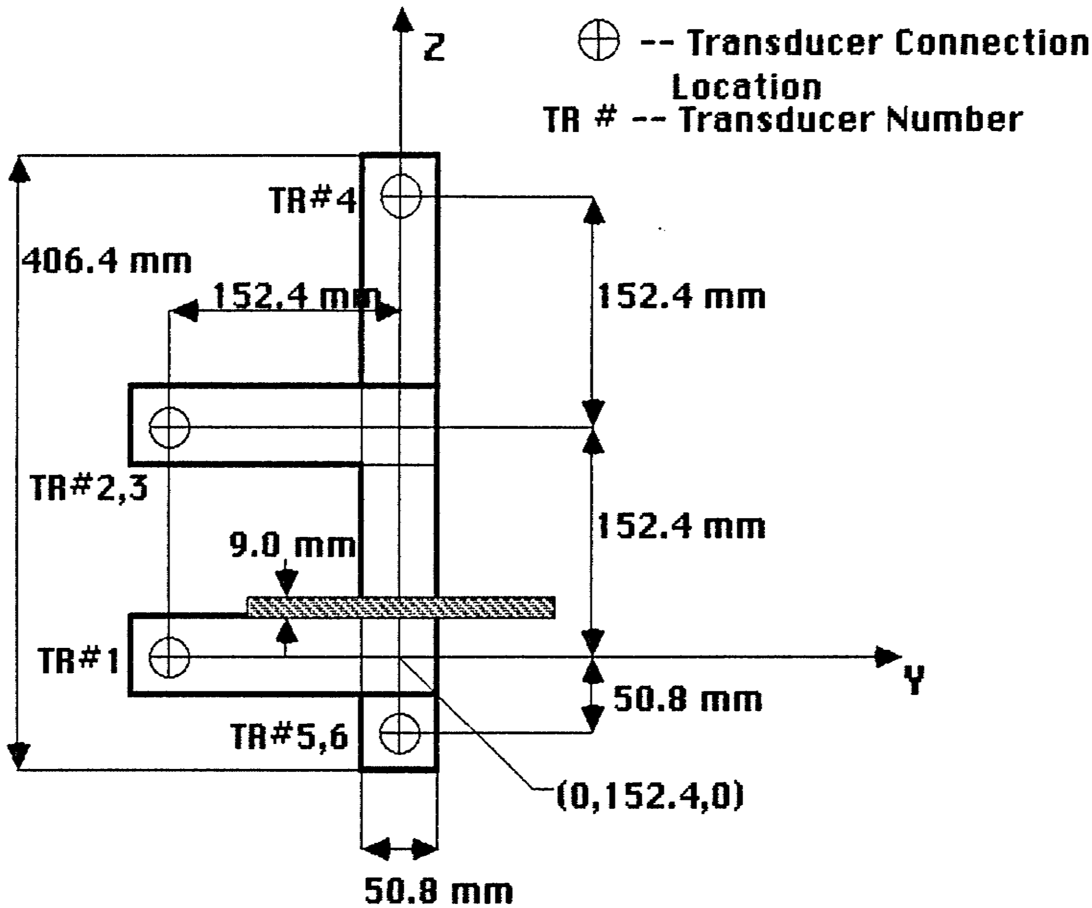

Figure 3.4: Passive Transducer Frame YZ Plane

3.2.2 Active Frame Subassembly

The active transducer frame was directly attached to the tillage implement of interest shown in Fig. 4.3 and Fig. 4.4. The active frame was made of 50.8 mm by 50.8 mm by 6.0 mm thick steel tubing. The active frame also had a mounting plate to allow the attachment of the tool bar that the tillage implement was attached to at angles of 0°, 30°, 60°, and 90° to the direction of travel of the soil bin carriage. The tool bar itself was made of 50.8 mm by 50.8 mm by 6 mm thick steel tubing. The origin for the coordinate system used in this thesis was located at the center of the active frame as shown in Fig. 3.5 through Fig. 3.7. The transducers' positions were given with reference to this location.

The transducer connection positions on the active frame with respect to the origin of the coordinate system for transducers 1 through 6 were; transducer 1 (330.2,0,0) mm, transducer 2 (279.4,0,0) mm, transducer 3 (-279.4,0,0) mm, transducer 4 (-177.8,0,304.8) mm, transducer 5

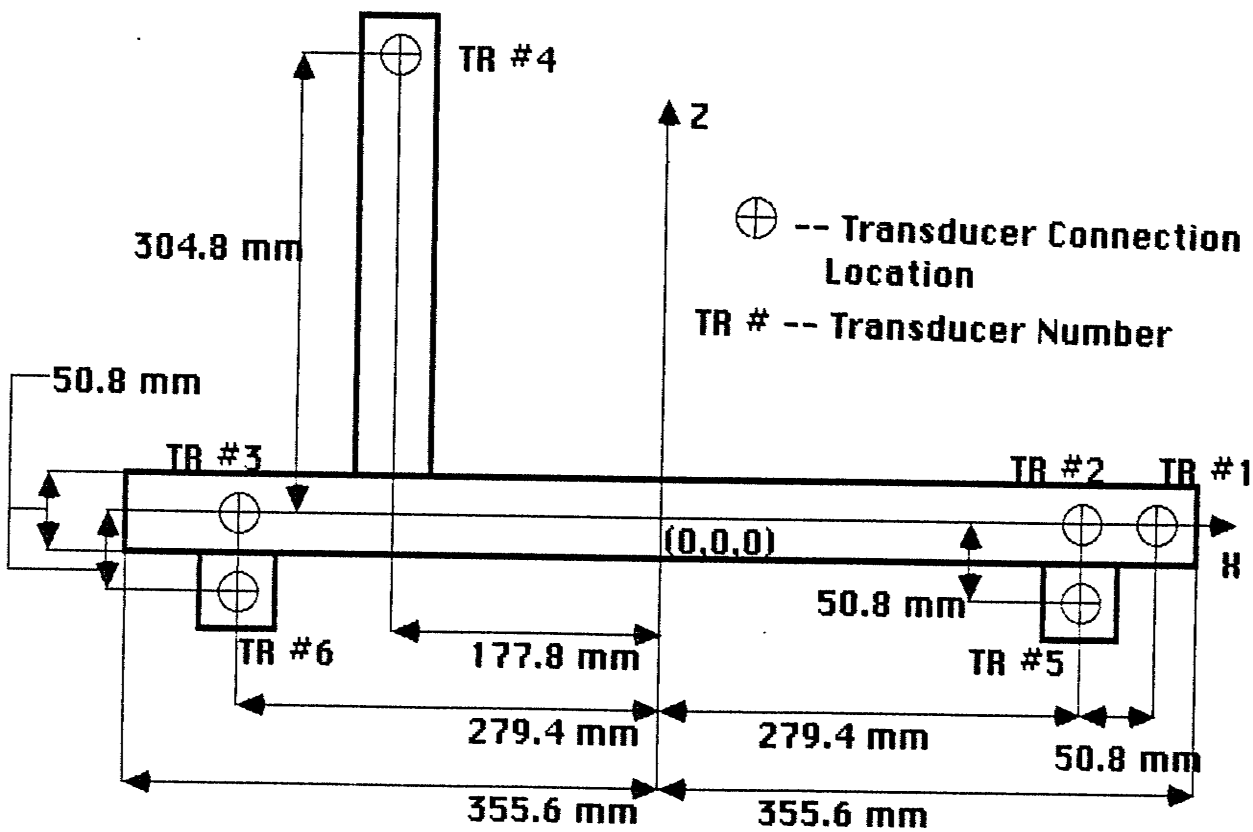

Figure 3.5: Active Transducer Frame XZ Plane

(279.4,0,-50.8) mm, transducer 6 (-279.4,0,-50.8) mm.

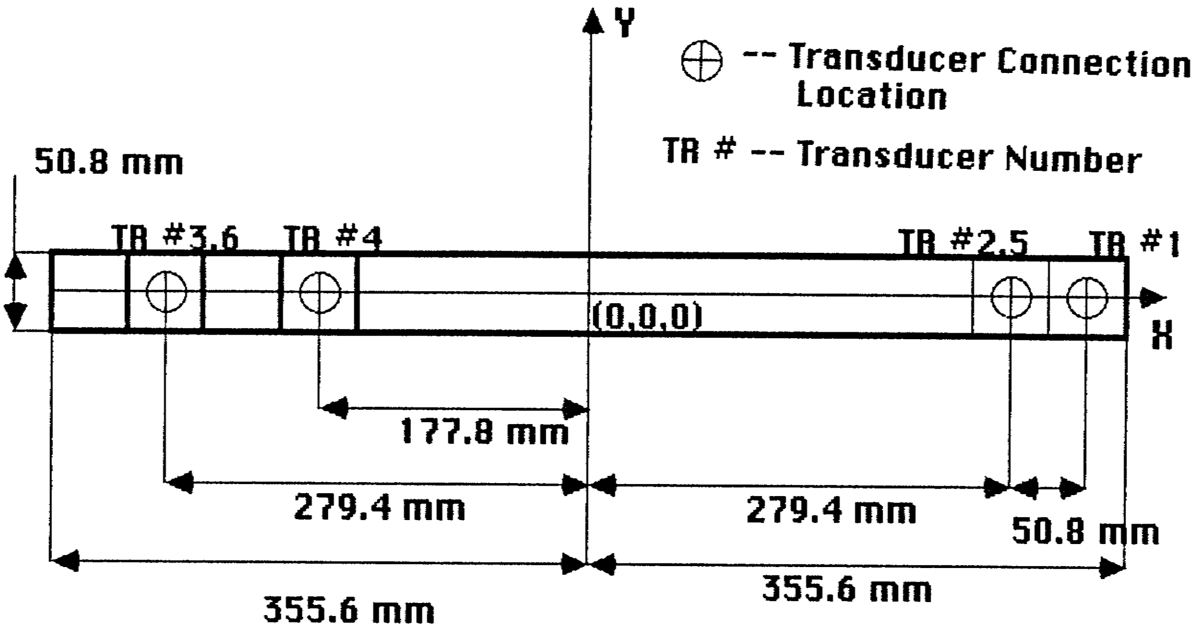

Figure 3.6: Active Transducer Frame XY Plane

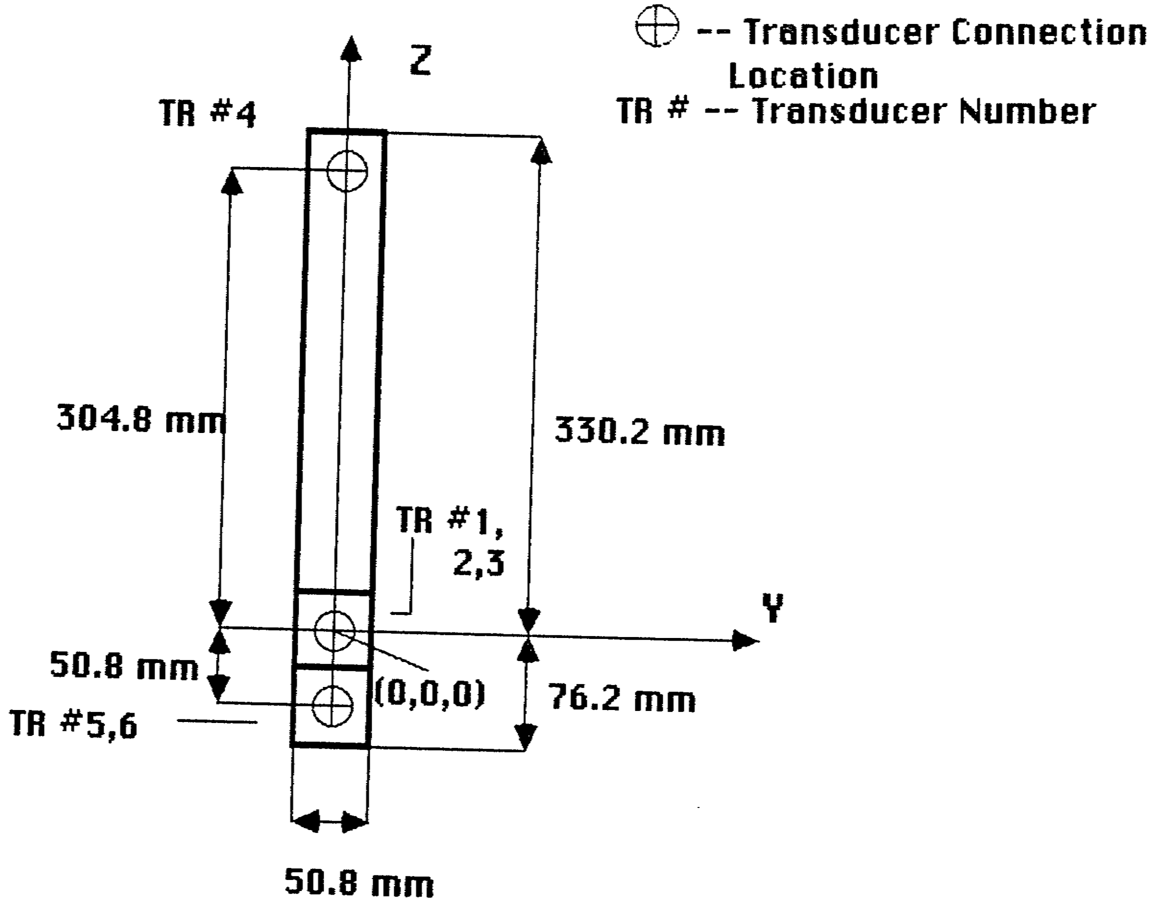

Figure 3.7: Active Transducer Frame YZ Plane

3.2.3 Transducer Subassembly

The transducer subassembly consisted of six cross type transducers as shown in Fig. 3.8. These transducers were developed by Bethge (1983) to replace C-shaped transducers when it was necessary to measure both compression and tension. A C-shaped transducer cannot be used for tension and compression since it becomes unstable in compression.

The six cross type transducers were not all of the same capacity since different transducers would be subjected to different maximum loads. The transducer measuring the draft load (force in the X direction) would be subjected to the largest force due to tillage tool soil forces. This transducer at the position labeled #1 in Fig. 3.2 through Fig.3.7 was designed with a maximum load of 10000 N with expected loads in the 5000 N range. Kiss and Bellows (1981) measured loads in the field amounting to 8000 N but this is not expected in the soil bin. The transducers at positions numbered 2 through 6 have a

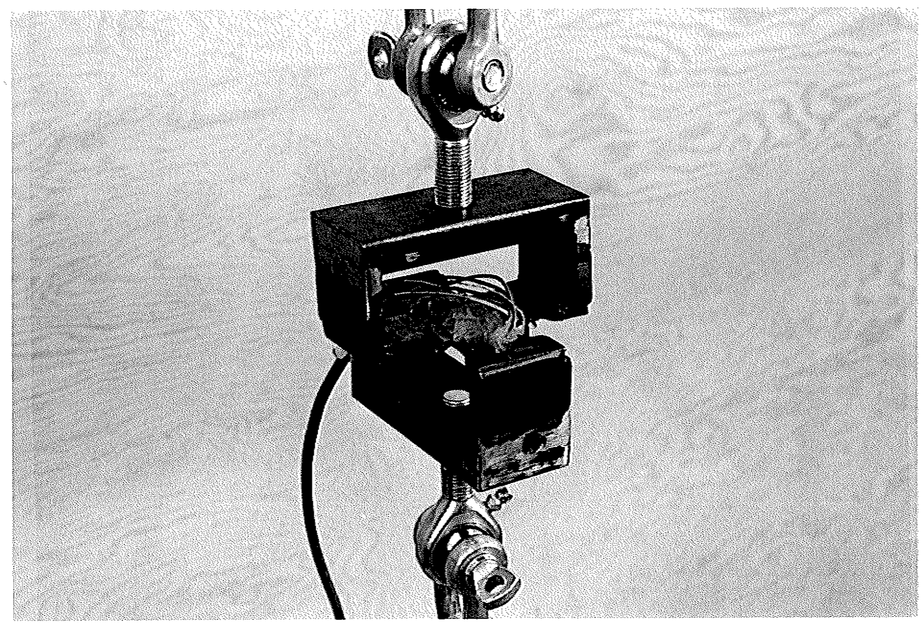

Figure 3.8: Cross-Type Tensional and Compressional Transducer

maximum capacity of 4000 N with expected loads in the 1200 N range.

3.2.4 Force and Moment Analysis of the Dynamometer Assembly

The forces and moments applied on the tillage dynamometer can be determined by analysis of the force and moment equations for the dynamometer. The distances from Fig. 3.2 through Fig. 3.7 are represented by the letters a, b, c, and d.

$a = 279.4$ mm
$b = 50.8$ mm
$c = 304.8$ mm
$d = 177.8$ mm

Using these distances and the coordinate system specified in Fig. 3.2 through Fig. 3.7 the force and moment equations for the three principal directions are:

$Fx = f_1$ (draft force) ....[12]
$Fy = f_4 + f_5 + f_6$ (lateral force) ....[13]
$Fz = f_2 + f_3$ (vertical force)..................[14]

$Mx = -f_4 * c + f_5 * b + f_6 * b$ ....[15]
$My = -f_2 * a + f_3 * a$ ....[16]
$Mz = -f_4 * d + f_5 * a - f_6 * a$ ....[17]

The forces measured in transducers #1 through #6 are represented by f_1 to f_6.

This method was Method #1 used to determine the three dimensional forces and moments at the origin of the coordinate system for the force and moment dynamometer. Any one transducer will respond to only one force direction but may respond to an applied moment in another direction. The transducer response to applied moments does not change the force measured in only one transducer but in a system of transducers. This allows the moment to be measured as a couple and the change in one transducer will be corrected by the other transducers in the system.

3.2.5 Data Acquisition System

The data acquisition unit used in this thesis was a Taurus-One data acquisition unit with a Corona microcomputer. This system allowed excellent speed, maximum scanning rate of 1000 channels per second, and met all requirements to monitor the six transducers used in the testing of the dynamometer.

The six cross-type transducers were designed to operate as a full Wheatstone bridge. To allow this the Taurus-One data acquisition system strain boards had to be modified from quarter bridges to full Wheatstone bridges. This modification amounted to the removal of the the resistors making up three of the arms of the bridge and reconnecting.

The voltage across the Wheatstone bridge was supplied by a Taurus-One D.C. voltage supply. This board supplied 10 volts across each of the six bridges. The Taurus data acquisition system measures the change in voltage across the bridges for ±10 volts and represents this change in terms of Taurus numbers. These Taurus numbers range from -2465 to +2455 and can be used with gains of 1, 10, 100, and 1000. For this thesis a gain of 1000 was used for both calibration tests and actual tillage trials in the soil bin.

3.3 CALIBRATION OF INDIVIDUAL TRANSDUCERS

The six cross-type force transducers were calibrated in both tension and compression. This enabled the development of equations to predict the forces applied along the major axis of the transducers as well as determine their linearity and stability in compression and tension. The calibration tests were done using the Taurus-One data acquisition unit with the readings being recorded by a Corona portable micro-computer. The data were then transferred to the University of Manitoba mainframe computer and statistical tests and regressions were done to determine the equations for each transducer.

The tensional load for each transducer was applied by hanging known loads on each transducer as shown in Fig. 3.9. The compressional load was applied by using a horizontal fulcrum as shown in Fig. 3.10. The readings were taken at a constant load increment of 197.2 N for tension and 588.6 N for compression. The larger increments were used in compression because of the multiplication effect of the fulcrum and the availability of only the 197.2 N calibration weights. Computer program SINGLCAL described in the Testing Procedure and Computer Programs section of this thesis was used to record the transducer readings. At each load increment ten readings were taken to give a better idea of the average value and to check the stability of the data acquisition system.

The transducers were calibrated over the ranges that should cover all of the expected loads when in actual operation in the three dimensional force and moment dynamometer frame. Transducers #1 through #4 were calibrated up to a maximum of ±2746.8 N. Transducer #1 could be expected to measure draft forces up to this load, whereas transducers #2 and #3 were loaded to this level to assure that they could remain linear under the large load induced by the moment created by the draft force and moment arm of a tillage implement. Transducer #4 was taken up to this level for only one calibration trial and then was calibrated over a smaller range of ±1962 N. Transducers #5 and #6 were also calibrated using the range of ±1962 N since it was not expected that they would experience loads higher that this range during normal operation.

For each increment there were ten readings taken for each trial done on each transducer. Each trial was loaded by the specified increments up to the maximum and then back down by the same increments to a zero load. For each transducer there were a total of four trials, two in tension and two in compression. The average was then calculated for each increment and then transferred to the University of Manitoba mainframe computer so that the equations for each transducer could be found using SAS (Statistical Analysis System) procedure GLM (General Linear Model). These equations were then used with the force moment and analysis equations for the three dimensional force and moment dynamometer as one method of determining the three dimensional forces and moments applied to tillage implements.

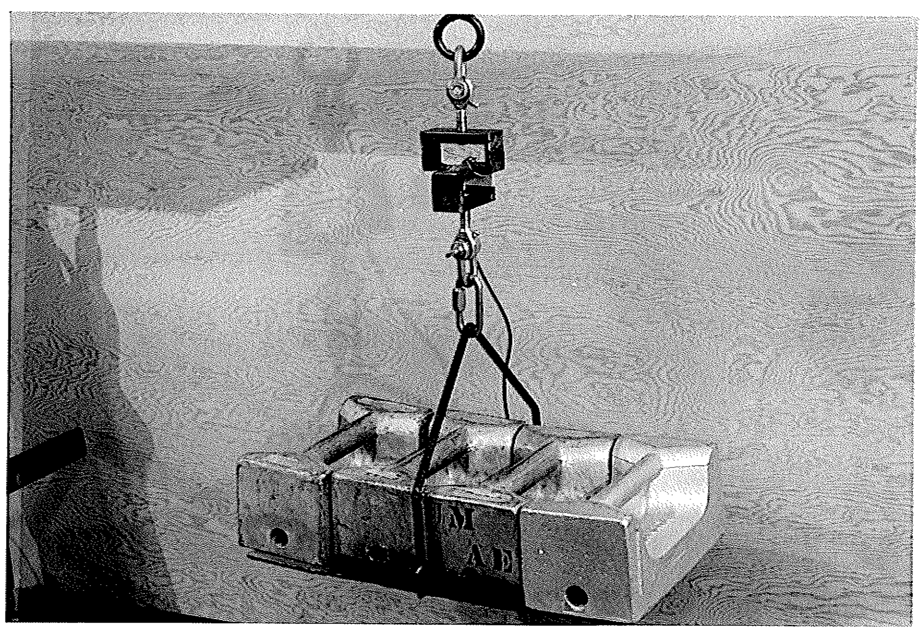

Figure 3.9: Calibration of Individual Transducer in Tension

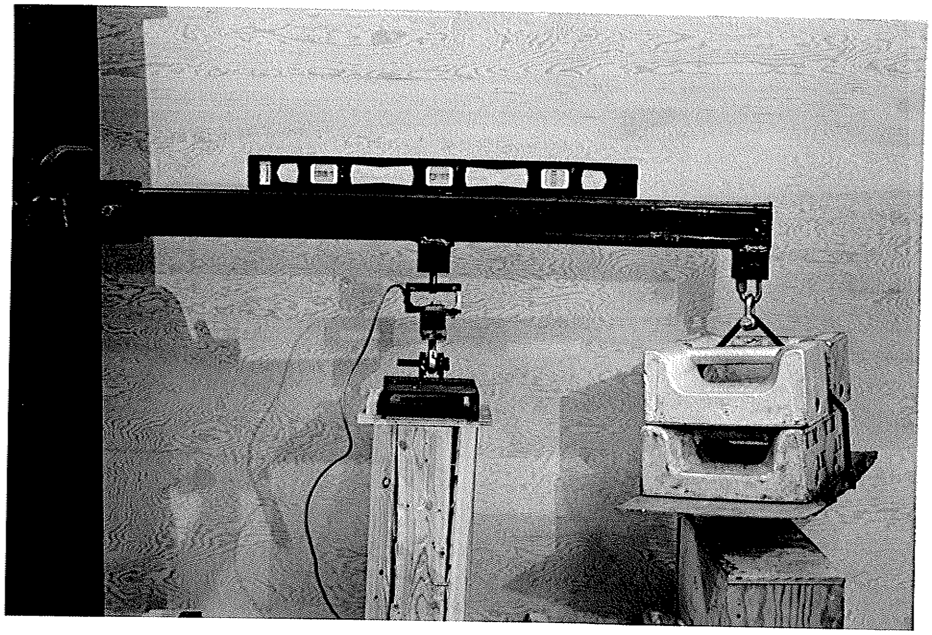

Figure 3.10: Calibration of Individual Transducer in Compression

3.4 CALIBRATION OF DYNAMOMETER FRAME

The three dimensional force and moment dynamometer frame was also calibrated using the Matrix Method. A known force or moment was applied in one of the three principal directions, X, Y, and Z. and the response of the system was then recorded and used to develop the coefficient matrix for the three dimensional force and moment transducer. These results were also used to check the accuracy of the force and moment equations [12] through [17] that used the individual calibrations of each transducer to determine the forces and moments in three dimensions. Three methods were used to develop the force and moment equations used in this thesis. The force and moment equations in Method #1 were constructed using the individual calibration results of the force transducers and the vector analysis equations of the dynamometer frame. The force and moment equations in Methods #2 and #3 were both developed using the Matrix Method for force and Moment Analysis. Method #2 used the regression coefficients from the slopes of the regression curves that were not forced through zero. Method #3 used the regression coefficients from the slopes of the regression curves that were forced through zero. To calibrate the dynamometer frame as a single unit the coefficient matrix K from equation [2] was found. The K matrix can be found by first determining the inverse matrix experimentally and taking it's inverse. The inverse coefficient matrix was found for this dynamometer system for the coordinate system shown in Fig. 3.2 through Fig. 3.7.

The first step in developing the coefficient matrix for the dynamometer system was to record the system's response to known forces and moments. The forces and moments in the three principal directions for the coordinate system used were applied using pullies, steel cable, and 50.8 mm by 50.8 mm by 6.0 mm thick steel tubing. The cable was attached to the dynamometer frame with 12.7 mm eye bolts that were attached in line with the forces applied to the frame so that there would be no moment arm. When a moment was applied two eyebolts were used with a 500 mm moment arm to apply a pure couple. Examples of the application of forces in the negative lateral direction and the positive vertical direction are shown in Fig. 3.11 and 3.12 respectivly. The application of a positive moment about the x-axis is shown in Fig. 3.13. The force in the positive z-direction was applied with a 500 mm eccentricity in the positive y-direction thus applying a positive moment in the x-direction. The force was removed by the application of a negative force in the z-direction applied at the origin of the coordinate system leaving a moment in the positive x-direction only.

Before calibration could take place initial testing was done. This testing was done to assure correct operation of the dynamometer system and to remove any gross interaction due to poor alignment of the force transducers. Minor adjustments were made and the dynamometer system was ready for calibration.

The calibration forces were applied in 196.2 N increments with ten readings being recorded for all six transducers in the dynamometer at all increments. The calibration forces were incremented up to a maximum value and then decremented to zero. The maximum load for the draft (longitudinal calibration force) was 2008 N. This range was used since forces in the draft direction were not expected to exceed this level when tests are run in the soil bin. Two trials were done over the maximum range in the X direction. The maximum load for the calibration force applied in the vertical, Z-direction, and the lateral, Y-direction, was ±1027 N. This maximum value was used since the loads in the vertical and lateral directions were not expected to exceed this value. The forces in the vertical and lateral directions were applied in both the positive and negative directions because both could occur when using different types of tillage implements. Therefore four trials were done in each of these directions, two positive and two negative.

Moments about the X, Y, and Z axis of the coordinate system were also applied to the dynamometer system. The moments were applied in 98.1 Nm increments for all directions. The moments were created by the application of a force with an eccentricity of 500 mm and a second force applied of equal magnitude but opposite direction at the origin of the coordinate system. The maximum moment applied in all three directions was ±514 Nm. There was no application of a moment in the negative y-direction since a moment in this direction could not be expected to occur given the dynamometers coordinate system. Moments were applied in both the negative and the positive directions for the X and Z directions since different tillage implements could cause moments in both directions. The moments, like the force calibration loads, were loaded to their maximum and then decremented back to zero. For the moments in the X and Z directions four trials were done, two positive and two negative, and only two trials were conducted for moments in the positive Y direction.

For each incremental load of each calibration trial ten readings were recorded of all six transducers. These responses of the transducers to an application of a force or moment were then used to develop the inverse coefficient matrix. The data was stored on microcomputer disk and then transfered to the University of Manitoba mainframe computer system. The average (transducer output)/N and the average (transducer output)/Nm were found for all six transducers for all three forces and moments using SAS (Statistical Analysis System) and procedure GLM (General Linear Model). The coefficients were then placed in position in the inverse coefficient matrix and the inverse matrix was found. This inverse represents the coefficient matrix for the dynamometer system and coordinate axis as located in Fig. 3.2 through Fig. 3.7.

From the coefficient matrix it is now possible to compute the three dimensional forces and moments that a tillage implement places on the dynamometer system. This method as well as the vector analysis equations [12] to [17] were used to calculate the three dimensional forces and moments. These methods were also compared by determining their predicted forces and moments to known forces and moments that were

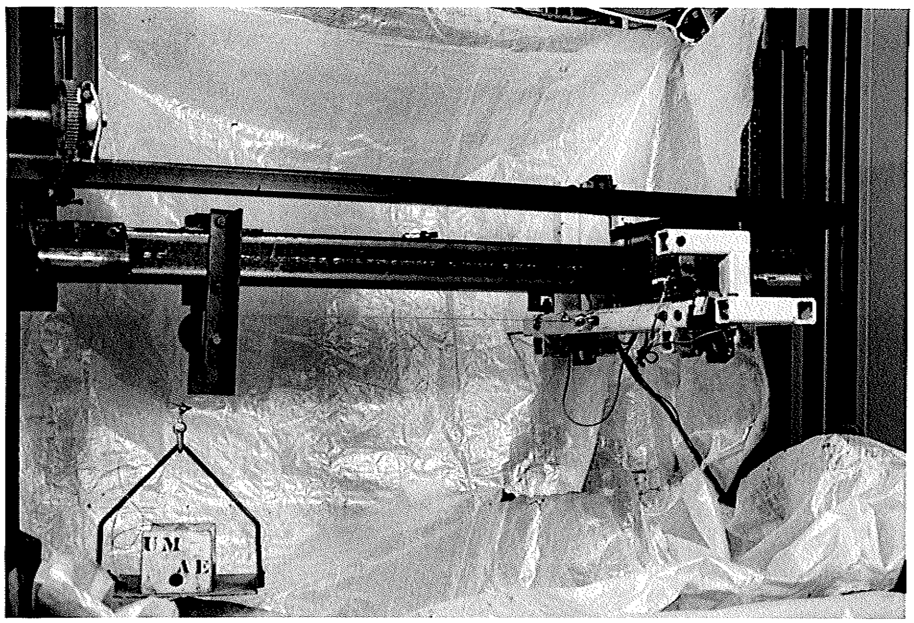

Figure 3.11: Calibration Force in the Negative Y Direction

applied.

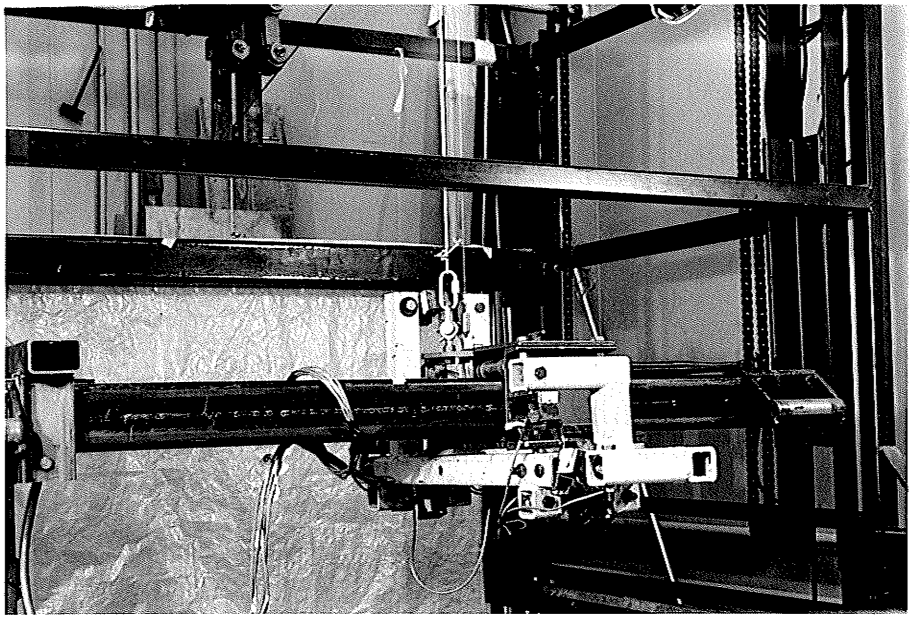

Figure 3.12: Calibration Force in the Positive Z Direction

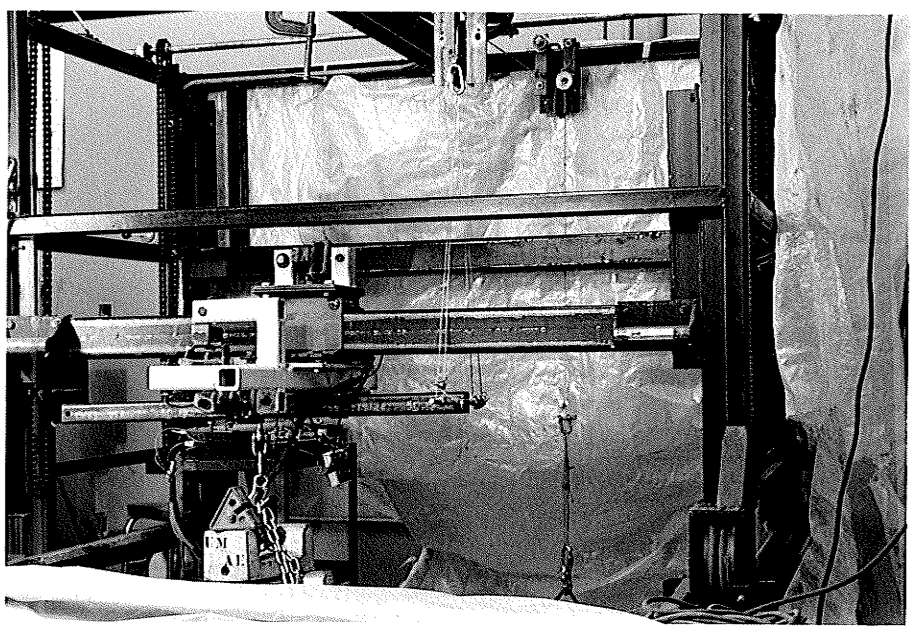

Figure 3.13: Calibration Moment in the Positive X Direction

3.5 APPLICATION OF THE WRENCH THEORY

The wrench for the three-dimensional forces and moments was determined in this thesis to allow the positioning of the resultant tillage force in space. The steps used to determine the wrench and its position in space for the three-dimensional forces and moments measured will be explained in this section.

Knowing the three forces Fx, Fy, and Fz and the three moments Mx, My, and Mz as measured by the three dimensional force and moment dynamometer allows us to calculate the resultant force vector Fr and the resultant moment vector Mr.

$$Fr = Fx + Fy + Fz \quad [18]$$

$$Mr = Mx + My + Mz \quad [19]$$

The magnitude of the two vectors can be given as

$$fr = \sqrt{Fx^2 + Fy^2 + Fz^2} \quad [20]$$

and

$$mr = \sqrt{Mx^2 + My^2 + Mz^2} \quad [21]$$

The projection of the resultant moment vector parallel to the direction of the force vector and perpendicular to the direction of the force vector was now found. The magnitude of the projection of the moment vector Mr parallel to Fr is known to be equal to:

$$mo = mr * \cos(\emptyset) \quad [22]$$

where $\cos(\emptyset)$ is equal to the dot product of the resultant moment and force vectors Mr and Fr divided by the magnitude of both vectors, mr and fr as shown in equation [23].

$$\cos(\emptyset) = \frac{Mr \bullet Fr}{mr * fr} \quad \text{..............................[23]}$$

The moment vector along the direction of the resultant force was then expressed in component form as shown in equation [24].

$$Mo = (mo*\cos \gamma x)i + (mo*\cos \gamma y)j + (mo*\cos \gamma z)k \quad \text{..[24]}$$

Were the cosines of the angles γ x, γ y, and γ z are the direction cosines for the resultant force vector Fr.

$$\gamma x = \frac{Fx}{fr} \quad \text{............................ [25]}$$

$$\gamma y = \frac{Fy}{fr} \quad \text{............................ [26]}$$

$$\gamma z = \frac{Fz}{fr} \quad \text{............................ [27]}$$

The moment that is not along the direction of the force but is perpendicular can be found using equation [28].

$$Mr = Mo + Mp \quad \text{............................ [28]}$$

Where Mp is the moment perpendicular to the force vector.

Using this equation the components of Mp become equal to.

$$Mpx = Mrx - Mox \quad \text{..................[29]}$$

$$Mpy = Mry - Moy \quad \text{..................[30]}$$

$$Mpz = Mrz - Moz \quad \text{..................[31]}$$

The moment vector Mo represents the minimum moment for the three dimensional force and moment system measured and Fr represents the resultant force vector. The moment vector Mp represents the moment that is created by the application of the resultant force Fr with some eccentricity, represented by distance vector R, from the origin of the coordinate system. If we can determine a location where the position from the origin of the force vector Fr balances the moment vector Mp we will have determined the central axis of the wrench, made up of force vector Fr and moment vector Mo, and uniquely located the line of action of the resultant force in space.

The determination of the line of action of the resultant force in two dimensions is a very easy task. But the same job in three dimensions involves the intersection of several planes in space. If we set the cross product of position vector R and force vector Fr equal to the perpendicular moment Mp we would be able to solve for the distance vector R. But in three dimensions there is an infinite number of solutions to the position of the force vector and a more complex method must be used to determine the position in space of the resultant force Fr.

Fortunately the force vector Fr and the moment and position vector Mp and R have some very convenient properties. By definition the force and moment vectors Fr and Mp are perpendicular to each other. The position vector R is also perpendicular to both vectors Fr and Mp. This also allows us to define a plane containing both vectors R and Fr using the moment vector Mp and one point on the plane (0,0,0), the origin of the coordinate axes. A plane that contains both the position vector R and force vector Fr is defined by the moment vector Mp. Since the vector Mp is perpendicular to both R and Fr it is normal to the plane containing both vectors. The moment vector direction numbers can be written as (Mx,My,Mz) and used to define the equation of the plane that contains both the force and position vectors. The equation of the plane becomes equal to:

$$Mx*X + My*Y + Mz*Z + D = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad [32]$$

Now using a point on the plane (0,0,0) we can determine coefficient D: and equation [32] becomes equal to:

$$Mx*X + My*Y + Mz*Z = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots [33]$$

Similarly the plane containing the position vector R and the moment vector Mp can be determined using the force vector Fr. The force vector Fr is also perpendicular to both moment and position vectors and is therefore normal to the plane that contains both of them. Therefore the equation of the plane that contains both the position and the moment vectors can be represented using the direction numbers for the resultant force Fr, (Fx,Fy,Fz), and a point on the plane (0,0,0) the origin of the coordinate system.

$$Fx*X + Fy*Y + Fz*Z = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots [34]$$

Now if these two planes were intersected they would intersect along the line representing the position vector R. Knowing that R is perpendicular to Mp and Fr allows us to define the following dot products.

$$Mp \bullet R = 0 = Mx*Rx + My*Ry + Mz\ Rz \ \ldots\ldots\ldots\ldots [35]$$

$$Fr \bullet R = 0 = Fx*Rx + Fy*Ry + Fz*Rz \ \ldots\ldots\ldots\ldots [36]$$

Now using the fact that R is perpendicular to Fr and that the cross product of R and Fr is equal to Mp we can write equation [37].

$$|R| = \frac{|Mp|}{|Fr|} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [37]$$

Equations [38] to [40] define the magnitude of the vectors R, Mp, and Fr.

$$|R| = \sqrt{Rx^2 + Ry^2 + Rz^2} \quad \ldots\ldots\ldots\ldots\ldots [38]$$

$$|Fr| = \sqrt{Fx^2 + Fy^2 + Fz^2} \quad \ldots\ldots\ldots\ldots\ldots [39]$$

$$|Mp| \quad \sqrt{Mx^2 + My^2 + Mz^2} \quad \ldots\ldots\ldots\ldots\ldots [40]$$

We now have three equations, [35] to [37], with nine variables. Six of the nine variables are known and it is now possible to determine the remaining three. The unknown variables are Rx, Ry, and Rz which represent a position vector that locates the force vector Fr at a position of minimum torque. Therefore the point in space (Rx,Ry,Rz) and the force vector Fr represent the line in space that coincides with the central axis of the wrench for the system of forces and moments.

The position vector variables will from now on be referred to as X, Y, and Z. If we now use equation [36] and solve for the X variable it becomes:

$$X = -\left|\frac{Fy(Y) + Fz(Z)}{Fx}\right| \quad \ldots\ldots\ldots\ldots\ldots\ldots [41]$$

and solving equation [35] for Y will give us equation [42].

$$Y = -\left|\frac{Mx(X) + Mz(Z)}{My}\right| \quad \ldots\ldots\ldots\ldots\ldots\ldots [42]$$

Substitute equation [42] into equation [41] for the Y value gives equation [43].

$$Fx(X) = Fy \left| \frac{Mx(x) + Mz(Z)}{My} \right| - Fz(Z) \quad \text{.............}[43]$$

Next separating variables X and Z

$$X \left| Fx - \frac{Mx\ Fy}{My} \right| = \left| \frac{Fy\ Mz}{My} - Fz \right| Z \quad \text{.............}[44]$$

and solving equation [44] for X will yield equation [45].

$$X = \frac{\left| \frac{Fy\ Mz}{My} - Fz \right|}{\left| Fx - \frac{Mx\ Fy}{My} \right|} Z \quad \text{..........................}[45]$$

Setting equation [45] equal to

$$X = \Delta 1\ Z \quad \text{....................................}[46]$$

where

$$\Delta 1 = \frac{\left| \frac{Fy\ Mz}{My} - Fz \right|}{\left| Fx - \frac{Mx\ Fy}{My} \right|} \quad \text{..........................}[47]$$

and substituting equation [47] into equation [42] we may develop equation [48].

$$Y = -Mx \left| \Delta 1\ Z \right| - \frac{Mz}{My} Z \quad \text{........................}[48]$$

Solving [48] for Z

$$Y = \left| \frac{-Mx\Delta 1}{My} - \frac{Mz}{My} \right| Z \quad \ldots\ldots\ldots\ldots [49]$$

and simplifying [49]

$$Y = \Delta 2 \; Z \quad \ldots\ldots\ldots\ldots [50]$$

will give equation [51].

$$\Delta 2 = \left| \frac{-Mx \; \Delta 1}{My} - \frac{Mz}{My} \right| \quad \ldots\ldots\ldots\ldots [51]$$

Now substituting equation [38] into equation [37] and solving for Z will give equation [52].

$$Z^2 = \frac{|Mp|}{|Fr|} - X^2 - Y^2 \quad \ldots\ldots\ldots\ldots [52]$$

Substituting $K = |Mp|/|Fr|$ and substituting for Y,equation [50], and X,equation [46], equation [52] now becomes:

$$Z^2 = K - [\Delta 1 \; Z]^2 - [\Delta 2 \; Z]^2 \quad \ldots\ldots\ldots\ldots [53]$$

solving for Z in equation [53] will give equation [54].

$$Z = \sqrt{\frac{K}{1 + \Delta 1^2 + \Delta 2^2}} \quad \ldots\ldots\ldots\ldots [54]$$

The procedure that was followed in this thesis to determine the line of action to the resultant force Fr was:

1. The resultant force Fr was found using equation [18].
2. The resultant moment Mr was found using equation [19].
3. The resultant moment was broken up into its components along and perpendicular to the resultant force using equations [24] and [28].

4. The values for the variables $\Delta 1$ and $\Delta 2$ were found using equations [47] and [51].

5. The value for Z was found using equation [54]

6. The value of X and Y were determined using equations [46] and [48].

Chapter IV

TILLAGE TOOL TESTING PROCEDURE AND COMPUTER PROGRAMS

4.1 TILLAGE IMPLEMENT TESTING PROCEDURE

4.1.1 Preparation of Soil Bin

The main advantage of using a soil bin to test tillage implements is the ability to control soil properties. Although the trials done in this thesis were more for demonstration purposes than actual tillage research the soil was prepared so that the soil variation could be minimized. The preparation steps taken in this thesis were:

1. The soil was first conditioned with a rotary tiller to allow uniform initial compaction throughout the entire soil bin (Fig. 4.1). The rotary tiller was operated to a depth of 150 mm with a rotational speed of 300 r/min at the slowest forward speed that the University of Manitoba Soil Bin Carriage will operate at, namely, 1.0 km/h.
2. The soil was then compacted using a 300 mm diameter smooth roller as shown in Fig. 4.2. The roller was passed over the soil a total of twenty times to achieve consistent compaction throughout the soil bin. After completion of soil conditioning the cone index of the first 150 mm was taken and found to be in the 3.0 kg/cm^2 to 6.0 kg/cm^2 range.

The soil was conditioned prior to every tillage test. All tillage tests were done using Elm Creek sandy loam soil.

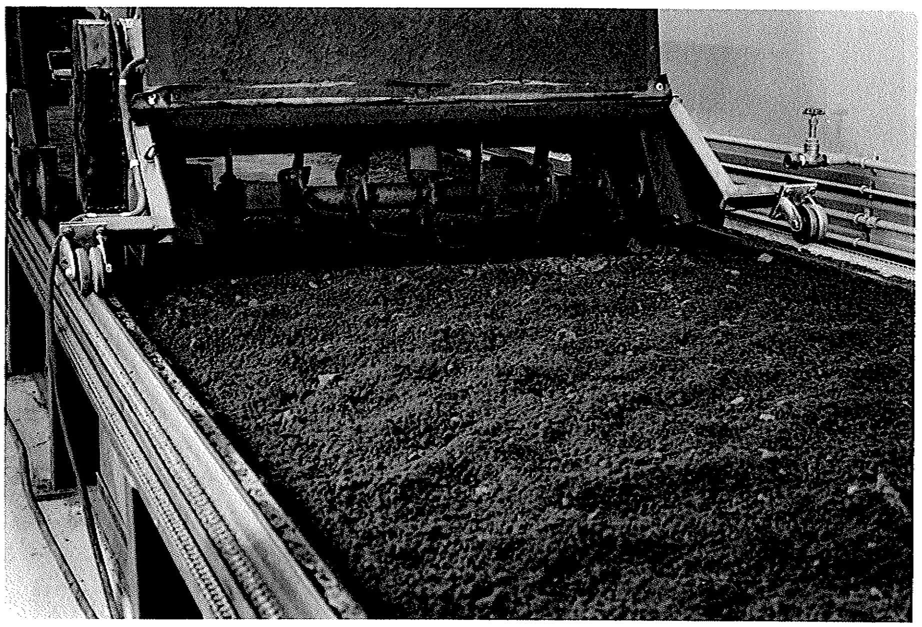

Figure 4.1: Rotary Tiller Conditioning of Soil

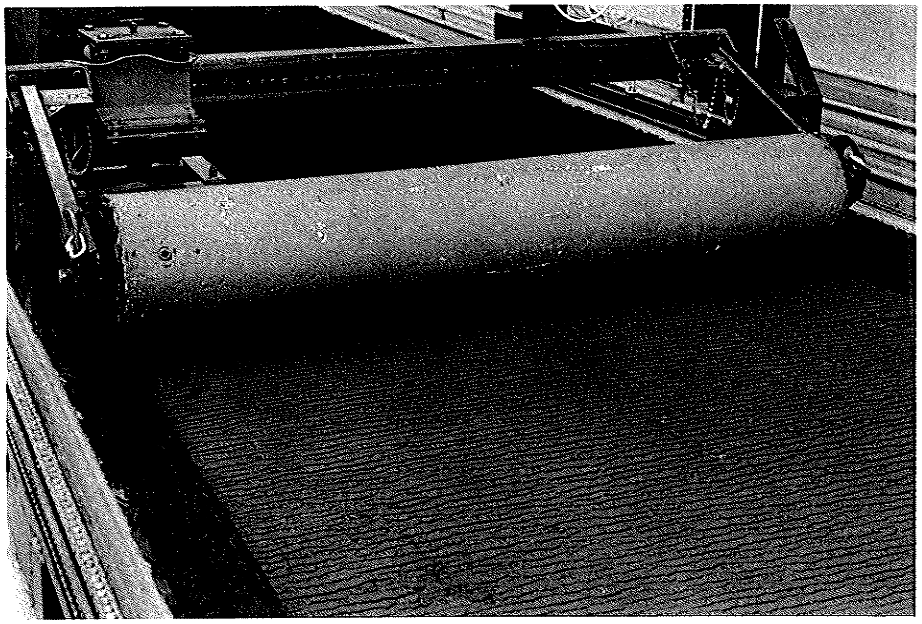

Figure 4.2: Soil Packing Roller on First Trip

4.1.2 Cultivator Shovel and 30 Degree Disk Blade Trials

The soil was prepared as described in the previous section and it was hoped that there would be room for five tillage trials after each soil conditioning. There were five disk blade trials run as well as six cultivator shovel trials. There was an extra cultivator shovel trial run because in trial #4 there was not enough room to avoid running in soil that had been disturbed by trial #3.

The cultivator shovel was mounted on the three dimensional force and moment dynamometer as shown in Fig. 4.3. The cultivator shovel was lowered to a depth 80 mm below the average soil level. This depth varied from 70 mm to 90 mm due to variation in the soil level. The tip of the cultivator was located at the coordinates (30,0,600) mm using the coordinate system defined in Fig. 3.5. The disk blade was mounted as shown in Fig. 4.4 making a 30 degree angle with the direction of travel. The center of the disk was positioned at coordinates (-0.056,-0.007,-0.370) and the radius of the disk was 180 mm. The disk blade was also placed at a depth 80 mm below the average soil level. The depth varied from 70 mm to 90 mm due to the soil level variation in the soil bin. Pictures of the cultivator shovel and the disk blade are shown in Fig. 4.5 and 4.6, respectivly, at the end of a run.

The data acquisition system was attached to the three dimensional force and moment transducer using the following procedure.

1. The Wheatstone bridge circuits of the three dimensional force and moment transducer were connected to the strain board of the Taurus-One data acquisition system using a 32 pin connector.
2. The Taurus strain board was then connected to the Taurus-One data acquisition unit with a ribbon connector.
3. The Taurus One data acquisition unit was then connected to the Corona PC serial port through the Taurus channel A serial port.
4. The program disk was placed in drive A of the Corona and a blank data disk placed in drive B.
5. When power was supplied to the system the disk in drive B was formated for data storage and the programs on drive A were loaded into memory. The main menu was displayed and the user was prompted to remove the program disk and place the data disk in drive A. The user was then ready to begin collecting, or analyzing data depending on what program was selected from the main menu.

With the data acquisition system attached to the three dimensional force and moment transducer, the program FORCEACQ was run for each tillage trial. The soil bin carriage motor was taken up to the desired speed of 3 km/h and the drive was engaged. The data acquisition program took 400 readings in eight seconds for each trial and then stored the the data in a compressed random access file on disk. This data was later run through the force conversion program FORCE3D that predicted the three dimensional forces and moments applied to the dynamometer and this data was saved to disk in an uncompressed sequential file. This data was used by the program WRENCH that determined the two component moments of the resultant moment Mr, Mo the moment vector parallel to the line of action of the resultant force Fr, and Mp the moment vector perpendicular to the line of action of the resultant force Fr. The minimum moment arm position (rx,ry,rz) was also found for the resultant force in space. These values were also saved to disk. The three dimensional forces and moment resultant vectors as well as the space position coordinate for the cultivator shovel and disk blade were uploaded to the University of Manitoba Mainframe computer to allow statistical analysis. These values were checked to see if there were statistical differences between runs and if so how large.

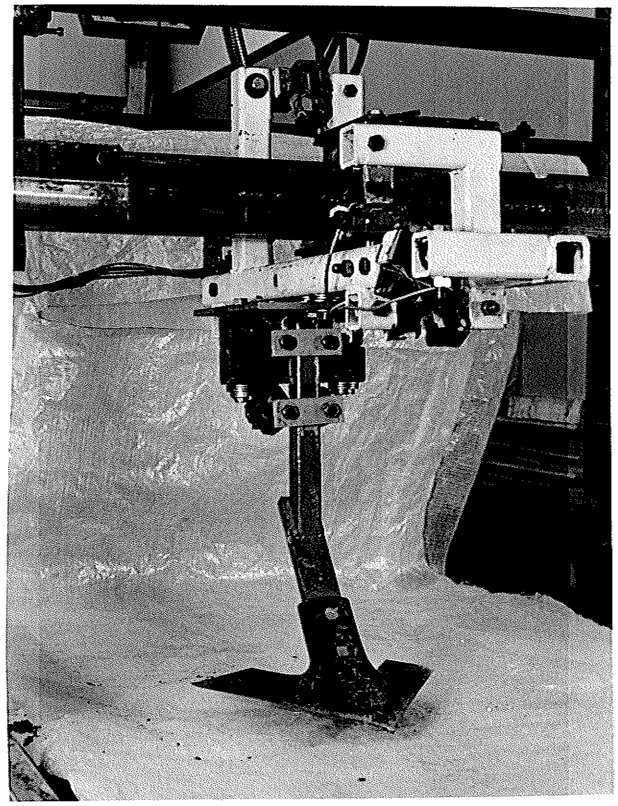

Figure 4.3: Three Dimensional Dynamometer and Cultivator Shovel

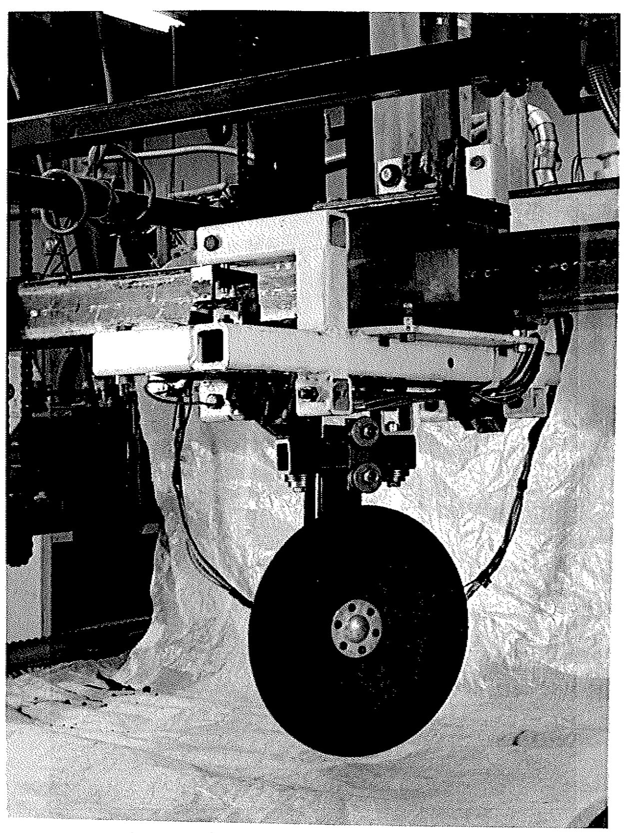

Figure 4.4: Three Dimensional Dynamometer and 30 Degree Disk Blade

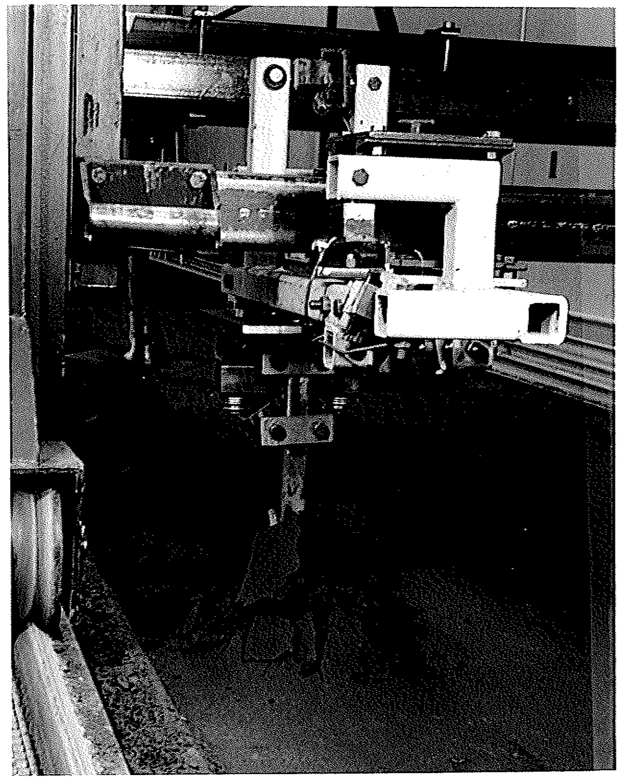

Figure 4.5: Cultivator Shovel in Soil

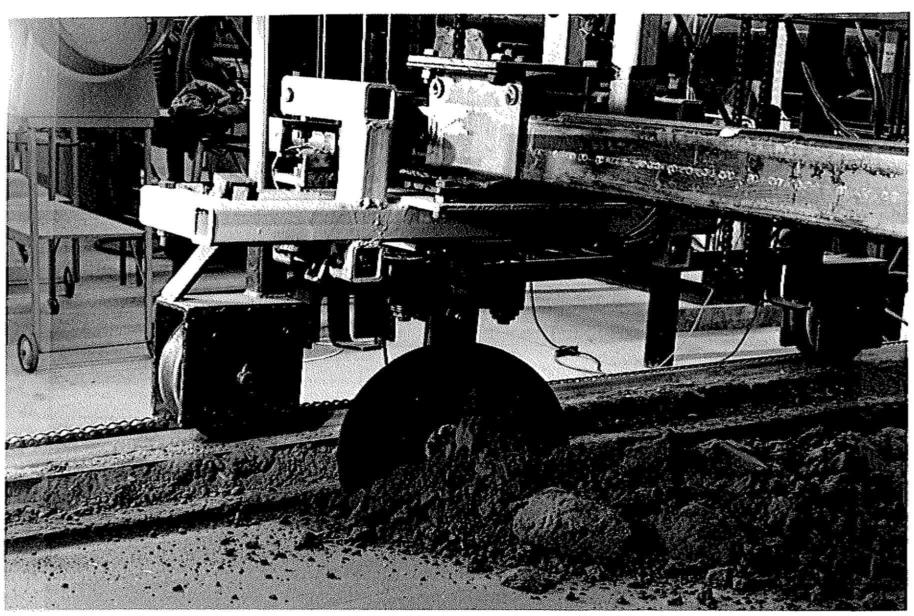

Figure 4.6: 30 Degree Disk Blade in Soil

4.2 TILLAGE IMPLEMENT TESTING COMPUTER PROGRAMS

The programs used for testing implements in this thesis have been written to be particularly user friendly. They were written using GWBASIC computer language with MS-DOS (Micro-Soft Disk Operating System). The programs described in this section can be found in Appendix C through Appendix G.

The programs for data acquisition and force analysis were combined into a complete software package. This package contained six integrated computer programs, MMENU, FORCEACQ, FORCE3D, FORCETRC, WRENCH, and INTERSEC.

The program MMENU allows access to the other five programs from its menu. The programs can be accessed in any order if all data are present but must be run in a logical order when determining forces and moments for the first time. If the data are not present on disk the program will prompt the user with "File Not Found". The order of execution to develop a new data base is as follows:

1. First the initial raw data must be collected using the program FORCEACQ from any tillage or force related trial. Several trials may be collected at one time without force and moment analysis or the forces and moments may be determined immediately.
2. Once the initial raw data are collected the program FORCE3D must be run to determine the three dimensional forces and moments. Program FORCETRC could also be run at this time. FORCETRC has been modified to allow its use for traction tests. Both programs store their data in a form that can be used by the next program WRENCH.

3. The WRENCH program will then determine the minimum position vector for the line of action of the resultant force with respect to the origin of the three dimensional force transducer. These data are also stored on disk. As well there is a complete computer print out available of all the mean forces, moments, and position vectors for the trial that is being analyzed.
4. The final program run is INTERSEC. This program determines the intersection point of the line of action of the resultant force and the plane in space that is used to describe the tillage implement being tested.

4.2.1 Tillage Implement Data Acquisition Program

The tillage implement data acquisition program FORCEACQ was used to monitor the three dimensional force and moment dynamometer during the testing of tillage implements. This program initially ran a continuous check of all six force transducers, using the Taurus-One data acquisition unit, and displayed the readings on the Corona microcomputer. This allowed the user to assure that all transducers were operating correctly. After the check procedure was finished the next stage of the program was to take the unstrained readings of the dynamometer system. These readings were taken with the tillage implement of interest attached so that its weight would be compensated for without manual subtraction. Twenty readings of the unstrained transducers were taken and stored. The computer program was then ready to take actual readings of the six force transducers while they were loaded by soil tillage forces.

The computer program then prompted the user to start the data acquisition by pressing the (S) key. When this was depressed the data acquisition unit would take 400 scans of the six force transducers in eight seconds. The data collected was stored by the Corona microcomputer in random access files.

4.2.2 Three Dimensional Force and Moment Analysis Program

The data that were collected in the program FORCEACQ do not in themselves allow the direct reading of the forces and moments applied to the dynamometer directly. The data represented the change in the voltages across the full Wheatstone bridge as represented in Taurus-One units at a gain of 1000. To determine the forces and moments in three dimensions the calibration equations developed during the calibration of the dynamometer frame were used. The equations were used in the program FORCE3D.

The program FORCE3D calculated the forces and moments applied to the dynamometer frame using Matrix Method #3 . This method will be described in more detail in Section 5.1.2. These equations give the forces and moments applied on the three dimensional force and moment dynamometer at the origin of the coordinate axis as shown in Fig. 3.5.

The program first subtracted the unstrained average reading from the values for each transducer taken during the tillage force and moment measurement. This removed the effect of the initial weight from the vertical force, giving the tillage tool soil forces only. The average, ten readings at a time, was then found for the resultant forces and moments and stored on disk in a expanded random access file. This data was used by the next program WRENCH to make its calculations.

4.2.3 Computer Program for the Determination of the Wrench

The program WRENCH used the values determined in the program FORCE3D. These values were used to determine the component moments of the resultant moment, Mr. These components consisted of the component Mo that was parallel to the direction of the resultant force and Mp that was perpendicular to the resultant force. This program also determined the value for the position vector R that gave the position of the resultant force from the origin of the system to achieve the minimum torque along the line of action of the resultant force. This point gave the position of the axis of the wrench for a system of forces and uniquely positions the resultant force along its true line of action. These values were then saved to disk on the Corona microcomputer in a random access file.

4.2.4 Intersection Determination Program

The program INTERSEC used the mean values determined in the programs FORCE3D and WRENCH and the equation that described the plane in space that represented the tillage implement of interest. The force and position vector components, and the coefficients for the plane in space describing the tillage implements, were entered into the INTERSEC program. The point of intersection was determined and printed to the printer, to provide a hard copy.

4.3 COMPUTER PROGRAMS FOR CALIBRATION

The calibration programs were also written in a user friendly style. They would prompt the user to place the correct calibration force or moment and then depress a key to begin the data acquisition phase. All calibration programs were written in GWBASIC using MS-DOS. The data that were collected were stored in compressed two byte numbers in random access files. The programs were also written to operate with the Corona microcomputer and the Taurus-One data acquisition unit. The programs described in this section can be found in Appendix F.

4.3.1 Individual Calibration of Transducers

The program used to calibrate the transducers when they were calibrated individually was CALIND. This program was set up so that it would scan one transducer at a time when it was being calibrated as described in section 3.3, Calibration of Individual Transducers. The program would first scan the transducer, with the use of the Taurus One data acquisition unit and the Corona microcomputer, to check for correct functioning. It would then take 10 unstrained readings and store the information on disk. The program would then allow the increment of loads up to a predetermined maximum and then allow an incremental lowering of these loads. At each increment the transducer would be scanned 10 times and the data stored on disk. The average transducer output was determined for each calibration increment and uploaded to the mainframe computer for statistical analysis using SAS.

4.3.2 Computer Programs for Calibration of the Dynamometer Frame

The program used to calibrate the dynamometer frame, for development of the coefficient matrix, was CALFRAME. This program scaned all six transducers initially to check for correct operation. The unstrained readings were then taken and stored on disk. The program then allowed for the incremental calibration forces or moments to be applied and took ten scans of each incremental increase. The increments reached a predetermined maximum and then were lowered, in stages, to zero. The data were then placed on disk on the Corona microcomputer. These data were then used to determine the matrix coefficients for the Matrix Method of force and moment analysis. The average transducer output for the force or moment increments was determined and transfered to the mainframe computer for statistical analysis.

Chapter V

RESULTS AND DISCUSSION

5.1 CALIBRATION RESULTS

5.1.1 Calibration Results From Individual Transducers

The calibration data collected for the six individual transducers were transfered to the University of Manitoba mainframe computer to allow statistical analysis using SAS. The SAS procedure used was GLM(General Linear Model) and the results were summerized in Table 5.1. The linearity of the transducers was good, never exceeding more than 1.02 % for transducers #2 through #6. The linearity of transducer #1 was 1.55 % which was the highest but still very acceptable. The sensitivity for transducer #1 is as expected lower than the other transducers due to its stronger construction. All of the R^2 values were above 0.9995 which is again very good. The estimate of the slopes of the calibration curves were used in the equations [12] through [17] for the calculation of the forces and moments applied to the origin of the coordinate system of the three dimensional force and moment dynamometer. This method of calculating the forces and moments was the force and moment vector analysis, Method #1. The equations [12] through [17] become equations [55] through [60].

$$Fx = 1.42967 * TR1 \quad \ldots\ldots [55]$$

$$Fy = 0.8461 * TR4 + 0.8444 * TR5 + 0.8179 * TR6 \quad \ldots\ldots [56]$$

$$Fz = 0.8553 * TR2 + 0.8757 * TR3 \quad \ldots\ldots [57]$$

$$Mx = -0.8461*TR4*c + 0.8444*TR5*b + 0.8179*TR6*b \quad \ldots\ldots [58]$$

$$My = -0.8553*TR2*a + 0.8757*TR3*a \quad \ldots\ldots [59]$$

$$Mz = -0.8461*TR4*d + 0.8444*TR5*a - 0.8179*TR6*a \quad \ldots\ldots [60]$$

where:

a = 279.4 mm
b = 50.8 mm
c = 304.8 mm
d = 177.8 mm

TABLE 5.1

Individual Transducer Calibration Results

Transducer #	Slope	R^2	Linearity
1	1.4297	0.99977	1.55%
2	0.8553	0.99964	1.01%
3	0.8758	0.99970	1.01%
4	0.8461	0.99977	0.96%
5	0.8444	0.99956	1.02%
6	0.8179	0.99993	0.62%

NOTE: Slopes have the units N/unit output from Taurus-One, gain 1000. Linearity is the largest residual over the full scale value.

5.1.2 Dynamometer Frame Calibration Results

The dynamometer frame calibration results are represented in Appendix A in Tables A.1 and A.2. In these tables the regression coefficients were given for all applied force and moment calibrations. These values are the slopes of the regression curves and are used to determine the matrix coefficients for the matrix method for force and moment analysis. Table

A.1 contains the values found when the regression curve was not forced through zero and Table A.2 contains the values found when the regression curve was forced through zero. The statistical values F, R^2, and linearity, for each transducer due to all six forces and moments are recorded in Tables A.1 and A.2.

The linearity for the transducers subjected to forces and moments that were along the transducers principal axes when mounted in the dynamometer frame was good. The linearity of the transducers when subject to a load that is not along their principal axes is not as important a statistic. The poor linearity is a result of the transducer response to interaction of the transducers, not a direct response to an applied load. What is more important is the accuracy of the two matrix methods that was developed from the information in these tables.

During construction of the inverse matrix, the F values were used to determine if the regression coefficient should be used. If a regression did not have a significant F value, there was a large variation in the readings leading to a large sum of squares for the error in the regression and a small sum of squares for the regression term. The values were not used in the inverse matrix. The inverse matrix was made up of the inverse of the slopes of the lines for the regressions shown in Tables A.1 and A.2. The values for the inverse slopes for nonsignificant regressions was set to zero. The coefficients of the slopes are in either N/(Taurus One transducer units) or Nm/(Taurus One transducer units). This means that the transducer with a nonsignificant F value could be represented as an infinite force or moment per transducer output unit. Once the inverse is taken this would represent a zero transducer output per unit force which describes the situation that occurs when the transducer does not interact with a force or couple that is not along their major axis.

The two inverse matrices that were developed are shown in Appendix B in Tables B.1 and B.2 and represent the matrix developed by not forcing the regression line through zero and forcing the regression line through zero respectivly. The zero coefficients in the matrices represent the regressions that did not have a significant F value at the 0.05 level of significance. The inverses of these matrices was taken and are shown in Appendix B Table B.3 and B.4. The equations for the analysis of the forces and moments applied to the origin of the coordinate system were formed from these matrices. The equations for Method #2 used the matrix that did not force the regression lines through zero and are shown in Table 5.2. The equations for Method #3 used the matrix that forced the regression lines through zero and are shown in Table 5.3.

TABLE 5.2

Equations for Forces and Moments Matrix Method #2

FORCE OR MOMENT	COEFFICIENTS FOR TRANSDUCERS #1 THROUGH #6					
	TR1	TR2	TR3	TR4	TR5	TR6
FX	1.467820	-.044060	-.044000	.004647	.004358	.004894
FY	0.021227	-.017320	.017488	.853275	.853109	.841137
FZ	0.021780	.857169	.859702	.002087	.007701	-.004060
MX	-3.0×10^{-4}	-8.0×10^{-4}	9.0×10^{-4}	-.261720	.042047	.041456
MY	-0.006300	-.246150	.241084	.011359	-.006730	-.003290
MZ	-0.005850	-.004080	-.200218	-.160280	.242973	-.236780

TABLE 5.3

Equations for Forces and Moments Matrix Method #3

FORCE OR MOMENT	COEFFICIENTS FOR TRANSDUCERS #1 THROUGH #6 TR1	TR2	TR3	TR4	TR5	TR6
FX	1.448800	-.040800	-.043740	.005122	.004569	.005163
FY	0.019996	-.011650	.010195	.852477	.853177	.841175
FZ	0.011826	.859050	.858498	-.009224	.009224	-.003800
MX	-2.0×10^{-4}	-.002730	.002676	-.261760	.042012	.041453
MY	-0.009730	-.243670	.238857	-.001780	-.004880	-.001160
MZ	-0.004260	-.002000	.002130	-.160280	.242948	-.001160

5.1.3 Comparison of Force and Moment Analysis Methods

Three methods were developed to determine the three dimensional forces and moments applied to the dynamometer. These methods were used to predict the forces and moments applied to the dynamometer. The three methods predict not only the forces and moments that were applied but also predict forces that are actually zero but can be produced due to the interaction of the transducers. First, we will look at the results of the prediction of the actual applied forces and moments and then later at the forces and moments predicted due to the interaction of the transducers.

Method #1 used the force and moment equations developed from the individual calibration of the transducers and the force and moment analysis of the dynamometer frame. Methods #2 and #3 used the force and moment equations developed using the matrix method for force and moment analysis. Method #2 used the regression coefficients from the regression curves that were not forced through zero. Method #3 used the regression coefficients from the regression curves that were forced through zero.

The difference between the actual and predicted forces and moments were compared statistically using an Analysis of Variance (ANOVA) Table and then performing a Least Significance Difference ,t-Test, (LSD). A summary of the ANOVA and LSD tests is shown in Table 5.4. The only two trials that showed a significant difference at the 0.05 level were the mean differences for the applied force Fx and applied moment My. In the first case, applied force Fx, all three methods are significantly different with Method #3, having the lowest mean difference from the actual applied load. For the applied moment My there is only a significant difference between Methods #1 and Method #2, and a significant difference between Method #3 and #2 but no significant difference between #3 and #1. The Methods #3 and #1 do however have a lower mean difference than Method #2.

These two cases are shown in Fig. 5.1, applied force Fx, and Fig. 5.2, applied moment My. In Fig. 5.1 we can see that the difference between the actual and applied forces is generally smaller for Method #3 whereas Methods #1 and #2 have in general larger differences between the actual and applied forces. The differences are not so large in Fig. 5.2 where Method #1 and Method #3 follow the same trends.

When we look at the error in the methods due to the interaction of the transducers in the dynamometer system we are comparing the predicted forces or moments to a zero actual force or moment. In Table 5.4 the cases where there were significant differences has been summerized. The only method that was ever significantly different than the other two was Method #3. This method has a significantly lower mean difference than the other two in five cases. Also in four other cases Method #3 is

TABLE 5.4

Summary of ANOVA for Predicted-Applied Forces and Moments

APPLIED FORCE OF MOMENT		METHOD OF FORCE AND MOMENT ANALYSIS M1	M2	M3	F
FX	Mean Difference	10.5159	-17.4332	-3.9750	23.92
		A	B	C	
Fy	Mean Difference	-5.3544	-5.4478	-5.4517	0.002
		No Significant Difference			
Fz	Mean Difference	-3.9773	-3.9245	-3.9671	0.0003
		No Significant Difference			
Mx	Mean Difference	0.2306	0.6346	0.7523	0.370
		No Significant Difference			
My	Mean Difference	1.3254	3.5031	0.7651	6.89
		A	B	A	
Mz	Mean Difference	1.8039	1.8150	1.7990	0.0005
		No Significant Difference			

NOTE: Mean difference in this table is the difference between the applied and predicted forces and moments.

A,B,C Rating: If there is a significant difference between the mean differences the methods are given different letters. If two have no significant differences then they are given the same letter.

significantly lower, for its mean difference , than at least one of the other two methods. This is caused by the removal of the interaction effect by the Matrix Method of force and moment analysis.

If Fig. 5.3 the effect of interaction is shown quite well. Method #1, the force and moment vector analysis method, shows a definite trend of increased prediction of a force in the Y direction with the increase of the force in the X direction. The two Matrix Methods show a much

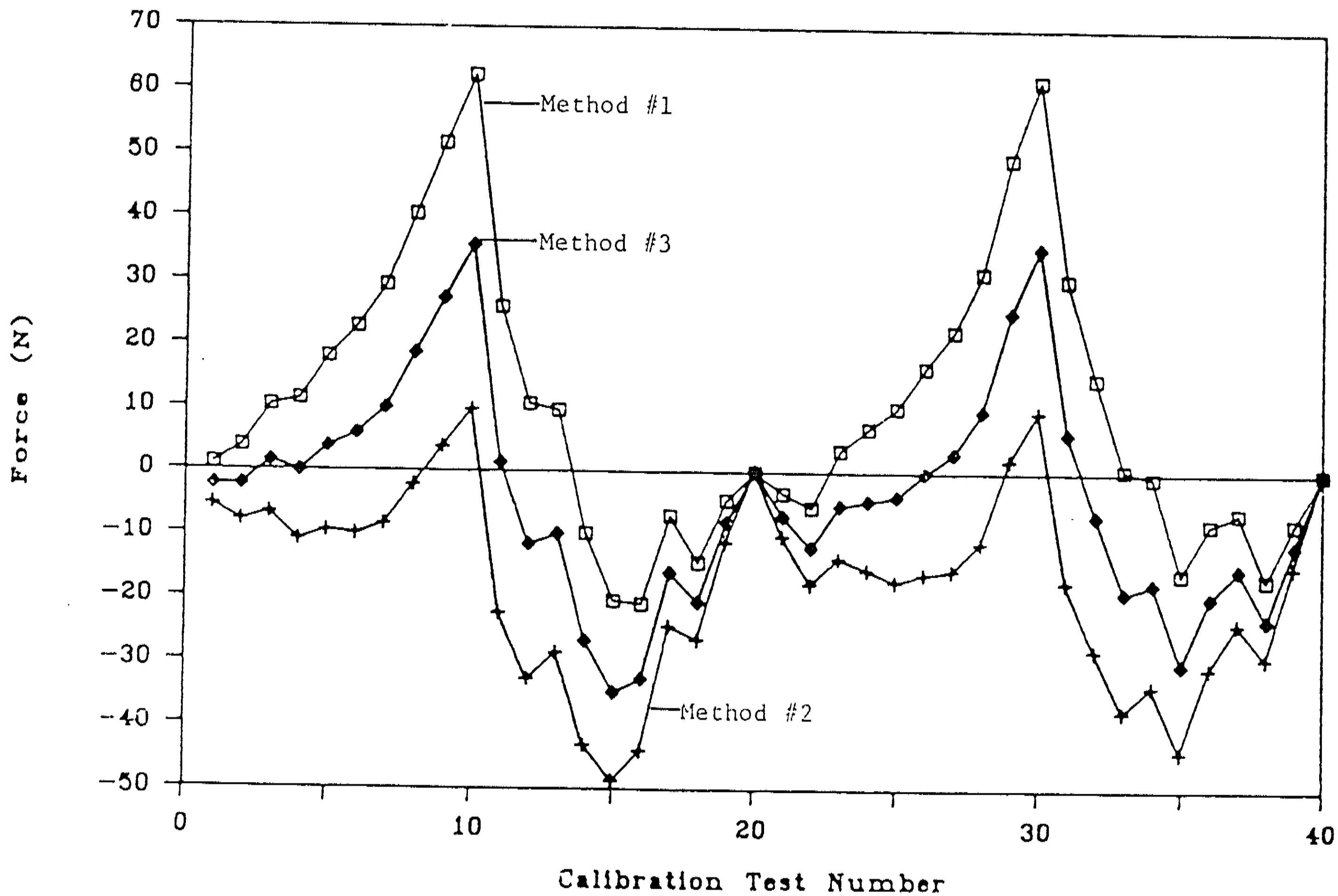

Figure 5.1: Difference Between Actual and Predicted Force in the X-Direction

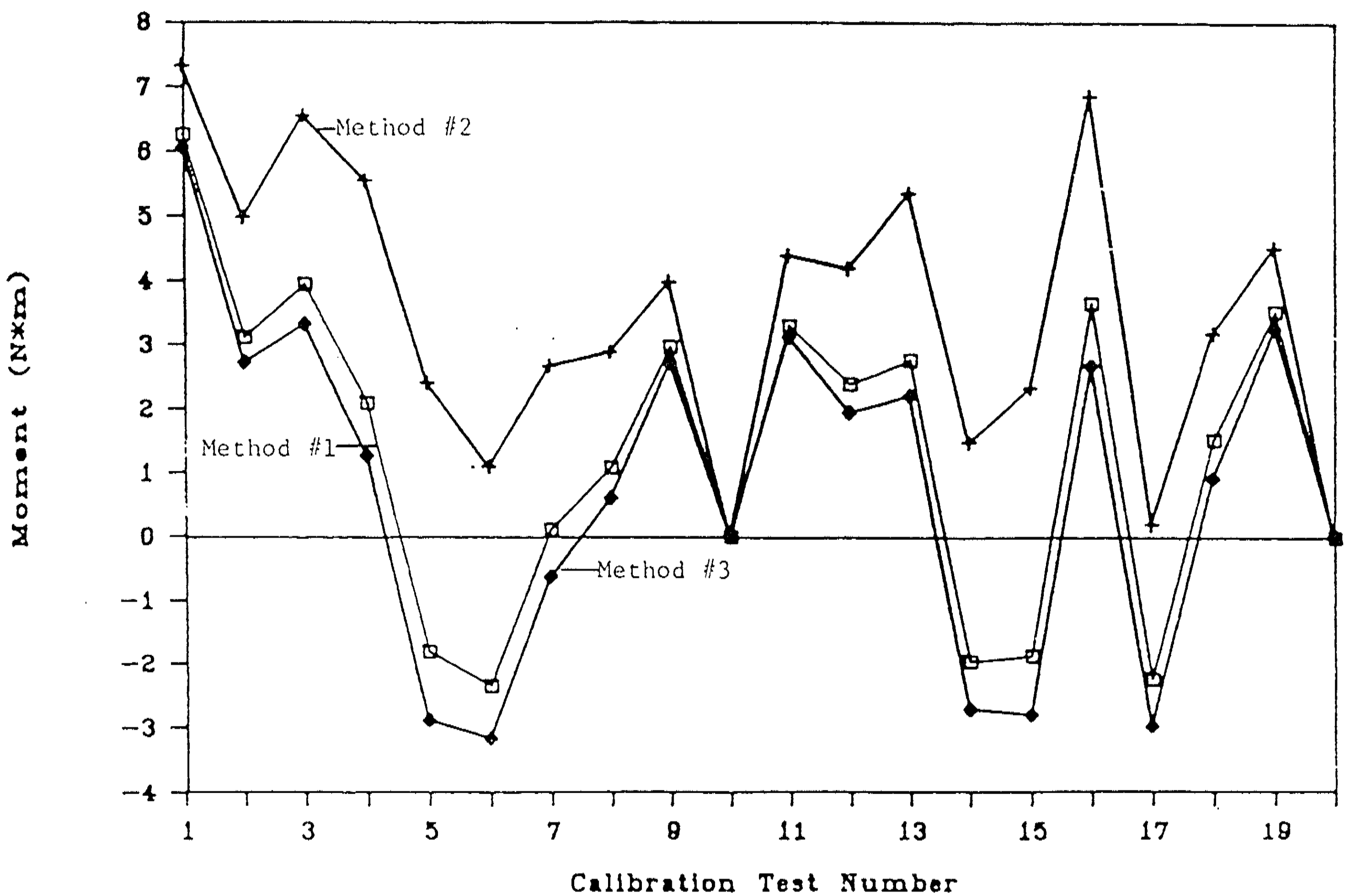

Figure 5.2: Difference Between Actual and Predicted Moment in the Y-Direction

smaller trend centered more about the zero horizontal line. Method #3 has the best overall performance having the lowest mean difference of -1.3536 N for the actual load in the Y direction (zero) minus the predicted load.

Method #3 was used in the tillage trials because of the consistently more accurate performance in the prediction of the applied forces and moments and the reduction of the interaction effect between transducers.

TABLE 5.5

Summary of ANOVA for Interaction Effects

APPLIED FORCE or MOMENT	PREDICTED FORCE or MOMENT		METHOD of FORCE or MOMENT ANALYSIS M1	M2	M3	F
Fx	Fy	Mean Diff.	12.6275 A	-2.7526 B	-1.3536 B	93.4
Fx	Fz	Mean Diff.	10.8483 A	-4.4526 B	2.8234 C	105.14
Fx	Mx	Mean Diff.	-0.4157 A	1.3387 B	-1.0572 A	4.02
Fx	My	Mean Diff.	-6.2923 A	-1.9321 B	0.4924 C	61.49
Fx	Mz	Mean Diff.	-2.5560 A	1.1759 B	0.4169 B	39.13
My	Fy	Mean Diff.	-12.1922 A	6.7841 B	.00643 C	57.00
My	Fz	Mean Diff.	12.1819 A	2.1711 B	0.4235 B	9.03
My	Mx	Mean Diff.	-2.7814 A	-1.8359 A	-0.0272 B	17.94
My	Mz	Mean Diff.	-2.1271 A	-1.1632 B	0.0457 C	20.92

NOTE: The Mean Difference in this table is the difference between the actual load, which is zero, and the predicted load.
The A,B,C ranking system is used to identify the means that have a significant difference at the 0.05 level of significance. If two means have the same letter there is no Significant difference.

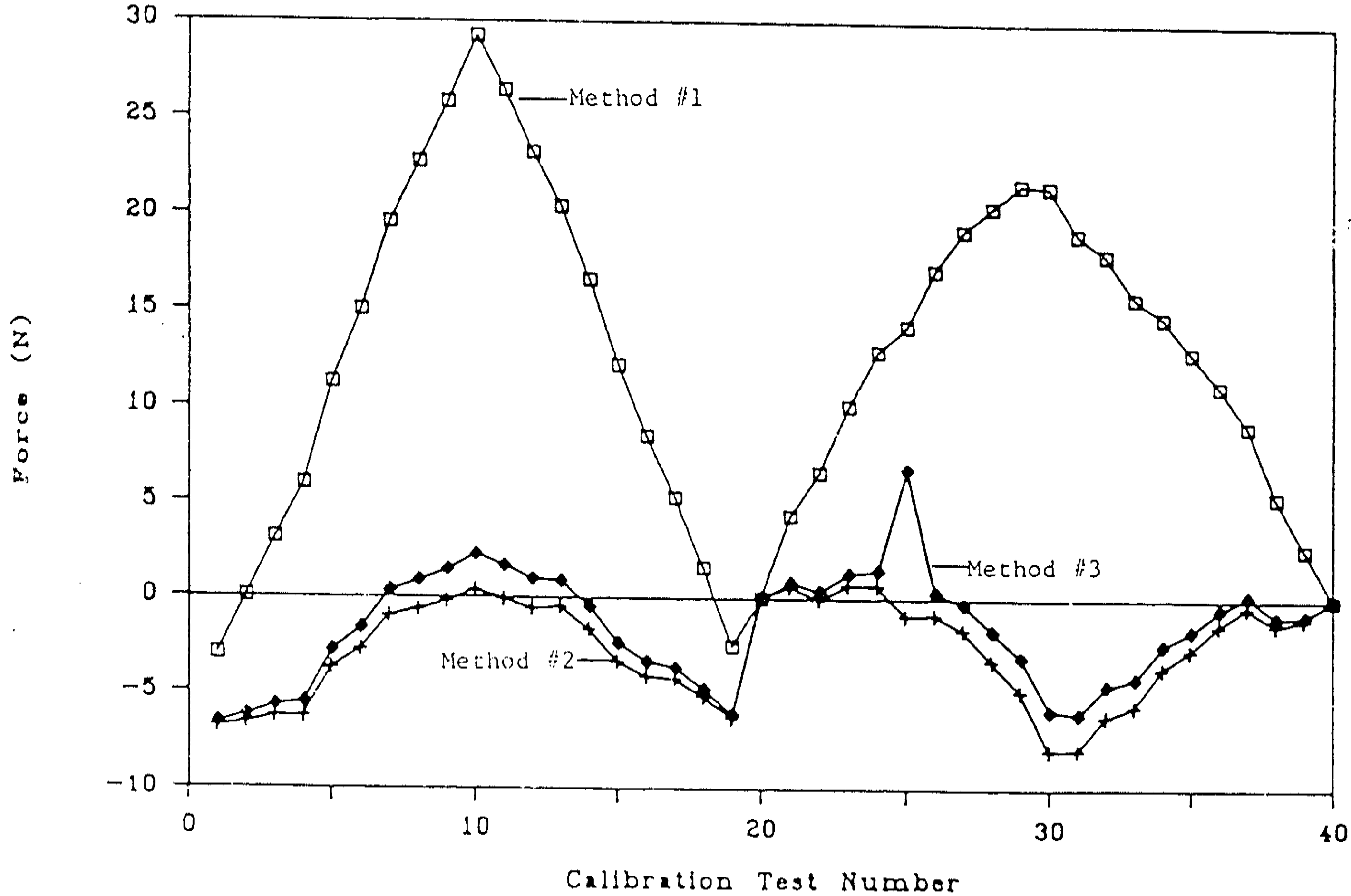

Figure 5.3: Interaction Force Predicted in Y-Direction by Force in X-Direction

5.2 TILLAGE IMPLEMENT TRIALS

5.2.1 Cultivator Shovel Trials

The method used to determine the three dimensional forces and moments was Matrix Method #3. This method was used because in the calibration trials it had the overall best performance when predicting applied forces and moments. The average forces and moments measured during the six tillage trials with the cultivator shovel were recorded (Table 5.6). The average parallel moment vector and force position vector were determined using the program WRENCH (Table 5.7 and Table 5.8). With this information and a mathematical model of the cultivator shovel the average intersection point of the resultant force and the cultivator shovel was determined (Table 5.9).

The largest force measured, for all six trials, was the force in the X direction (positive in the direction of travel). The largest mean force for the trials was -622.2 N, occurring in trial #5. The overall mean draft force was -504.4 N. The draft force as measured by Kiss and Bellow (1981) at the same depth of operation was of the same magnitude, 600 N. This trial was significantly different than the other five trials. This difference could be due to soil variation in compaction, moisture content, and depth. The smallest mean force for the six trials occurred in trial #4. This trial had a mean value of -344.8 N and was significantly different than the five other trials. This reduction in the magnitude of the draft force can be accounted for by experimental error. When trial #4 was run the path of the cultivator shovel overlaped with that of trial #3. The soil for this run was not at the same compaction as the other trials and this lead to the lower force being measured. This type of reduction of draft force was also shown by Kiss and Bellow (1981) for the draft force on a trailing cultivator shovel. They found that a trailing cultivator shovel could have a reduction on average of 27% in the draft force. The reduced compaction of trial #4 also was evident in the measurements of the force in the Z direction. Trial #4 was significantly different than all five other trials and had the lowest magnitude for the vertical force of -90.8 N. No other trial was significantly different in the measurements of the force in the vertical direction. The vertical force measured by Kiss and Bellow was also downward except for a shovel at a shallow depth. The magnitude of the vertical force when compared to the draft force in work by Kiss and Bellow was found to be 20% of the draft force. The mean vertical force measured in this thesis was 27% of the mean draft force. The lateral force measured by Kiss and Bellow was considered small or nonexistent when compared to the draft of vertical force. This was also the case with the cultivator shovel tested in this thesis having an overall mean lateral force of -27.7 N.

The resultant moments for all six trials were measured and their mean values recorded and broken down into their components in the X, Y, and Z directions (Table 5.6). The moments measured in the Y direction were quite large with a maximum of 352.8 Nm in trial #5 and a minimum of 200.4 Nm measured for trial #4. The moment measured in the Y direction is a function of the displacement from the origin of the resultant force, the magnitude of the resultant force, and the non-symmetrical distribution of the soil pressure over the tillage implement. The moment in the Y direction is made up of a large negative force in the X direction, when compared to the forces in the Z direction, and a larger displacement in the Z direction than in the X direction. These combinations result in the magnitude and direction of the resultant moment in the Y direction, being a function of the force in the X direction. The large moment in trial #5 and smaller moment in trial #4 are a direct result of the corresponding larger and smaller forces applied in the X direction in the two trials.

The components of the resultant moment in the X and Z directions are small when compared to the moment in the Y direction. This is as expected with the smaller forces in the Y and Z directions and the smaller displacements in the X and Y directions. The moment in the X direction has a maximum recorded value of -19.2 Nm in trial #4 and a minimum of -1.9 Nm in trial #5. The moment in the Z direction has a maximum mean value of -3.6 Nm in trial #6 and a minimum mean value of -0.87 Nm in trial #4.

The parallel component moment of the resultant moment was also determined for the six component trials (Table 5.7). This moment represents the portion of the resultant moment that has the same vector sense as the resultant force vector. This parallel moment and the resultant force define the Wrench of the force system.

The only trial that was significantly different, in the mean parallel moment, from the other five trials was trial #4. The largest difference was recorded in the component in the X direction (Table 5.7). The moments in this table represent the actual moment or moments applied to the cultivator due to non-symmetrical soil pressures over the surface of the cultivator shovel. This difference in the moment in the X direction is a function of the soil pressures in the Y and Z directions. If one or both of these pressures are not distributed symmetrically a moment in the X direction will be created. The moment in the X direction in trial #4 was -2.8 Nm, a difference of 6.5 Nm from the average of the other 5 trials. This difference is due to the reduced compaction of the soil in part of trial #4.

The moments parallel to the resultant force (Table 5.7) were all quite small showing that the distribution of soil pressures were symmetrical about the cultivator shovel. Again trial #4 differed in its results due to non-symmetrical soil pressures. These results also show that the soil in the University of Manitoba, Department of Agriculture Engineering Soil Bin can achieve, if proper care is taken, a consistent soil for tillage trials.

The position vector was also determined for the resultant force vector (Table 5.8) using the WRENCH program. Using these two vectors we are then able to uniquely define the line of action of the resultant force in space. If we then develop a three dimensional mathematical model for the implement we can determine the point of application of the resultant force.

The cultivator shovel was represented in three dimensional space by the equation of a plane. The plane was developed from three non-collinear points measured on the cultivator shovel. The equation of the plane used to represent the cultivator in space was:

$$-0.085\ X - 0.1375\ Z - 0.0535625 = 0 \qquad [61]$$

The intersection points of the plane representing the cultivator shovel and the force vectors from the six trials were determined (Table 5.9). The mean value for all six trials for the intersection point in the X, Y and Z directions was (0.2047,0.0111,-0.5157)m. The cultivator shovel has its forward tip at (0.3000,0.0000,-0.5750)m and the sweep changed from a shallow to a sharp angle at the location (0.1625,0.0000,-0.4900) m with respect to the origin of the dynamometer system. The cultivator was run at a depth of 80 mm below the average soil level. The mean intersection point recorded for the six cultivator trials in the Z direction was 20 mm below the average level of the top of the soil. The mean value for the intersection in the Y direction of 7 mm shows that the resultant force is located near the center of the cultivator shovel depending on the soil conditions. The X value for the intersection lies 95 mm back of the tip of the cultivator shovel.

TABLE 5.6

Cultivator Shovel Tillage Trials Resultant Forces and Moments

Force or Moment	Trial #1-6						Mean	F
Fx(N)	4	3	1	6	2	5		
Mean	-344.8	-493.5	-507.2	-510.0	-548.6	-622.2	-504.4	16.28
Fy(N)	5	6	2	4	1	3		
Mean	-9.4	-22.5	-26.6	-29.3	-34.1	-38.1	-26.7	11.48
Fz(N)	4	6	5	2	3	1		
Mean	-90.8	-140.5	-143.42	-145.4	-146.6	-153.6	-136.7	10.82
Mx(Nm)	5	6	2	3	1	4		
Mean	-1.9	-6.4	-7.5	-15.4	-16.8	-19.2	-11.2	25.87
My(Nm)	4	3	1	6	2	5		
Mean	200.4	284.5	285.83	295.3	313.8	352.8	288.8	65.45
Mz(Nm)	6	5	4	1	2	3		
Mean	-3.7	-1.9	-0.87	2.7	- 3.1	3.6	0.5	56.32

NOTE: The mean value in this table is the average value for the trial. This represents the average of four hundred readings taken over eight seconds. The forces and moments were determined using the equations from Method #3. The mean values that are not significantly different at the 0.05 level of significance are underlined.

TABLE 5.7

Cultivator Shovel Parallel Component Moment Mo

Moment	Trial #1-6						Mean	F
Mx(Nm)	4	5	1	6	3	2		
Mean	-2.8	2.8	2.8	5.20	6.9	7.9	4.43	29.00
My(Nm)	4	5	1	6	2	3		
Mean	-0.16	0.12	0.25	0.31	0.49	0.62	0.27	21.19
Mz(Nm)	4	5	1	6	2	3		
Mean	-0.84	0.69	0.86	1.45	2.11	2.14	1.07	26.60

NOTE: The mean value in this table is the average value for the trial. This represents the average of four hundred readings taken over eight seconds. The moments were determined using equations from Method #3, and the equations in the force and moment analysis program WRENCH.
Values that are not significantly different at the 0.05 level of significance are underlined.

TABLE 5.8

Cultivator Shovel Position Vector

Direction	Trial #1-6						Mean	F
Rx(m)	5	2	4	6	1	3		
Mean	0.121	0.138	0.141	0.148	0.152	0.153	0.142	4.35
Ry(m)	6	5	2	4	1	3		
Mean	-0.003	-0.002	0.009	0.012	0.013	0.015	0.007	105.43
Rz(m)	4	5	6	2	3	1		
Mean	-0.542	-0.538	-0.537	-0.532	-0.527	-0.514	-0.532	15.81

NOTE: The mean value in this table is the average value for the trial. This represents the average of four hundred readings taken over eight seconds. The position vectors were determined using equations from Method #3, and the equations in the force and moment analysis program WRENCH.
Values that are not significantly different at the 0.05 level of significance are underlined.

TABLE 5.9

Intersection of Cultivator Shovel and Resultant Force Vector

Trial	X Position m	Y Position m	Z Position m
1	0.1851	0.0172	-0.5039
2	0.2027	0.0124	-0.5148
3	0.2053	0.0190	-0.5164
4	0.2151	0.0189	-0.5225
5	0.2092	-0.0007	-0.5189
6	0.2106	-0.0002	-0.5197
mean	0.2046	-0.0111	-0.5157

Note: The values for the intersection point of the resultant force and the cultivator shovel are the mean values for four hundred readings taken over eight seconds for each trial.

5.2.2 Disk Blade Trials

The largest force on the disk that was measured was the force in the Y, or side direction (TABLE 5.10). The force was negative and had a maximum of -681.6 N in trial #3 and a minimum of -493.7 N in trial #4. The large forces in the Y direction were created by the 30 degree angle that the disk blade had with the X axis, the direction of travel. The side force measured by Orlandea et al. (1982) on a disk blade mounted at 22 degrees to the direction of travel was not found to be the largest of the three component forces. Their work did show a reduction in the draft force and an increase in the side force as the angle to the direction of travel became greater.

The force measured in the X direction was the second largest force measured for the disk trials. The force in the X direction for the disk trials was of similar magnitude as those measured for the force in the X direction during the cultivator trials. The largest force was -601.6 N recorded in trial #3 and the lowest force was recorded in trial #4 of -493.7 N. Orlandea et al. found draft forces of -570 N on a disk set at a -22 degree angle. The force measured in the Z direction was positive, vertically upwards, for the disk trials. This is different than the cultivator trial where the force in the vertical direction was negative. The maximum vertical force was recorded in trial #3 of 361.4 N and the minimum vertical force was recorded in trial #4 of 237.2 N. The overall mean vertical force of 298 N was only slightly higher than the 250 N measured by Vaishnav et al. (1982).

The largest component of the resultant moment was in the X direction. This moment was created by the forces in the Y and Z direction combined with the displacement of the forces from the origin of the dynamometer system. The large forces in the negative Y direction and the negative displacement in the Z direction created a negative moment in the X direction. The positive force in the Z direction and the negative displacement in the Y direction also gave a negative moment in the X direction. The smaller force and offset for the force in the Z direction created a smaller moment about the origin of the dynamometer system than the moment created by the force in the Y direction and the displacement in the X direction. The moments created by these two combinations were both negative and combined to give a larger moment in the X direction.

The moment in the Y direction was also a large moment when compared to the moment in the Z direction. This moment was created by the forces in the X and Z direction combined with their displacements from the origin of the dynamometer system in the X and Z direction. The negative force in the X direction combined with the negative displacement in the Z direction and the positive force in the Z direction combined with the negative displacement in the X direction both created a positive moment in the Y direction. These two combined to create a larger positive moment in the Y direction with the major portion coming from the combination of the force in the X direction and the displacement in the Z direction.

The component of the resultant moment in the Z direction was small due mainly to the small displacements of the forces in the X and Y direction from the origin of the dynamometer system. Also the force in the X direction created a negative moment in the Z direction and the force in the Y direction created a moment in the positive Z direction. This combination does not add up to a larger moment in the Z direction but a reduced moment. Therefore, the component of the resultant moment in the Z direction was small when compared to the moment in the X or Y direction.

The moment parallel to the resultant force was determined (Table 5.12) and found to be small showing that the distribution of soil pressures across the tillage disk were symmetrical. The maximum parallel moment in the X direction was -15.6 Nm, in the Y direction was -17.9 Nm, and 9.27 Nm in the Z direction.

The position vector was determined with the program WRENCH for the five disk trials (Table 5.12). This point represented the minimum position vector from the origin of the dynamometer system to the line of action of the resultant force. The 30 degree tillage disk was represented by the equation for the plane in space:

$$-0.00125928\ X - 0.0022446\ Y - 0.00008668 = 0 \quad ..[62]$$

The equation of the line in space representing the line of action of the resultant force and the equation for the plane in space representing the tillage disk were used in determining the mean intersection point for each trial. The mean for intersection point for all five trials was, (-0.006,-0.033,-0.48) m. The largest difference in the X direction from the mean value occurred in trial #5 of .005 m. The largest difference from the mean in the Y direction was 0.004 m. The largest difference from the mean in the Z direction was -0.011 m. All of these differences were small and not considered significant.

TABLE 5.10

Disk Blade Tillage Trials Resultant Forces and Moments

Force or Moment	Trial # 1-5					Mean	F
Fx(N)	4	2	5	1	3		
Mean	-458.5	-466.0	-515.2	-529.1	-601.6	-514.1	16.28
Fy(N)	4	2	1	5	3		
Mean	-493.7	-520.8	-557.2	-614.2	-691.6	-575.5	36.69
Fz(N)	4	2	1	5	3		
Mean	237.2	265.8	304.7	324.4	361.4	298.7	27.00
Mx(Nm)	4	2	1	5	3		
Mean	-250.6	-268.5	-297.2	-314.3	-364.0	-298.9	38.98
My(Nm)	4	2	5	1	3		
Mean	202.7	210.4	233.8	239.9	276.8	232.7	27.71
Mz(Nm)	5	4	3	2	1		
Mean	-0.89	-4.32	-6.22	-9.37	-13.44	-6.9	36.41

NOTE: The mean value in this table is the average value for the trial. This represents the average of four hundred readings taken over eight seconds. The forces and moments were determined using the equations from Method #3. The mean values that are not significantly different at the 0.05 level of significance are underlined.

TABLE 5.11

Disk Blade Parallel Component Moment Mo

Moment	Trial # 1-5					Mean	F
Mx(Nm)	2	4	5	1	3		
Mean	-10.8	-12.4	-12.4	-15.1	-15.6	-13.3	15.24
My(Nm)	2	4	5	1	3		
Mean	-12.0	-13.2	-14.7	-15.7	-17.9	-14.7	15.24
Mz(Nm)	2	4	5	1	3		
Mean	6.19	6.36	7.76	8.63	9.27	7.6	15.52

NOTE: The mean value in this table is the average value for the trial. This represents the average of four hundred readings taken over eight seconds. The moments were determined using equations from Method #3, and the equations in the force and moment analysis program WRENCH.
Values that are not significantly different at the 0.05 level of significance are underlined.

TABLE 5.12

Disk Blade Position Vector

Direction	Trial # 1-5					Mean	F
Rx(m)	4	2	1	3	5		
Mean	-0.090	-0.091	-0.095	-0.098	-0.100	-0.095	16.46
Ry(m)	4	2	5	3	1		
Mean	-0.119	-0.135	-0.136	-0.138	-0.142	-0.134	28.71
Rz(m)	5	4	2	1	3		
Mean	-0.419	-0.425	-0.425	-0.428	-0.431	-0.426	5.02

NOTE: The mean value in this table is the average value for the trial. This represents the average of four hundred readings taken over eight seconds. The position vectors were determined using equations from Method #3, and the equations in the force and moment analysis program WRENCH.
Values that are not significantly different at the 0.05 level of significance are underlined.

TABLE 5.13

Intersection of Disk Blade and Resultant Force Vector

Trial	X Position m	Y Position m	Z Position m
1	0.0015	-0.0404	-0.4836
2	-0.0097	-0.0392	-0.4598
3	-0.0082	-0.0348	-0.4849
4	-0.0103	-0.0344	-0.4601
5	-0.0070	-0.0355	-0.4775
mean	-0.0067	-0.0369	-0.4732

Note: The values for the intersection point of the resultant force and the 30 Degree Disk are the mean values for four hundred readings taken over eight seconds for each trial.

Chapter VI

CONCLUSION

1. A three dimensional tillage force and moment dynamometer was developed for use at the University of Manitoba, Department of Agricultural Engineering Tillage Tool Testing Soil Bin. The dynamometer was capable of measuring three dimensional forces and moments using a Taurus One data acquisition unit and a Corona Microcomputer.

2. The Matrix Method of calibration improved the performance of the six transducer dynamometer system by reducing the effects of the interaction between the six transducers. This improvement was significant at the 0.05 level of confidence.

3. The wrench for a system of three dimensional forces and moments was determined and used to determine the unique line of action of the resultant force.

4. The surface of the tillage implements tested were described using the equation of a plane in space. These equations were then used to determine the intersection point of the line of action of the resultant force and the surface of the tillage implement.

5. The integrated software package developed here allows a person of limited computer experience to use the three dimensional tillage dynamometer system for, data acquisition, analysis of three dimensional forces and moments, determination of the unique line of action of the resultant force, and the intersection of the resultant force and a mathematical model of the surface of a tillage implement.

6. The largest mean component force for the cultivator trials was the force in the X direction of -622.3 N. The force in the Z direction was negative, vertically down, for the cultivator shovel tested. The largest force in the Z direction was -153.6 N. The force in the Y direction was small ranging from -9.4 N to -38.1 N. The mean resultant force for all six trials was 523.3 N $(-0.964\hat{i},-0.051\hat{j},-0.261\hat{k})$. This shows that the side force that was measured on the cultivator shovel was not large or consistent in positive or negative directionss. This minimal mean side force is due to the symmetrical soil pressure distribution about the Z axis.

7. The mean resultant moment measured for the six cultivator trials was 289.0 Nm $(-.0388\hat{i},0.999\hat{j},0.002\hat{k})$. The large moment in the Y direction was created by the large force in the X direction and the moment arm in the Z direction.

8. The parallel component moments for the cultivator were small for all three directions showing that the soil pressure was distributed symmetrically around the surface of the tillage implement. The mean resultant parallel component moment for the six cultivator trials was determined to be 4.57 Nm $(0.97\hat{i},0.05\hat{j},0.23\hat{k})$.

9. The average intersection point , for the six cultivator trials, for the resultant force and the mathematical model of the cultivator shovel was $(0.205\hat{i},0.011\hat{j},-0.516\hat{k})$m from the origin of the transducer system.

10. The mean resultant force measured for all five of the 30 degree disk blade trials was 827.5 N $(-0.621\hat{i},-0.695\hat{j},0.361\hat{k})$. The largest mean value for all trials was measured in the Y direction ranging from -493.7 N to -691.3 N. The force measured in the X direction ranged from -458.5 to -601.6. The force in the Z direction ranged from 237.2 N to -361.4 N.

11. The mean resultant moment measured for all five 30 degree disk blade trials was 378.9 Nm $(-0.789\hat{i},0.614\hat{j},-0.018\hat{k})$. The largest component of the resultant moment occured in the X direction ranging from -250.6 Nm to -364.0 Nm. The component of the resultant moment in the Y direction ranged from 202.7 Nm to 276.8 Nm. The component of the resultant moment in the Z direction ranged from -0.89 Nm to -13.44 Nm.

12. The mean parallel component moment for all five 30 degree blade disk trials was 21.2 Nm $(-0.625\hat{i},-0.693\hat{j},0.360\hat{k})$. The largest component of the parallel moment was in the Y direction ranging from -12.0 Nm to -17.9 Nm. The component of the the parallel moment in the X direction ranged from -10.8 Nm to -15.6 Nm The smallest component of the parallel moment occured in the Z direction ranging from 6.2 Nm to 9.3 Nm.

13. The mean position vector for all five 30 degree disk blade trials was 0.456 m $(-0.208\hat{i},-0.294\hat{j},-0.933\hat{k})$. The position components ranged from, -0.90 m to -0.100 m, -.119 m to -.142 m, -.419 m to -0.431, in the X,Y and Z directions, respectively.

14. The mean intersection point for the five 30 degree disk blade trials was $(-.007\hat{i},-0.037\hat{j},-0.473\hat{k})$m from the origin of the transducer system. The intersection point ranged, for the mean values for the individual trials, from, 0.002 m to -0.010 m, -0.035 m to -0.036 m, -0.460 m to -0.485 m in the X,Y, and Z position, respectively.

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Appendix A

REGRESSION ANALYSIS FOR DYNAMOMETER FRAME CALIBRATION

TABLE A.1

Regression Analysis for Dynamometer Frame Calibration Method #2

Regression Curve Not Forced Through Zero

Applied Force/Moment	Transducer #	Slope	F	R^2	Linearity
Fx	1	1.4688	58459	0.999350	1.54
	2	-57.5172	695	0.948210	17.78
	3	64.5495	42	0.522100	38.24
	4	330.7870	235	0.860800	26.59
	5	261.465	15	0.277040	54.48
	6	69.099	256	0.871100	25.09
Fy	1	-26.619	179	0.824550	25.42
	2	-117.580	662	0.945740	40.12
	3	185.911	218	0.851428	27.21
	4	6.163	81548	0.999533	1.36
	5	1.180	F>99999	0.999909	0.68
	6	2.171	F>99999	0.999901	1.16
Fz	1	38.015	5949	0.992675	3.36
	2	1.735	F>99999	0.999635	1.51
	3	1.699	F>99999	0.999791	1.22
	4	128.460	31	0.444049	46.74
	5	136.803	111	0.744403	28.97
	6	-115.769	37	0.490093	40.16
Mx	1	38.015	23	0.373234	52.48
	2	-10.511	86	0.693975	35.24
	3	8.997	108	0.740092	49.84
	4	0.30377	F>99999	0.999947	1.00
	5	1.8443	F>99999	0.999338	1.36
	6	0.35903	F>99999	0.999806	0.82
My	1	-6.137	.19	0.010399	51.56
	2	-0.48678	39892	0.999545	1.17
	3	0.48815	34757	0.999482	1.73
	4	25.231	26	0.585958	43.77
	5	-20.119	249	0.932546	14.20
	6	-28.3	316	0.9464	15.36
Mz	1	4.0777	.08	0.002003	52.43
	2	-35.0520	340.86	0.899699	22.66
	3	-37.285	40.23	0.514245	48.54
	4	32.827	5.45	0.125478	52.91
	5	.483225	F>999999	0.999850	1.07
	6	-0.476336	F>999999	0.999916	0.68

TABLE A.2

Regression Analysis for Dynamometer Frame Calibration Method #3

Applied	Transducer #	Slope	F	R^2	Linearity
Fx	1	-1.449294	F>99999	0.999789	1.72
	2	53.839840	2830	0.986409	20.01
	3	-110.604640	125	0.760600	59.66
	4	418.600670	660	0.944211	27.68
	5	539.970400	93	0.703862	60.95
	6	80.261350	970	0.961342	22.29
Fy	1	-245.366500	129	0.767458	28.48
	2	-111.075570	326	0.893424	28.33
	3	183.475900	205	0.840273	21.95
	4	6.1619400	65609	0.999406	1.56
	5	1.7993200	F>99999	0.999688	1.12
	6	2.1712290	F>99999	0.999825	1.46
Fz	1	28.4064400	2497	0.984627	9.88
	2	1.7277000	80169	0.999514	1.3
	3	1.6992300	F>99999	0.999787	1.11
	4	67.929300	12	0.235287	56.57
	5	91.300110	39	0.496804	54.43
	6	-40.452800	8	0.171250	57.83
Mx	1	9.844400	4	0.696653	58.56
	2	-6.241035	27	0.412065	51.16
	3	5.550250	33	0.456555	47.95
	4	-0.303764	F>99999	0.999924	0.68
	5	1.841296	16826	0.997688	2.62
	6	0.359015	F>99999	0.999773	1.07
My	1	-37.602800	2	0.106301	114.59
	2	-0.482838	F>99999	0.999869	1.27
	3	0.482427	F>99999	0.999829	1.54
	4	33.87622	132	0.879920	48.63
	5	-20.27	1132	0.983501	14.53
	6	-29.68	1405	0.986654	14.98
Mz	1	1.37020	0.03	0.000673	51.45
	2	-31.74410	172	0.814794	22.18
	3	-17.09716	12	0.235812	59.92
	4	9.773687	1.51	0.373559	57.58
	5	0.483257	F>99999	0.999757	1.36
	6	-0.476309	F>99999	0.999857	0.97

Appendix B

COEFFICIENT MATRIX

TABLE B.1

Coefficient Matrix for Calibration Method #2

1.46782	-0.04406	-0.04400	0.00465	0.00436	0.00489
0.02123	-0.01732	0.01749	0.85328	0.85311	0.84114
0.02178	0.85717	0.85970	0.00209	0.00770	-0.00406
-0.00030	-0.00080	0.00090	-0.26172	0.04205	0.04146
-0.00630	-0.24615	0.24108	0.01136	-0.00673	-0.00329
-0.00585	-0.00408	-0.00218	-0.16028	-0.24273	-0.23678

TABLE B.2

Coefficient Matrix for Calibration Method #3

1.44880	-0.04390	-0.04374	0.00512	0.00457	0.00516
0.02000	-0.01165	0.01020	0.85248	0.85318	0.84118
0.01183	-0.85905	0.85850	-0.00169	0.00922	-0.00380
-0.00020	-0.00273	0.00268	-0.26176	0.04201	0.04145
-0.00973	-0.24367	0.23886	-0.00178	-0.00488	-0.00116
-0.00426	-0.00200	0.00221	-0.16028	0.24295	-0.23680

TABLE B.3

Inverse Coefficient Matrix for Calibration Method #2

0.68082	-0.00379	0.03492	0.00000	0.00000	0.00000
-0.01736	-0.00850	0.57540	-0.09514	-2.05430	-0.02853
0.00000	0.00538	0.58850	0.11115	2.04855	0.00000
-0.00302	0.16227	0.00000	-3.29200	0.00000	0.00000
0.00000	0.55564	0.00731	0.54220	-0.04970	2.06932
-0.01447	0.46052	-0.00868	-2.78528	-0.34490	-2.09940

TABLE B.4

Inverse Coefficient Matrix for Calibration Method #3

0.68999	-0.00408	0.03520	0.00000	0.00000	0.00000
-0.01857	-0.00900	0.57545	0.00000	-2.07110	-0.03150
0.00904	0.00545	0.58850	0.00000	2.07285	0.00000
-0.00239	0.16229	0.00000	-3.29200	0.02952	0.00000
-0.00186	0.55577	0.00000	0.54309	-0.04932	2.06951
-0.01246	0.46056	0.00000	2.78540	-0.32370	-2.09950

Appendix C

MAIN MENU PROGRAM FOR CONTROL OF SOFTWARE PACKAGE

```
1  REM *MAIN MENU*
10 CLS
20 REM UNIVERSITY OF MANITOBA THREE DIMENSIONAL
30 REM TILLAGE FORCE AND MOMENT DYNAMOMETER SYSTEM
40 LOCATE 5,5:PRINT
 "UNIVERSITY OF MANITOBA, DEPARTMENT OF AGRICULTURAL ENGINEERING"
50 LOCATE 6,10:PRINT "THREE DIMENSIONAL
   TILLAGE FORCE AND MOMENT DYNAMOMETER"
60 LOCATE 7,20:PRINT "INTERGRATED ANALYSIS PROGRAMS"
61 LOCATE 9,15:PRINT "WRITTEN AND DEVELOPED BY CHARLES I. KITSON"
62 LOCATE 11,23:PRINT "FOR USE WITH THE "
63 LOCATE 12,15:PRINT "TAURUS ONE DATA AQUISITON SYSTEM AND THE"
64 LOCATE 13,10:PRINT "THREE DIMENSIONAL
   TILLAGE FORCE AND MOMENT DYNAMOMETER"
65 LOCATE 14,7:PRINT
 "IN THE UNIVERSITY OF MANITOBA, DEPT. AGRICULTURAL ENGINEERING"
66 LOCATE 15,27:PRINT "SOIL BIN"
68 LOCATE 20,10:COLOR 2,7:PRINT "PRESS ANY KEY TO CONTINUE":COLOR 6,2
69 Q$=INKEY$:IF Q$="" THEN GOTO 69
70 CLS:LOCATE 3,10:PRINT "1) FORCEACQ
80 LOCATE 3,22:PRINT "INITIAL DATA ACQUASITON DURING TILLAGE OR TRACTION"
90 LOCATE 4,12:PRINT "TRIALS WITH THE TAURUS ONE DATA ACQUSITON SYSTEM."
100 LOCATE 6,10:PRINT "2) FORCE3D
101 LOCATE 6,22:PRINT
 "DETERMINATION OF THE THREE DIMENSIONAL FORCES AND MOMENTS"
102 LOCATE 7,12:PRINT
 "FROM THE DATA COLLECTED USING PROGRAM FORCEACQ FOR TILLAGE TRIALS"
103 LOCATE 9,10:PRINT "3) FORCETRC
104 LOCATE 9,22:PRINT
 "DETERMINATION OF THE THREE DIMENSIONAL FORCES AND MOMENTS"
105 LOCATE 10,12:PRINT
 "FROM THE DATA COLLECTED USING PROGRAM FORCEACQ FOR TRACTION TESTS"
110 LOCATE 12,10:PRINT "4) WRENCH
111 LOCATE 12,22:
PRINT "DETERMINATION THE WRENCH AND THE POSITON VECTOR FOR A"
112 LOCATE 13,12:
PRINT "SYSTEM OF THREE DIMENSIONAL FORCES AND MOMENTS"
120 LOCATE 15,10:PRINT "5) INTERSEC
121 LOCATE 15,22:PRINT
 "DETERMINATION OF THE INTERSECTION POINT OF THE RESULTANT"
122 LOCATE 16,12:PRINT
 "FORCE AND THE PLANE IN SPACE USED TO DEFINE THE TILLAGE IMPLEMENT"
123 LOCATE 21,3:PRINT
 "NOTE: THE MEAN RESULTANT FORCE AND
  THE MEAN RESULTANT POSITION VECTORS MUST BE"
124 LOCATE 22,9:PRINT
 "KNOWN AS WELL AS THE EQUATION FOR THE TILLAGE IMPLEMENT FOR PROGRAM #4."
125 LOCATE 19,10:PRINT "6) QUIT
130 LOCATE 25,10:COLOR 0,7:PRINT "SELECT DESIRED PROGRAM";
    :COLOR 7,0:INPUT PRG$
140 IF PRG$="" THEN BEEP:GOTO 130
150 IF VAL(PRG$)>6 THEN BEEP:
LOCATE 25,10:
PRINT "                                                  ":GOTO 130
160 IF VAL(PRG$)<1 THEN BEEP:GOTO 130
```

```
170 IF VAL(PRG$)=1 THEN CHAIN "DATACQ"
180 IF VAL(PRG$)=2 THEN CHAIN "FORCE3D"
181 IF VAL(PRG$)=3 THEN CHAIN "FORCETRC"
190 IF VAL(PRG$)=4 THEN CHAIN "WRENCH"
200 IF VAL(PRG$)=5 THEN CHAIN "INT1"
210 IF VAL(PRG$)=6 THEN GOTO 1000
1000 CLS:LOCATE 10,20:PRINT "ENDING SESSION"
2000 END
```

Appendix D

DATA ACQUISITION PROGRAM FOR DYNAMOMETER

```
1  REM *DATA ACQUSITION PROGRAM*
10 OPTION BASE 1
20 DIM AVP(6,40)
30 DIM VAU$(6,20)
40 DIM VAU(6,20)
50 DIM VALU$(120)
60 DIM AVZ(6)
70 KEY OFF
80 CLS
90 LOCATE 2,5:PRINT
 "DATA ACQUSITION PROGRAM FOR SIX TRANSDUCER FORCE DYNAMOMETER"
100 LOCATE 3,5:PRINT
 "************************************************************"
110 LOCATE 5,15:PRINT "1) START TEST (SKIPS DIRECTIONS)"
120 LOCATE 7,15:PRINT"2) OPERATIONAL DIRECTIONS"
130 LOCATE 25,20
140 PRINT "INPUT DESIRED OPTION"
150 S$=INKEY$:IF S$="" GOTO 150
160 NUM=VAL(S$)
170 IF NUM=1 OR NUM=2 THEN GOTO 180 ELSE 110
180 IF NUM=1 GOTO 500
190 CLS
200 LOCATE 5,10:PRINT"PROGRAM IMFORMATION"
210 LOCATE 10,20:PRINT
"THIS PROGRAM TAKES 400 READINGS OF THE SIX TRANSDUCER DYNAMOMETER"
220 LOCATE 11,20:PRINT
"OVER A PERIOD OF EIGHT SECONDS AND STORES THE DATA ON DISK DRIVE B"
230 LOCATE 12,20:PRINT
"THIS DATA IS STORED IN SIX RECORDS OF 400 READINGS BY TRANSDUCER NUMBER"
240 LOCATE 25,10:PRINT "INPUT (C) TO CONTINUE"
250 S$=INKEY$:IF S$<>"C" GOTO 250
260 CLS
270 LOCATE 10,20:PRINT "PROGRAM STEPS"
280 LOCATE 12,20:PRINT "1) TEST SCAN
290 PRINT #1,"$A0 1 AA (20,20)
300 LOCATE 14,20:PRINT "3) LOADED DATA ACQUSIOTION"
310 LOCATE 15,20:PRINT "4) START TEST"
320 LOCATE 25,20:PRINT "INPUT DESIRED OPTION FOR MORE IMFORMATION"
330 O$=INKEY$:IF O$="" THEN GOTO 330
340 CLS
350 O=VAL(O$)
360 ON O GOTO 370,410,450,500
370 LOCATE 10,20:PRINT
"THE TEST SCAN MONITORS THE SIX CHANNALES TO TEST FOR CORRECT OPERATION"
380 LOCATE 25,10:PRINT "PRESS (C) TO CONTINUE"
390 C$=INKEY$:IF C$="" GOTO 390
400 GOTO 260
410 LOCATE 10,20:PRINT
"THE UNLOADED DATA ACQUISITON GIVES US
THE UNLOADED READINGS FOR THE SIX TRANSDUCERS"
420 LOCATE 25,10:PRINT "PRESS (C) TO CONTINUE"
430 C$=INKEY$:IF C$="" GOTO 430
440 GOTO 260
450 LOCATE 10,20:PRINT
"THE LOADED DATA ACQUSITON TAKES
```

```
400 SCANS OF THE SIX TRANSDUCERS"
460 LOCATE 25,10:PRINT "PRESS (C) TO CONTINUE"
470 C$=INKEY$:IF C$="" GOTO 470
480 GOTO 260
490 LOCATE 25,10:PRINT "PRESS (C) TO CONTINUE"
500 DIM VA(2400)
510 DIM VA$(400)
520 DIM VAD(6,400)
530 CLS
540 PLAY "C10D16"
550 LOCATE 13,25
560 PRINT "*****************************"
570 LOCATE 14,25
580 PRINT  "** PRESS (C) TO CONTINUE **"
590 LOCATE 15,25
600 PRINT "*****************************"
610 G$=INKEY$:IF G$<>"C" GOTO 610
620 REM*********************************************************************
630 REM PROGRAM FOR DATA ACQUISITION OF 3 DIMENSIONAL SIX TRANCDUCER SYSTEM
640 REM*********************************************************************
650 REM
660 REM***********************************************************
670 REM SETTING UP  COMMUNICATION BETWEEN TAURUS ONE AND CORONA**
680 REM***********************************************************
690 CLS:OPEN "COM1:9600,E,7,1,RS,CS,DS" AS #1
700 PRINT #1,"$A0 0 UC CA (18 10)"
710 LINE INPUT #1,B$
720 REM***********************************************************
730 REM** SETTING UP SCAN TABLE FOR 6 FULL BRIDGE TRANCDUCERS   *
740 REM***********************************************************
750 PRINT #1,"$A0 1 AS CL (0,192,6)
760 REM***********************************************************
770 REM*STATMENTS GET RETURN MESSAGE FROM TAURUS AND CHECK ERROR
780 REM***********************************************************
790 INPUT #1,B$
800 INPUT #1,E$
810 IF E$="E" THEN INPUT #1,B$: PRINT "ERROR ";B$:GOTO 2980
820 REM**********************************************************
830 REM**INITIAL SCAN OF SIX CHANNELS PRINTS FOR ERROR CHECK   *
840 REM**********************************************************
850 LOCATE 25,20
860 PRINT "(Q)UIT"
870 LOCATE 12,20
880 PRINT "***************************************************"
890 LOCATE 13,20
900 PRINT "* PRESS  Q  TO QUIT INITIAL SCAN OF SIX CHANNELS  *"
910 LOCATE 14,20
920 PRINT "***************************************************"
930 LOCATE 14,20:PRINT"****************************************"
940 PRINT #1,"$A0 1 AA (1,0)"
950 LINE INPUT #1,B$
960 LINE INPUT #1,B$
970 PRINT B$
980 REM *PRINT
990 FOR CHAN=1 TO 6
```

```
1000 PRINT #1,"$A0 1 AR (1)"
1010 INPUT #1,B$
1020 INPUT #1,R$
1030 INPUT #1,E$
1040 IF E$="E" THEN PRINT" ERROR FOUND" ;R$:GOTO 2980
1050 RE=VAL(R$)
1060 PRINT RE;"    ";
1070 NEXT CHAN
1080 Q$=INKEY$
1090 IF Q$="Q" THEN GOTO 1110
1100 GOTO 940
1110 PRINT:PRINT
1120 PLAY "C10B12"
1130 CLS
1140 REM**********************************************************
1150 REM** ACQ STRAIN DATA FOR UNLOADED CONDITION INTO TAURUS UNIT
1151 REM**********************************************************
1160 LOCATE 12,20
1170 PRINT "*********************************************"
1180 LOCATE 14,20
1190 PRINT "*********************************************"
1200 LOCATE 13,20
1210 REM***********************************************************
1220 INPUT "TEST DESIGNATION = FILENAME FOR DATA STORAGE";F$:F$="B:"+F$
1230 CLS
1240 PLAY "C24D24"
1250 LOCATE 12,20:PRINT"***************************************"
1260 LOCATE 13,20:PRINT"* PRESS (U) TO TAKE UNLOADED READINGS *"
1270 LOCATE 14,20:PRINT"***************************************"
1280 G$=INKEY$:IF G$<>"U" THEN GOTO 1280
1290 PRINT #1,"$A0 1 AA (20,20)
1300 LINE INPUT #1,B$
1310 LINE INPUT #1,B$
1320 PRINT B#
1330 REM*******************************************************
1340 REM** TRANSFER DATA FROM TAURUS TO CORONA                *
1341 REM** AND PLACES ON DISK IN A FILE                       *
1350 REM** CALLED "UNLOADED$".THE DATA IS UNDER               *
1351 REM** THE TEST DESIGNATION TITLE                         *
1360 REM** PLUS "U".                                          *
1370 REM*******************************************************
1380 UNLOADED$=F$ + "U"
1390 OPEN "R",#2,UNLOADED$,240
1400 B=0
1410 FOR X=1 TO 120
1420     FIELD #2,B AS TRASH$,2 AS VALU$(X)
1430     B=B+2
1440 NEXT X
1450 FOR SCAN= 1 TO 20
1460     FOR TRAN=1 TO 6
1470     PRINT #1,"$A0 1 AR (1)"
1480     INPUT #1,B$
1490     INPUT #1,R$
1500     INPUT #1,E$
1510     IF E$="E" THEN PRINT "ERROR FOUND" ;R$:GOTO 2980
```

```
1520      VAU(TRAN,SCAN)=VAL(R$)
1530      NEXT TRAN
1540 NEXT SCAN
1550 FOR TRAN=1 TO 6
1560      COUNT=0
1570         AZ=0
1580      FOR SCAN=1 TO 20
1590          COUNT=COUNT+1
1600         AZ=VAU(TRAN,SCAN)+AZ
1610          LSET VALU$(COUNT)=MKI$(VAU(TRAN,SCAN))
1620      NEXT SCAN
1630       AVZ(TRAN)=AZ/20
1640      PUT #2,TRAN
1650 NEXT TRAN
1660 CLOSE #2
1670 REM*********************************************
1680 REM** ACQ DATA FOR TAURUS FOR LOADED CONDITION.  *
1681 REM*  TAKES 400 READINGS OF THE                  *
1690 REM** SIX TRANSDUCERS WITH A DELAY OF A          *
1691 REM** LENGTH OF 20USEC BETWEEN READINGS          *
1700 REM*********************************************
1710 CLS
1720 PLAY "C10B12C10"
1730 LOCATE 13,1
1740 PRINT
"*****************************************************************"
1750 PRINT
"**PRESS ANY KEY TO START COLLECTION OF DATA FOR LOADED CONDITION**"
1760 PRINT
"*****************************************************************"
1770 A$= INKEY$:IF A$="" THEN GOTO 1770
1780 CLS
1790 PLAY "MB C20P1P1C20P1P20P1C20P2P20 O0C1O4"
1800 OPEN "R",#2,F$,802
1810      B=0
1820      C=0
1830      D=0
1840      E=0
1850 CLS
1860 LOCATE 12,35
1870 PRINT "*****************"
1880 LOCATE 13,35
1890 PRINT "* FIELDING DISK *"
1900 LOCATE 14,35
1910 PRINT "*****************"
1920      FOR NUM=1 TO 400
1930          IF B<250 THEN B=B+2 ELSE GOTO 1950
1940             GOTO 2000
1950          IF B=250 AND C<250 THEN C=C+2 ELSE GOTO 1970
1960             GOTO 2000
1970          IF B=250 AND C=250 AND D<250 THEN D=D+2 ELSE GOTO 1990
1980             GOTO 2000
1990          IF B=250 AND C=250 AND D= 250 AND E<250 THEN E=E+2
2000          FIELD #2
    ,B AS TRASH1$,C AS TRASH2$,D AS TRASH3$,E AS TRASH4$,2 AS VA$(NUM)
```

```
2010     NEXT NUM
2020 REM*********************************************************
2030 REM ANALOG AQUISITION NOW TAKES PLACE 400 READINGS WITH    *
2031 REM A 20MSEC DELAY                                         *
2040 REM*********************************************************
2050 REM NOTE:RECORD LENGTH IS 800 WITH RECORD NUMBERED BY TRAN**
2060 REM ********************************************************
2070 CLS
2080 LOCATE 11,20
2090 PRINT "***********************************************"
2100 LOCATE 12,20
2110 PRINT "**  PRESS (S) TO START TEST AT DESIRED POINT  **"
2120 LOCATE 13,20
2130 PRINT "** THIS TAKES 400 READINGS OF 6 CHANNELS WITH **"
2140 LOCATE 14,20
2150 PRINT "**         A 20MS DELAY BETWEEN SCANS         **"
2160 LOCATE 15,20
2170 PRINT "***********************************************"
2180 LOCATE 25,20
2190 PRINT "(S)TART"
2200 PLAY "C24D24"
2210 G$=INKEY$:IF G$<>"S" THEN GOTO 2210
2220 REM *********************************************************
2230 REM **  THE NEXT STATMENT PERFORMS THE ANALOG ACQUISITIOIN **
2240 REM *********************************************************
2250 CLS :PLAY "C24D24"
2260 LOCATE 12,20:PRINT"***************************************"
2270 LOCATE 13,20:PRINT"**   PERFORMING ANALOG ACQUISITION   **"
2280 LOCATE 14,20:PRINT"***************************************"
2290 PRINT #1,"$A0 1 AA (400,20)"
2300 LINE INPUT #1,B$
2310 LINE INPUT #1,B$
2320 CLS:PRINT B$
2330 CLS
2340 COUNT=0
2350 CLS
2360 PLAY "C24D24"
2370 LOCATE 12,20:PRINT"**********************************************"
2380 LOCATE 13,20:PRINT"*NOW TRANSFERING DATA FROM TAURUS 1 TO CORONA*"
2390 LOCATE 14,20:PRINT"**********************************************"
2400 LOCATE 25,20:PRINT "TO CHECK STATUS OF TRANSFER PRESS (S)"
2410 FOR LOOP=1 TO 150
2420     PRINT #1,"$A0 1 AR (16)"
2430     INPUT #1,B$
2440     FOR I=1 TO 16
2450         COUNT=COUNT+1
2460         INPUT #1,R$
2470         VA(COUNT)=VAL(R$)
2480     NEXT I
2490     Q$=INKEY$:IF Q$="S" THEN PRINT "COUNT=";COUNT
2500     INPUT #1,E$
2510     IF E$="E" THEN PRINT "ERROR":GOTO 2980
2520 NEXT LOOP
2530 PLAY "C24D24"
2540 CLS
```

```
2550 LOCATE 12,20:PRINT"********************************************"
2560 LOCATE 13,20:PRINT"**  PLACING DATA IN AN ARRAY VAM(6,400)   **"
2570 LOCATE 14,20:PRINT"********************************************"
2580 LOCATE 25,20:PRINT "PRESS (S) FOR STATUS"
2590 PLAY "C24D24"
2600 COUNT=0
2610 FOR SCAN=1 TO 400
2620     FOR TRANS=1 TO 6
2630          COUNT=1+COUNT
2640          VAD(TRANS,SCAN)=VA(COUNT)
2650     NEXT TRANS
2660          C$=INKEY$:IF C$="S" THEN PRINT "COUNT=";COUNT
2670 NEXT SCAN
2680 CLS
2690 LOCATE 12,20:PRINT"************************************************"
2700 LOCATE 13,20:PRINT"** PLACING DATA ON DISK IN 6 RECORDS OF 400   **"
2710 LOCATE 14,20:PRINT"** TWO BYTE NUMBERS(6 TRANS, 400 SCANS)       **
2720 LOCATE 15,20:PRINT"************************************************"
2730 LOCATE 25,20:PRINT"PRESS (S) FOR STATUS"
2740 PLAY "C24D24"
2750 COUNT=0
2760 FOR TRANS=1 TO 6
2770     FOR SCAN=1 TO 400
2780          LSET VA$(SCAN)=MKI$(VAD(TRANS,SCAN))
2790          COUNT=COUNT+1
2800     NEXT SCAN
2810          Q$=INKEY$:IF Q$="S" THEN PRINT"COUNT=";COUNT
2820     PUT #2,TRANS
2830 NEXT TRANS
2840 CLOSE #2
2841 REM STOP
2850 CLS
2860 PLAY"C24D24"
2870 LOCATE 10,25:PRINT "1) PRINT DATA COLLECTED ON SCREEN"
2890 LOCATE 11,25:PRINT "2) PRINT THREE DIMENSIONAL FORCES"
2900 LOCATE 12,25:PRINT "3) QUIT"
2910 LOCATE 25,20:PRINT "INPUT DESIRED FUNCTION"
2920 O$=INKEY$:IF O$=""THEN GOTO 2920
2930 NUM=VAL(O$)
2940 IF NUM>3 GOTO 2850
2950 IF NUM=0 GOTO 2850
3000 ON NUM GOTO 4000,5000,6000,7000
4000 CHAIN "A:PRPRIN1",ALL
4500 GOTO 2850
5000 CHAIN "A:FORC32",ALL
5500 GOTO 2850
6000 PRINT "***************END************":END
7000 PRINT "***************END************":END
```

Appendix E

FORCE AND MOMENT ANALYSIS PROGRAMS

```
1  REM *FORCE ANALYSIS PROGRAM*
10 NUM=40
20 DIM TRAV(40,6):DIM RE$(20)
30 DIM FXSZ(NUM):DIM FYSZ(NUM):DIM FZSZ(NUM):
DIM MXSZ(NUM):DIM MYSZ(NUM):DIM MZSZ(NUM)
40 DIM VA$(400)
41 REM ********************************************
50 REM *  PROGRAM TO CALCULATE THE FORCES AND MOMENTS*
51 REM *  IN THREE DIMENSIONS                        *
60 REM *  FOR A TRIAL OF 400 READINGS FROM THE       *
61 REM *  SIX TRANSDUCER  FORCE                      *
70 REM *                DYNAMOMETER                  *
80 REM ********************************************
100 DIM AV10(6,40)
101 DIM VALU$(120)
102 DIM VAU(6,20)
103 DIM VAD(6,400)
104 DIM VAD$(6,400)
110 CLS
120 LOCATE 10,10:
PRINT "PROGRAM TO CALCULATE THE RESULTANT FORCE AND MOMENT"
130 LOCATE 11,10:
PRINT "IN THREE DIMENSIONS USING THE MATRIX METHOD OF FORCE"
140 LOCATE 14,10:
PRINT "THE RESULTS ARE STORED ON DISK IN A SEQUENTIAL FILE"
150 LOCATE 15,10:
PRINT "SUITABLE FOR USE WITH LOTUS 123 OR MICROCOM"
160 LOCATE 20,10:PRINT "PRESS RETURN TO CONTINUE";
170 INPUT C$
180 GOSUB 1750
230 CLS
231 REM
240 LOCATE 10,10:
INPUT "TEST DESIGNATION = FILENAME OF STORED DATA ";F$:S$=F$:F$="A:"+F$
241 LOCATE 23,20:PRINT SPACE$(20)
250 FAN$="A:"+"L"+S$+".PRN"
251 UNLOADED$=F$ + "U"
252 LOCATE 12,10:PRINT "                                              "
253 ON ERROR GOTO 2000
254 NAME UNLOADED$ AS "E:JUNK11"
256 ON ERROR GOTO 0
260 LOCATE 12,16:
PRINT "RAW DATA FILE = ";F$;"          DRIVE A: INPUT FILE"
270 LOCATE 13,10:
PRINT "ZERO LOAD DATA FILE = ";UNLOADED$;"          DRIVE A: INPUT FILE"
290 LOCATE 14,14:
PRINT "FORCE DATA FILE = ";FAN$;"     DRIVE A: OUTPUT FILE"
300 LOCATE 18,10:PRINT "ARE FILE NAMES OK Y/N";:INPUT Q$
310 IF Q$="" THEN BEEP:GOTO 300
320 IF Q$="N" THEN GOTO 230
330 IF Q$="Y" THEN GOTO 350
340 BEEP:GOTO 300
350 REM
355 OPEN "R",#2,UNLOADED$,240
360 B=0
```

```
370 CLS:LOCATE 10,10:PRINT "RETRIEVING  RAW DATA"
380 FOR X=1 TO 120
390     FIELD #2,B AS TRASH$,2 AS VALU$(X)
400     B=B+2
410 NEXT X
420 FOR TRAN=1 TO 6
430     GET #2,TRAN
440     COUNT=0
450     FOR SCAN=1 TO 20
460         COUNT=COUNT+1
470         VAU(TRAN,SCAN)=CVI(VALU$(COUNT))
480     NEXT SCAN
490 LOCATE 12,10:PRINT "FOR ZERO LOAD CONDITION"
500 LOCATE 12,35:PRINT "TRANSDUCER #";TRAN
510 NEXT TRAN
520 CLOSE #2
530 FOR TRAN=1 TO 6
540     AZ=0
550     FOR SCAN=1 TO 20
560         AZ=AZ+VAU(TRAN,SCAN)
570     NEXT SCAN
580     AVU(TRAN)=AZ/20
590 NEXT TRAN
600 REM ** LOOP TO GET TEST DATA**
610 LOCATE 12,10:PRINT "                                                      "
620 LOCATE 10,10:PRINT "                                                      "
630 LOCATE 10,10:PRINT "RETRIEVING RAW DATA FOR TEST CONDITION"
640 OPEN "R",#2,F$,802
650     B=0
660     C=0
670     D=0
680     E=0
690     FOR NUM=1 TO 400
700         IF B<250 THEN B=B+2 ELSE GOTO 720
710            GOTO 770
720         IF B=250 AND C<250 THEN C=C+2 ELSE GOTO 740
730            GOTO 770
740         IF B=250 AND C=250 AND D<250 THEN D=D+2 ELSE GOTO 760
750            GOTO 770
760         IF B=250 AND C=250 AND D= 250 AND E<250 THEN E=E+2
770         FIELD #2
  ,B AS TRASH1$,C AS TRASH2$,D AS TRASH3$,E AS TRASH4$,2 AS VA$(NUM)
780     NEXT NUM
790 NUM=40
800 FOR TRAN=1 TO 6
810     GET #2,TRAN
820     FOR SCAN=1 TO 400
830         VAD(TRAN,SCAN)=CVI(VA$(SCAN))
840     NEXT SCAN
850 LOCATE 12,10:PRINT "FOR DATA FILE=";F$
860 LOCATE 12,33:PRINT "TRANSDUCER #";TRAN
870 NEXT TRAN
880 CLOSE #2
890 GOTO 910
900 REM **CALCULATING THE AVERAGE TRANSDUCER OUTPUTS  FOR 10 READINGS **
```

```
910 REM **CALCULATING THE AVERAGE TRANSDUCER OUTPUTS  FOR 10 READINGS **
920 CLS:LOCATE 10,10:PRINT "CALCULATING ";
930 FOR TRAN=1 TO 6
940     COUNT=0
950     FOR SCAN=1 TO 40
960         AVDAT=0
970         FOR NRED=1 TO 10
980             AVDAT=AVDAT+VAD(TRAN,COUNT)
990             COUNT=COUNT+1
1000         NEXT NRED
1010         AV10(TRAN,SCAN)=AVDAT/10
1020 PRINT ".";
1030     NEXT SCAN
1040 NEXT TRAN
1050 REM **LOOP TO PRINT AVERAGES FOR TRIAL**
1060 FOR TRAN=1 TO 6
1070     FOR SCAN=1 TO 40
1080         TRAV(SCAN,TRAN)=AV10(TRAN,SCAN)
1090     NEXT SCAN
1100 PRINT ".";
1110 NEXT TRAN
1120 CLS
1130 REM ** CALCULATING THE AVERAGE FORCE OVER TEN READINGS FOR 400 ***
1140 REM ** FROM A TRIAL USING THE MATRIX METHOD #3                   ***
1150 REM ***********************************************************
1160 LOCATE 1,1:PRINT
"FORCE ANALYSIS BY MATRIX METHOD
INTERCEPT FOR REGRESSIONS FORCED THROUGH"
1170 LOCATE 2,1:PRINT
"ZERO. SIGNIFICANT VALUES FROM REGRESSIONS USED ONLY"
1180 LOCATE 3,1:PRINT
"FORCE X(I)    ";"FORCE Y(J)    ";"FORCE Z(K)    ";"MOMENT X(I) "
 ;"MOMENT Y(J) ";"MOMENT Z(K)"
1190 PLACE=3
1200 FOR INC=1 TO NUM
1201 FXSZ(INC)=1.4488*TRAV(INC,1)-.0439*TRAV(INC,2)-.04374*TRAV(INC,3)
+.00512*TRAV(INC,4)+.004569*TRAV(INC,5)+.005163*TRAV(INC,6)
1220 FYSZ(INC)=.019996TRAV(INC,1)-.0116TRAV(INC,2)+.0101195*TRAV(INC,3)
+.85248*TRAV(INC,4)+.853177*TRAV(INC,5)+.84118*TRAV(INC,6)
1230 FZSZ(INC)=.011826*TRAV(+.85905*TRAV(INC,2)+.858498*TRAV(INC,3)
-.00169*TRAV(INC,4)+9.224001E-03*TRAV(INC,5)-.0038*TRAV(INC,6)
1240 MXSZ(INC)=-.0002*TRAV(INC,1)-.00273*TRAV(INC,2)+.002676*TRAV(INC,3)
-.26176*TRAV(INC,4)+.042012*TRAV(INC,5)+.041453*TRAV(INC,6)
1250 MYSZ(INC)=-.00973*TRAV(INC,1)-.24367*TRAV(INC,2)+.238857*TRAV(INC,3)
-.00178*TRAV(INC,4)-.00488*TRAV(INC,5)-.00116*TRAV(INC,6)
1260 MZSZ(INC)=-.00426*TRAV(INC,1)-.002*TRAV(INC,2)+.002213*TRAV(INC,3)
-.16028*TRAV(INC,4)+.242948*TRAV(INC,5)-.2368*TRAV(INC,6)
1270 IF INC>20 THEN PLACE=-17
1280 LOCATE PLACE+INC,1:
PRINT "                                                     "
1300 LOCATE PLACE+INC,1:PRINT USING"######.#      "
 ;FXSZ(INC);FYSZ(INC);FZSZ(INC);MXSZ(INC);MYSZ(INC);MZSZ(INC)
1310 NEXT INC
1320 LOCATE 24,10:PRINT "PRESS RETURN TO CONTINUE";:INPUT C$
1330 FOR I=1 TO 6:SUM(I)=0:NEXT
```

```
1340 CLS
1350 FOR INC=1 TO NUM
1360 SUM(1)=FXSZ(INC)+SUM(1)
1370 SUM(2)=FYSZ(INC)+SUM(2)
1380 SUM(3)=FZSZ(INC)+SUM(3)
1390 SUM(4)=MXSZ(INC)+SUM(4)
1400 SUM(5)=MYSZ(INC)+SUM(Y)
1410 SUM(6)=MZSZ(INC)+SUM(6)
1420 NEXT INC
1430 FOR I=1 TO 6
1440   SUM(I)=SUM(I)/40
1450 NEXT I
1460 LOCATE 5,1:PRINT
"FORCE ANALYSIS BY MATRIX METHOD INTERCEPT
FOR REGRESSIONS FORCED THROUGH ZERO."
1470 LOCATE 6,8:PRINT " SIGNIFICANT VALUES FROM REGRESSIONS USED ONLY"
1490 LOCATE 10,1:
PRINT"FORCE X(I)    ";"FORCE Y(J)    ";"FORCE Z(K)    ";
"MOMENT X(I) ";"MOMENT Y(J) ";"MOMENT Z(K)"
1500     LOCATE 11,1:
PRINT USING"######.#     ";SUM(1);SUM(2);SUM(3);SUM(4);SUM(5);SUM(6)
1510 LOCATE 15,10:PRINT "SEND MEAN DATA TO PRINTER Y/N";:INPUT Q$
1520 IF Q$="" THEN BEEP:GOTO 1510
1530 IF Q$="N" THEN :GOTO 1600
1540 IF Q$="Y" THEN :GOTO 1560
1550 BEEP:GOTO 1510
1560 LPRINT "                  FORCE ANALYSIS METHOD #3."
1561 LPRINT
"             MATRIX WITH INTERCEPT FOR REGRESSIONS FORCED THROUGH ZERO."
1570 LPRINT "                ONLY SIGNIFICANT VALUES FROM REGRESSIONS USED "
1571 LPRINT
1580 LPRINT
"          MEAN VALUES FOR THE RESULTANT FORCE AND MOMENT VECTORS":LPRINT
1581 LPRINT "    TRIAL = ";F$
1590 LPRINT"FORCE X(I)    ";"FORCE Y(J)    ";"FORCE Z(K)    ";
"MOMENT X(I) ";"MOMENT Y(J) ";"MOMENT Z(K)"
1595 LPRINT USING"######.#     ";
SUM(1);SUM(2);SUM(3);SUM(4);SUM(5);SUM(6)
1596 LPRINT
" _____________________________________________
_____________________________________________________"
1600 OPEN "R",#2,FAN$,49
1610  FIELD #2
 ,8 AS RE$(1),8 AS RE$(2),8 AS RE$(3)
 ,8 AS RE$(4),8 AS RE$(5),8 AS RE$(6),1 AS RET$
1620 FOR INC = 1 TO NUM
1630     LSET RE$(1)=STR$(FXSZ(INC))
1640     LSET RE$(2)=STR$(FYSZ(INC))
1650     LSET RE$(3)=STR$(FZSZ(INC))
1660     LSET RE$(4)=STR$(MXSZ(INC))
1670     LSET RE$(5)=STR$(MYSZ(INC))
1680     LSET RE$(6)=STR$(MZSZ(INC))
1690      LSET RET$=CHR$(13)
1700                      PUT #2,INC
1710 NEXT INC
```

```
1720 CLOSE #2
1730 GOTO 180
1740 END
1750 REM SUBROUTINE MENU
1760 CLS
1770 LOCATE 10,10:
PRINT "1) CALCULATE THREE DIMENSIONAL FORCES
1780 LOCATE 12,10:
PRINT "2) RETURN TO MAIN MENU
1781 LOCATE 13,10:COLOR 15,0:
PRINT "PLACE DATA DISK IN DRIVE A:":COLOR 7,0
1790 LOCATE 15,15:PRINT "INPUT SELECTION";
1800 INPUT Q$:IF Q$="" THEN BEEP:GOTO 1790
1810 IF VAL(Q$)>2 THEN BEEP:GOTO 1790
1820 IF VAL(Q$)<1 THEN BEEP:GOTO 1790
1830 IF VAL(Q$)=1 THEN RETURN
1840 LOCATE 13,20:COLOR 31,0:
PRINT "LOADING MAIN MENU":COLOR 7,0
1841 IF VAL(Q$)=2 THEN CHAIN"MMENU",70
1900 END
2000 REM ERROR
2001 IF ERR=53 THEN BEEP:BEEP:BEEP:
CLS:LOCATE 23,20:COLOR 15,0
 :PRINT "FILE NOT FOUND":COLOR 7,0:RESUME 240
2002 IF ERR=74 THEN RESUME NEXT
```

Appendix F

WRENCH ANALYSIS PROGRAM

```
1  REM *WRENCH DETERMINATION PROGRAM*
10 DEFDBL R
20 NUM=40
30 DIM TRAV(40,6),RE$(30),REN$(30),RE(30)
40 DIM FXSZ(NUM),FYSZ(NUM),FZSZ(NUM),MXSZ(NUM),MYSZ(NUM),MZSZ(NUM)
50 DIM MPXSZ(NUM),MPYSZ(NUM),MPZSZ(NUM),MCXSZ(NUM),MCYSZ(NUM),MCZSZ(NUM)
60 DIM XSZ(NUM),YSZ(NUM),ZSZ(NUM)
70 REM ***********************************************************
80 REM PROG WRENCH CALCULATION
90 DIM AV10(6,40)
100 GOSUB 2080
110 CLS
120 LOCATE 10,10:INPUT "TEST DESIGNATION = FILENAME FOR DATA ";F$:S$=F$
121 LOCATE 23,20:PRINT SPACE$(23)
130 WAN$="A:LW"+S$+".PRN"
140 FAN$="A:"+"L"+S$+".PRN"
141 ON ERROR GOTO 9000
142 NAME FAN$ AS "E:JUNK11"
143 ON ERROR GOTO 0
150 LOCATE 12,13:PRINT
"DATA FILE NAME = L+FILENAME  = ";FAN$;" INPUT FILE"
160 LOCATE 13,10:PRINT
"WRENCH FILE NAME = LW+FILENAME  = ";WAN$;" OUTPUT FILE"
170 LOCATE 15,10:PRINT "DATA FILE NAMES CORRECT Y/N";:INPUT Q$
180 IF Q$="" THEN BEEP:GOTO 170
190 IF Q$="N" THEN BEEP:GOTO 220
200 IF Q$="Y" THEN GOTO 270
210 BEEP:GOTO 170
220 LOCATE 12,10:
PRINT"                                                            "
230 LOCATE 13,10:
PRINT"                                                            "
240 LOCATE 15,10:
PRINT"                                                            "
250 GOTO 120
260 BEEP:GOTO 170
270 OPEN "R",#2,FAN$,49
280  FIELD #2,8 AS RE$(1),8 AS RE$(2),8 AS RE$(3),
8 AS RE$(4),8 AS RE$(5),8 AS RE$(6),1 AS RET$
290 CLS:LOCATE 10,10:PRINT
"RETRIEVING RESULTANT FORCE AND MOMENT DATA"
300 FXMEAN=0:FYMEAN=0:FZMEAN=0
310 MXMEAN=0:MYMEAN=0:MZMEAN=0
320 FOR INC = 1 TO NUM
330 LOCATE 10,55:PRINT "NUMBER ";INC
340                           GET #2,INC
350      FXSZ(INC)=VAL(RE$(1))
360      FXMEAN=VAL(RE$(1))+FXMEAN
370      FYSZ(INC)=VAL(RE$(2))
380      FYMEAN=VAL(RE$(2))+FYMEAN
390      FZSZ(INC)=VAL(RE$(3))
400      FZMEAN=VAL(RE$(3))+FZMEAN
410      MXSZ(INC)=VAL(RE$(4))
420      MXMEAN=VAL(RE$(4))+MXMEAN
430      MYSZ(INC)=VAL(RE$(5))
```

```
440      MYMEAN=VAL(RE$(5))+MYMEAN
450      MZSZ(INC)=VAL(RE$(6))
460      MZMEAN=VAL(RE$(6))+MZMEAN
470 NEXT INC
480 FXMEAN=FXMEAN/NUM
490 FYMEAN=FYMEAN/NUM
500 FZMEAN=FZMEAN/NUM
510 MXMEAN=MXMEAN/NUM
520 MYMEAN=MYMEAN/NUM
530 MZMEAN=MZMEAN/NUM
540 CLOSE #2
550 CLS:LOCATE 10,10:PRINT
551 REM ******************************************
560 REM WRENCH PROGRAM CALCULATION OF WRENCH VECTOR
561 REM (MOMENT AND FORCE) AND
570 REM COMPONENT MOMENT VECTOR AND MOMENT ARM FOR
571 REM PLACEMENT OF THE FORCE
572 REM ******************************************
580 REM FOR C=1 TO 3
590 LOCATE 12,10:PRINT "CALCULATING";
600 FOR INC=1 TO NUM
610 PRINT ".";
620 REM IF C=1 THEN GOTO 680 ELSE GOTO 720
630 REM   FOR CASE 1
640 REM   FX=FXC(INC):FY=FYC(INC):FZ=FZC(INC):
641 REM   MX=MXC(INC):MY=MYC(INC):MZ=MZC(INC)
650 REM GOTO 800
660 REM
670 REM IF C=2 THEN GOTO 730 ELSE GOTO 770
680 REM  FOR CASE 2
690 REM   FX=FXS(INC):FY=FYS(INC):FZ=FZS(INC):
691 REM   MX=MXS(INC):MY=MYS(INC):MZ=MZS(INC)
700 REM GOTO 800
710 REM
720 REM  FOR CASE 3
730        FX=FXSZ(INC):FY=FYSZ(INC):FZ=FZSZ(INC):
731         MX=MXSZ(INC):MY=MYSZ(INC):MZ=MZSZ(INC)
740 REM GOTO 800
750 REM  CALCULATION LOOP
760 FDM=FX*MX+FY*MY+FZ*MZ
770 F=SQR(FX^2+FY^2+FZ^2)
780 M=SQR(MX^2+MY^2+MZ^2)
790 IF M=0 THEN GOTO 800 ELSE 820
800        CTH=0
810 GOTO 830
820 CTH=FDM/(F*M)
830 MP=M*CTH
840 MPX=(FX/F)*MP :MTX=MPX*10^6+.5:MTX=INT(MTX):MTX=MTX/10^6
850 MPY=(FY/F)*MP :MTY=MPY*10^6+.5:MTY=INT(MTY):MTY=MTY/10^6
860 MPZ=(FZ/F)*MP :MTZ=MPZ*10^6+.5:MTZ=INT(MTZ):MTZ=MTZ/10^6
870 MCX=MX-MPX:MTX=MX-MTX
880 MCY=MY-MPY:MTY=MY-MTY
890 MCZ=MZ-MPZ:MTZ=MZ-MYZ
900 IF MTY=0 THEN GOTO 940 ELSE GOTO 910
910    IF MTX=0 THEN GOTO 1120 ELSE GOTO 920
```

```
920        IF MTZ=0 THEN GOTO 1100 ELSE GOTO 930
930           GOTO 1180
940     IF MTX=0 THEN GOTO 1010 ELSE GOTO 950
950        IF MTZ=0 THEN GOTO 990 ELSE GOTO 970
960           REM MY=0
970           D1=-MCZ/MCX:D2=(FX*MCZ/MCX-FZ)/FY:GOTO 1210
980   REM ********************************************
990           REM MY=0 MZ=0
1000           D1=0:D2=-FZ/FY:GOTO 1210
1010        IF MTZ=0 THEN  GOTO 1020 ELSE GOTO 1040
1020              REM  MY=0  MX=0  MZ=0
1030              X=0:Y=0:Z=0:GOTO 1240
1040              REM  MY=0  MX=0
1050 K=(MCX^2+MCY^2+MCZ^2)/(FX^2+FY^2+FZ^2)
1060              D1=-FY/FX:D2=SQR((K)/(1+D1^2)):Y=D2
1070         IF MCZ>0 THEN DIR=1 ELSE DIR=-1
1080         IF FX>0 THEN DIF=1 ELSE DIF=-1
1090         Y=Y*DIR*DIF:X=D1*Y:Z=0:GOTO 1240
1100       REM  MZ=0
1110              D1=-MCY/MCX:D2=-FZ(FY-FX*MCY/MCX):GOTO 1210
1120     IF MTZ=0 THEN GOTO 1130 ELSE 1160
1130 REM  MX=0 MZ=0
1140      D1=-FZ/FX:D2=0:GOTO 1210
1150 REM MX=0
1160      D1=(FY*MCZ/MCY-FZ)/FX:D2=-MZ/MY
1170      GOTO 1210
1180 D1=(FY*MCZ/MCY-FZ)/(FX-FY*MCX/MCY)
1190 D2=(-MCX*D1/MCY)-(MCZ/MCY)
1200 K=(MCX^2+MCY^2+MCZ^2)/(FX^2+FY^2+FZ^2)
1210 Z=SQR((K)/(1+D1^2+D2^2)):Z=Z*(-1)
1220 Y=(D2*Z)
1230 X=D1*Z
1240 REM **********************************
1250    MPXSZ(INC)=MPX:MPYSZ(INC)=MPY:MPZSZ(INC)=MPZ:
1251    MCXSZ(INC)=MCX:MCYSZ(INC)=MCY:MCZSZ(INC)=MCZ:GOTO 1270
1260 REM XS(INC)=X:YS(INC)=Y:ZS(INC)=Z:GOTO 1530
1270 XSZ(INC)=X:YSZ(INC)=Y:ZSZ(INC)=Z
1280 REM LPRINT USING "####.## ";MCX;MCY;MCZ;MPX;MPY;MPZ;MX;MY;MZ;CTH
1290 NEXT INC
1300 REM NEXT C
1310 REM PLACING DATA ON DISK IN A LOTUS FILE NAMED WAN$
1320 OPEN "R",#2,WAN$,73
1330 B=0
1340 FOR X=1 TO 9
1350     IF X=9 THEN GOTO 1380
1360   FIELD #2,B AS TRASH1$,8 AS REN$(X)
1370     GOTO 1390
1380   FIELD #2,B AS TRASH1$,8 AS REN$(X),1 AS RET$
1390   B=B+8
1400 NEXT X
1410   CLS:LOCATE 10,10:PRINT
"STORING WRENCH ANALYSIS DATA ON DISK. FILENAME = ";WAN$
1420 FOR I=1 TO 9:SUM(I)=0:NEXT I
1430 FOR INC=1 TO NUM
1440 PRINT ".";
```

```
1450     RE(1)=XSZ(INC)
1460    SUM(1)=XSZ(INC)+SUM(1)
1470     RE(2)=YSZ(INC)
1480    SUM(2)=YSZ(INC)+SUM(2)
1490     RE(3)=ZSZ(INC)
1500    SUM(3)=ZSZ(INC)+SUM(3)
1510     RE(4)=MPXSZ(INC)
1520    SUM(4)=MPXSZ(INC)+SUM(4)
1530     RE(5)=MPYSZ(INC)
1540    SUM(5)=MPYSZ(INC)+SUM(5)
1550     RE(6)=MPZSZ(INC)
1560    SUM(6)=MPZSZ(INC)+SUM(6)
1570     RE(7)=MCXSZ(INC)
1580    SUM(7)=MCXSZ(INC)+SUM(7)
1590     RE(8)=MCYSZ(INC)
1600    SUM(8)=MCYSZ(INC)+SUM(8)
1610     RE(9)=MCZSZ(INC)
1620    SUM(9)=MCZSZ(INC)+SUM(9)
1630     FOR X=1 TO 9
1640         LSET REN$(X)=STR$(INT((RE(X)+.000005)*100000!)/100000!)
1650     NEXT X
1660         LSET RET$=CHR$(13)
1670          PUT #2,INC
1680 NEXT INC
1690 CLOSE #2
1700 FOR I=1 TO 9:SUM(I)=SUM(I)/NUM:NEXT I
1710 CLS
1720 LOCATE 2,12:PRINT "RESULTS OF WRENCH ANALYSIS FOR TRIAL = ";F$
1730 LOCATE 5,15:PRINT "MEAN MINIMUM POSITION VECTOR"
1740 REM LOCATE 6,1:
PRINT "--------------------------------
-----------------------------------"
1750 LOCATE 7,5:
PRINT "                 RX(M)                    RY(M)                    RZ(M)"
1760 LOCATE 8,13:
PRINT USING "####.####               ";SUM(1);SUM(2);SUM(3)
1770 LOCATE 9,1:PRINT
"-----------------------------------
-------------------------------"
1780 LOCATE 11,15:PRINT "MEAN PARALLEL MOMENT  (WRENCH MOMENT)"
1790 LOCATE 13,5:
PRINT "                 MPX(N*M)                 MPY(N*M)                 MPZ(N*M)"
1800 LOCATE 14,13:
PRINT USING "####.####               ";SUM(4);SUM(5);SUM(6)
1810 LOCATE 15,1:PRINT
 "---------------------------------
-----------------------------------"
1820 LOCATE 17,15:PRINT "MEAN PERPENDICULAR MOMENT "
1830 LOCATE 18,5:
PRINT "                 MCX(N*M)                 MCY(N*M)                 MCZ(N*M)"
1840 LOCATE 19,13:
PRINT USING "####.####               ";SUM(7);SUM(8);SUM(9)
1850 LOCATE 20,1:
PRINT "--------------------------------
--------------------------------------"
```

```
1860 LOCATE 25,10:PRINT "PRINT MEAN VALUES TO PRINTER Y/N";:INPUT Q$
1870 IF Q$="" THEN BEEP:GOTO 1860
1880 IF Q$="Y" THEN GOTO 1910
1890 IF Q$="N" THEN GOTO 100
1900 BEEP:GOTO 1860
1910 LPRINT "                              RESULTS OF WRENCH ANALYSIS "
1911 LPRINT
"     FOR THE THREE DIMENSIONAL FORCE AND MOMENT SYSTEM DETERMINED"
1912 LPRINT "          BY THE FORCE AND MOMENT TILLAGE DYNAMOMETER"
1915 LPRINT "                              FOR TRIAL = ";F$
1920 LPRINT :LPRINT:LPRINT :LPRINT
1930 LPRINT "                    MEAN MINIMUM POSITION VECTOR"
1940 LPRINT :
LPRINT "         RX(M)                    RY(M)                    RZ(M)"
1950 LPRINT "          ";
 :LPRINT USING "####.####           ";SUM(1);SUM(2);SUM(3)
1960 LPRINT :LPRINT
"-----------------------------------------------------------------------"
1970 LPRINT :
LPRINT "        MEAN PARALLEL COMPONENT MOMENT  (WRENCH MOMENT)"
1980 LPRINT :
LPRINT "          MPX(N*M)                 MPY(N*M)                 MPZ(N*M)"
1990 LPRINT "           ";
:LPRINT USING "####.####           ";SUM(4);SUM(5);SUM(6)
2000 LPRINT :LPRINT
"-----------------------------------------------------------------------"
2010 LPRINT :LPRINT "        MEAN PERPENDICULAR COMPONENT MOMENT"
2020 LPRINT :
LPRINT "         MPDX(N*M)                MPDY(N*M)                MPDZ(N*M)"
2030 LPRINT "           ";
 :LPRINT USING "####.####           ";SUM(7);SUM(8);SUM(9)
2040 LPRINT :LPRINT
"-----------------------------------------------------------------------"
2050 LPRINT :LPRINT "                  MEAN RESULTANT FORCE "
2060 LPRINT :
LPRINT "           FX(N)                    FY(N)                    FZ(N)"
2070 LPRINT
"          ";
 :LPRINT USING "####.####           ";FXMEAN;FYMEAN;FZMEAN
2071 LPRINT :LPRINT
"-----------------------------------------------------------------------"
2072 LPRINT :LPRINT "                  MEAN RESULTANT MOMENT"
2073 LPRINT
 :LPRINT "           MX(N*M)                  MY(N*M)                  MZ(N*M)"
2074 LPRINT
"          ";
 :LPRINT USING "####.####           ";MXMEAN;MYMEAN;MZMEAN
2075 LPRINT :LPRINT
"-----------------------------------------------------------------------"
2076 LPRINT CHR$(12)
2079 GOTO 100
2080 REM SUBROUTINE FOR MAIN MENU
2090 CLS
2100 LOCATE 2,10:PRINT "PROGRAM TO DETERMINE THE WRENCH OF A SYSTEM OF"
2110 LOCATE 3,14:PRINT "THREE DIMENSIONAL FORCES AND MOMENTS"
```

```
2120 LOCATE 4,9:
PRINT "AND THE MINIMUM POSITION VECTOR FROM THE ORIGIN OF THE "
2130 LOCATE 5,23:PRINT "DYNAMOMETER SYSTEM"
2140 LOCATE 7,1:PRINT
"
______________________________________________________________"
2150 LOCATE 10,10:PRINT "1) WRENCH ANALYSIS PROGRAM
2160 LOCATE 12,10:PRINT "2) RETURN TO MAIN MENU
2161 LOCATE 14,10:COLOR 15,0:
PRINT "PLACE DATA DISK IN DRIVE A":COLOR 7,0
2170 LOCATE 20,10:PRINT "INPUT DESIRED SELECTION";:INPUT N$
2180 IF N$="" THEN BEEP:GOTO 2170
2190 IF VAL(N$)>2 THEN BEEP:GOTO 2170
2200 IF VAL(N$)<1 THEN BEEP:GOTO 2170
2210 IF VAL(N$)=1 THEN GOTO 2230
2220 IF VAL(N$)=2 THEN GOTO 2240
2230 RETURN
2240 LOCATE 15,20:COLOR 31,0:PRINT "LOADING MAIN MENU":COLOR 7,0
2241 CHAIN "MMENU",70
9000 REM ERROR
9010 IF ERR=53
THEN BEEP:BEEP:BEEP:CLS:
LOCATE 23,20:COLOR 15,0:PRINT "FILE NOT FOUND":COLOR 7,0:RESUME 120
9020 IF ERR=74 THEN RESUME NEXT
```

Appendix G

INTERSECTION ANALYSIS PROGRAM

```
1  REM *INTERSECTION PROGRAM*
10 CLS
20 LOCATE 2,5
 :PRINT "INTERSECTION PROGRAM FOR THE RESULTANT MEAN TILLAGE FORCE"
30 LOCATE 3,7
 :PRINT "AND THE PLANE USED TO REPRESENT THE TILLAGE IMPLEMENT"
40 LOCATE 5,5
 :PRINT "PROGRAM USES THE MEAN POSITION VECTOR AND THE MEAN FORCE"
50 LOCATE 6,5
 :PRINT "VECTOR RESULTS FROM PROGRAM WRENCH"
60 LOCATE 13,20:COLOR 0,7:
PRINT "PRESS RETURN TO CONTINUE";:COLOR 7,0:INPUT Q$
100 REM PROGRAM WILL GIVE INTERSECTION POINT OF
110 REM PLANE AND FORCE VECTOR
120 CLS
130 GOTO 260
140 REM SUBROUTINE FOR INTERSECTION DETERMINATION
150 A=VAL(A$):B=VAL(B$):C=VAL(C$):D=VAL(D$)
160 A1=VAL(A1$):B1=VAL(B1$):C1=VAL(C1$)
170 XO=VAL(XO$):YO=VAL(YO$):ZO=VAL(ZO$)
180 REM
190 TTOP=-A*XO-B*YO-C*ZO-D
200 TBOT=A*A1+B*B1+C*C1
210 T=TTOP/TBOT
220 X=XO+T*A1
230 Y=YO+T*B1
240 Z=ZO+T*C1
250 RETURN
260 CLS
270 I=1
271 LOCATE 2,5:COLOR 15,0:PRINT
"INTERSECTON PROGRAM FOR THE LINE OF ACTION OF THE RESULTANT FORCE AND"
272 LOCATE 3,10:PRINT
"THE PLANE USED TO REPRESENT THE TILLAGE IMPLEMENT":COLOR 7,0
280 LOCATE 9,5,0:PRINT "PLANE EQUATION"
290 LOCATE 5,5,0:PRINT "1) A=";A
300 LOCATE 6,5,0:PRINT "2) B=";B
310 LOCATE 7,5,0:PRINT "3) C=";C
320 LOCATE 8,5,0:PRINT "4) D=";D
330 IF I=0 THEN GOTO 610
340 LOCATE 9,25,0:PRINT "FORCE VECTOR"
350 LOCATE 5,25,0:PRINT "5)FX=";A1
360 LOCATE 6,25,0:PRINT "6)FY=";B1
370 LOCATE 7,25,0:PRINT "7)FZ=";C1
380 IF I=0 THEN GOTO 610
390 LOCATE 9,45,0:PRINT "POSITION VECTOR"
400 LOCATE 5,45,0:PRINT "8)XO=";XO
410 LOCATE 6,45,0:PRINT "9)YO=";YO
420 LOCATE 7,45,0:PRINT "10)ZO=";ZO
430 IF I=0 THEN GOTO 610
440 LOCATE 10,5,0:PRINT "11) CALCULATE INTERCEPT"
450 LOCATE 10,30,0:PRINT "12) RETURN TO MAIN MENU"
460 IF I=0 THEN GOTO 610
470 GOTO 610
480 REM
```

```
490 LOCATE 18,5,0:PRINT "X=";X
500 LOCATE 18,25,0:PRINT "Y=";Y
510 LOCATE 18,50,0:PRINT "Z=";Z
520 LOCATE 14,10,0:PRINT " PRESS ANY KEY TO CONTINUE    "
530 LOCATE 17,10,0:COLOR 17,1:PRINT "INTERCEPT POINT                 "
540 Q$=INKEY$:IF Q$="" GOTO 540
550 LOCATE 15,10,0:COLOR 2,6:PRINT "                                  "
560 LOCATE 14,10,0:COLOR 2,6:PRINT "                                  "
570 LOCATE 17,10,0:COLOR 2,6:PRINT "                                  "
580 LOCATE 18,5,0:COLOR 2,6:
PRINT "                                                               "
590 LOCATE 16,1,0:COLOR 2,6:
PRINT "                                              "
600 IF I=0 THEN GOTO 610
610 LOCATE 15,10,0:
PRINT"                                                          ";
LOCATE 15,10,0:PRINT "SELECT VARIABLE TO CHANGE=";
620 INPUT VCH$
630 VCH=VAL(VCH$)
640 IF VCH$="" THEN :BEEP:GOTO 610
650 IF VCH>12 THEN:BEEP:GOTO 610
660 IF VCH=0 THEN:BEEP:GOTO 610
670 IF VCH<0 THEN:BEEP:GOTO 610
680 LOCATE 15,10,0:PRINT "                                   "
690 I=0
700 ON VCH GOTO 710,740,770,800,830,860,890,920,950,980,1010,1030
710 LOCATE 15,10,0:
PRINT "   INPUT NEW A VALUE A=";:INPUT A$:IF A$="" THEN GOTO 280
720 A=VAL(A$)
730 GOTO 280
740 LOCATE 15,10,0:
PRINT "   INPUT NEW A VALUE B=";:INPUT B$:IF B$="" THEN GOTO 280
750 B=VAL(B$)
760 GOTO 280
770 LOCATE 15,10,0:
PRINT "   INPUT NEW A VALUE C=";:INPUT C$:IF C$="" THEN GOTO 280
780 C=VAL(C$)
790 GOTO 280
800 LOCATE 15,10,0:
PRINT "   INPUT NEW A VALUE D=";:INPUT D$:IF D$="" THEN GOTO 280
810 D=VAL(D$)
820 GOTO 280
830 LOCATE 15,10,0:
PRINT "   INPUT NEW A VALUE FX=";:INPUT A1$:IF A1$="" THEN GOTO 340
840 A1=VAL(A1$)
850 GOTO 340
860 LOCATE 15,10,0:
PRINT "   INPUT NEW A VALUE FY=";:INPUT B1$:IF B1$="" THEN GOTO 340
870 B1=VAL(B1$)
880 GOTO 340
890 LOCATE 15,10,0:
PRINT "   INPUT NEW A VALUE FZ=";:INPUT C1$:IF C1$="" THEN GOTO 340
900 C1=VAL(C1$)
910 GOTO 340
920 LOCATE 15,10,0:
```

```
PRINT "   INPUT NEW A VALUE XO=";:INPUT XO$:IF XO$="" THEN GOTO 390
930 XO=VAL(XO$)
940 GOTO 390
950 LOCATE 15,10,0:
PRINT "   INPUT NEW A VALUE YO=";:INPUT YO$:IF YO$="" THEN GOTO 390
960 YO=VAL(YO$)
970 GOTO 390
980 LOCATE 15,10,0:
PRINT "   INPUT NEW A VALUE ZO=";:INPUT ZO$:IF ZO$="" THEN GOTO 390
990 ZO=VAL(ZO$)
1000 GOTO 390
1010 GOSUB 140
1020 GOTO 480
1030 CHAIN "MMENU",70
```

Appendix H

CALIBRATION PROGRAMS

```
1  REM *CALIBRATION PROGRAM FOR INDIVIDUAL TRANSDUCERS*
10 DIM VA$(10)
20 DIM VA(10)
30 REM*************************************************************
40 REM PROGRAM FOR INDIVIDUAL CALIBRATION OF TRANSDUCERS            **
50 REM*************************************************************
60 REM
70 CLS: OPEN "COM1:9600,E,7,1,RS,CS,DS" AS #1
80 PRINT #1, "$A0 0 UC CA (18 10)"
90 LINE INPUT #1,B$
100 REM*************************************************************
110 REM ABOVE LINES OPEN COMMUNICATION WITH TAURUS AND CORONA       **
120 REM ************************************************************
130 PRINT #1,"$A0 1 AS CL (0 192 1)
140 INPUT #1,B$
150 INPUT #1,E$
160 IF E$="E" THEN INPUT #1,B$:PRINT "**ERROR**";B$;GOTO 1440
170 REM*************************************************************
180 REM SETS UP SCAN TABLE FOR BUS ZERO, STARTING AT CHANNEL 0 BUT  **
190 REM WITH A GAIN OF 100.  THE INPUT STATEMENTS CHECK FOR ERRORS. **
200 REM*************************************************************
210 PRINT #1,"$A0 1 AA (1,0)"
220 LINE INPUT #1,B$
230 LINE INPUT #1,B$
240 PRINT B$
250 PRINT "TEST SCAN"
260 PRINT
270 PRINT #1,"$A0 1 AR (1)
280 INPUT #1,B$
290 INPUT #1,R$
300 INPUT #1,E$
310 IF E$="E" THEN PRINT "**ERROR FOUND**";R$:GOTO 1460
320 RE=VAL(R$)
330 PRINT RE;"   "
340 REM***************************************************************
350 REM CHECKS FOR ERRORS IN THE SET UP BY DOING A SINGLE SCAN OF THE **
360 REM TRANSDUCER BEING TESTED.                                      **
370 REM***************************************************************
380 CLS
390 INPUT "TRANSDUCER NUMBER";TR$:TR$="B:TR"+TR$
400 CLS
410 PRINT "PRESS ANY KEY TO CONTINUE THIS TAKES UNSTRAINED READINGS"
420 A$=INKEY$: IF A$="" THEN 420
430 PRINT #1,"$A0 1 AA (1,0)
440 LINE INPUT #1,B$
450 LINE INPUT #1,B$
460 PRINT B$
470 REM **************************************************************
480 REM ANALOG ACQUISITON OF 1 CHANNEL FOR UNLOADED CONDITIONS        **
490 REM **************************************************************
500 UNLOADED$=TR$ + "U"
510 OPEN "R",#2,UNLOADED$,2
520 FIELD #2,2 AS VA$
530 PRINT #1,"$A0 1 AR (1)"
540 INPUT #1,B$
```

```
550 INPUT #1,R$
560 INPUT #1,E$
570 IF E$="E" THEN PRINT "ERROR FOUND";R$:GOTO 1480
580 VA=VAL(R$)
581 PRINT "UNLOADED READING";VA
590 LSET VA$=MKI$(VA)
600 PUT #2,1
610 CLOSE #2
620 REM ***************************************************************
630 REM ABOVE STATEMENTS TRANSFERS DATA FOR THE UNSTRAINED CONDITION **
640 REM TO DISK IN A FILE UNDER THE TRANSDUCER NUMBER, TR#U          **
650 REM ***************************************************************
660 CLS
670 PRINT "************************************************************"
680 PRINT "************************************************************"
690 PRINT "*PRESS ANY KEY TO START DATA AQUASITON FOR LOADED CONDITION"
700 PRINT "************************************************************"
710 PRINT "************************************************************"
720 A$= INKEY$:IF A$="" THEN GOTO 720
730 CLS
740 PRINT "LOAD TRANSDUCER"
750 OPEN "R",#2,TR$,20
 FIELD #2,2 AS VA$(1),2 AS VA$(2),2 AS VA$(3),
2 AS VA$(4),2 AS VA$(5),2 AS VA$(6),2 AS VA$(7),
2 AS VA$(8),2 AS VA$(9),2 AS VA$(10)
770 FOR X= 1 TO 28
780 'CLS
781 PRINT :PRINT
790 IF X>14 GOTO 850
800 PRINT "PLACE LOAD FOR CALIBRATION #";X;" A LOAD OF ";20*X;"KG"
810 PRINT "***********PLACE LOAD ON*********************"
820 PRINT "///////// HIT ANY KEY TO CONTINUE ///////////////"
830 A$=INKEY$:IF A$="" THEN GOTO 830
840 GOTO 890
850 PRINT "PLACE LOAD FOR CALIBRATION #";X;" A LOAD OF ";20*(28-X)
860 PRINT "***********PLACE LOAD ON*********************"
870 PRINT "///////// HIT ANY KEY TO CONTINUE ///////////////"
880 A$=INKEY$:IF A$="" THEN GOTO 880
890 PRINT #1,"$A0 1 AA (10,50)
900 LINE INPUT #1,B$
910 LINE INPUT #1,B$
920 PRINT B$
930 REM ***************************************************************
940 REM ABOVE STATMENTS PERFORM AN AA                                 *
941 REM FOR 1 CH 10 TIMES WITH A 50MSEC DELAY                         *
950 REM ***************************************************************
960 FOR Y=1 TO 10
970 PRINT #1,"$A0 1 AR (1)
980 INPUT #1,B$
990 INPUT #1,R$
1000 INPUT #1,E$
1010 IF E$="E" THEN PRINT "ERROR":GOTO 1040
1020 VA(Y)=VAL(R$)
1021 PRINT VA(Y);
1030 GOTO 1060
```

```
1040 REM INPUT #1,E$
1050 PRINT E$:GOTO 1460
1060 LSET VA$(Y)=MKI$(VA(Y))
1070 NEXT Y
1080 PUT #2,X
1090 NEXT X
1100 REM ***************************************************************
1110 REM ABOVE STATEMENTS PLACE READINGS ON DISK UNDER FILE NAME TR#  **
1120 REM AND RECORD LENGTHS OF 10 READINGS EACH 2 BITES               **
1130 REM ***************************************************************
1140 CLS
1150 PRINT"***************************************************************"
1160 PRINT "** DO YOU WANT DATA PRINTED OUT  **"
1170 INPUT "YES OR NO(Y?,N?)";Q$
1180 IF Q$="N" GOTO 1480
1190 CLS
1200 PRINT "**************************************************************"
1210 PRINT "** DO YOU WANT ALL STEPS **"
1220 INPUT "YES OR NO(Y?,N?)";Q$
1230 IF Q$="N" GOTO 1340
1240 FOR X=1 TO 28
1250 IF X>14 THEN L=28
1260 PRINT "LOAD ";L*20;"KG"
1270 PRINT "*****************************************************************"
1280 GET #2, X
1290 FOR Y=1 TO 10
1300 PRINT USING " ########";CVI(VA$(Y))
1310 NEXT Y
1320 NEXT X
1330 GOTO 1420
1340 INPUT "INPUT LOAD TO BE PRINTED";LO
1350 GET #2,LO/20
1360 PRINT "LOAD ";LO;"KG"
1370 FOR Y=1 TO 10
1380 PRINT USING "########";CVI (VA$(Y))
1390 NEXT Y
1400 INPUT"INPUT (Y) TO PRINT MORE LOADING CONDITIONS";Q$
1410 IF Q$="Y" GOTO 1340
1420 PRINT " ************************* END *************************"
1430 GOTO 1500
1440 PRINT "*********ERROR********* 160"
1450 GOTO 1500
1460 PRINT "*********ERROR********* 310,1040"
1470 GOTO 1500
1480 PRINT "*********ERROR********* 570"
1490 GOTO 1500
1500 PRINT "END"
1510 CLOSE #2
```

```
1  REM *CALIBRATION PROGRAM FOR DYNAMOMETER FRAME*
10 DIM VAU$(6)
20 DIM VAU(6)
30 DIM VA(60)
40 DIM VA$(60)
50 REM*****************************************************************
60 REM PROGRAM FOR CALIBRATION OF TRANSDUCER FRAME (SIX TRANSDUCERRS**
70 REM*****************************************************************
80 REM
90 CLS: OPEN "COM1:9600,E,7,1,RS,CS,DS" AS #1
100 PRINT #1, "$A0 0 UC CA (18 10)"
110 LINE INPUT #1,B$
120 REM*****************************************************************
130 REM ABOVE LINES OPEN COMMUNICATION WITH TAURUS AND CORONA        **
140 REM ****************************************************************
150 PRINT #1,"$A0 1 AS CL (0 128 6)
160 INPUT #1,B$
170 INPUT #1,E$
180 IF E$="E" THEN INPUT #1,B$:PRINT "**ERROR**";B$;GOTO 1330
190 REM*****************************************************************
200 REM SETS UP SCAN TABLE FOR BUS ZERO, STARTING AT CHANNEL 0 BUT  **
210 REM WITH A GAIN OF 100.  THE INPUT STATEMENTS CHECK FOR ERRORS. **
220 REM*****************************************************************
230 PRINT #1,"$A0 1 AA (1,0)"
240 LINE INPUT #1,B$
250 LINE INPUT #1,B$
260 PRINT B$
270 PRINT "TEST SCAN FOR SIX CHANNELS"
280 PRINT
290 FOR TRANSDUCER=1 TO 6
300 PRINT #1,"$A0 1 AR (1)
310 INPUT #1,B$
320 INPUT #1,R$
330 INPUT #1,E$
340 IF E$="E" THEN PRINT "**ERROR FOUND**";R$:GOTO 1350
350 RE=VAL(R$)
360 PRINT RE;"   "
370 NEXT TRANSDUCER
380 REM*******************************************************************
390 REM CHECKS FOR ERRORS IN THE SET UP BY DOING A SINGLE SCAN OF THE **
400 REM TRANSDUCERS BEING TESTED.                                      **
410 REM*******************************************************************
420 CLS
430 INPUT "TEST CONDITION(FX,FY,FZ,MX,MY,MZ)";FR$:FR$="B:FR"+FR$
440 CLS
450 PRINT "PRESS ANY KEY TO CONTINUE THIS TAKES UNLOADED READINGS"
460 A$=INKEY$: IF A$="" THEN 460
470 PRINT #1,"$A0 1 AA (1,0)
480 LINE INPUT #1,B$
490 LINE INPUT #1,B$
500 REM ******************************************************************
510 REM ANALOG ACQUISITON OF 6 TRANSDUCERS UNLOADED CONDITIONS        **
520 REM ******************************************************************
530 UNLOADED$=FR$ + "U"
540 OPEN "R",#2,UNLOADED$,12
```

```
550 FIELD #2,2 AS VAU$(1),2 AS VAU$(2),2 AS VAU$(3),
2 AS VAU$(4),2 AS VAU$(5),2 AS VAU$(6)
560 FOR TRANS=1 TO 6
570 PRINT #1,"$A0 1 AR (1)"
580 INPUT #1,B$
590 INPUT #1,R$
600 INPUT #1,E$
610 IF E$="E" THEN PRINT "ERROR FOUND";R$:GOTO 1370
620 VAU(TRANS)=VAL(R$)
630 PRINT "UNLOADED READING";VAU(TRANS)
640 LSET VAU$(TRANS)=MKI$(VAU(TRANS))
650 PUT #2,1
660 NEXT TRANS
670 CLOSE #2
680 REM ****************************************************************
690 REM ABOVE STATEMENTS TRANSFERS THE DATA FOR  UNLOADED CONDITION **
700 REM TO DISK IN A FILE UNDER THE TRANSDUCER NUMBER, FR(CON)      **
710 REM ****************************************************************
720 CLS
730 PRINT "***************************************************************"
740 PRINT "***************************************************************"
750 PRINT "*PRESS ANY KEY TO START DATA AQUASITON FOR LOADED CONDITION*"
760 PRINT "***************************************************************"
770 PRINT "***************************************************************"
780 A$= INKEY$:IF A$="" THEN GOTO 780
790 CLS
800 PRINT "LOAD TRANSDUCER FRAME"
810 OPEN "R",#2,FR$,120
820 B=0
830 FOR X=1 TO 60
840 FIELD #2,B AS TRASH$,2 AS VA$(X)
850 B=B+2
860 NEXT X
870 REM *****************************************************************
880 REM *  FEILDS RECORD FOR THE TRANSDUCER READINGS                    **
890 REM *****************************************************************
900 FOR X= 1 TO 28
910 'CLS
920 PRINT :PRINT
930 PRINT "PRESENT X VALUE IS";X
940 INPUT "INPUT PRESENT X VALUE OR NEW VALUE";N
950 X=N
960 IF X>14 THEN L=28-X ELSE L=X
970 PRINT "PLACE LOAD FOR CALIBRATION #";X;" A LOAD OF ";20*L;"KG"
980 PRINT "***********PLACE LOAD ON*********************"
990 PRINT "///////// HIT ANY KEY TO CONTINUE ///////////////"
1000 PRINT
1010 PRINT
1020 A$=INKEY$:IF A$="" THEN GOTO 1020
1030 PRINT #1,"$A0 1 AA (10,50)
1040 LINE INPUT #1,B$
1050 LINE INPUT #1,B$
1060 PRINT B$
1070 REM ****************************************************************
1080 REM STATMENTS PERFORM AN AA FOR 6 CH 10 TIMES WITH A 50MSEC DELAY*
```

```
1090 REM *************************************************************
1091 MAR=0
1100 PRINT "TRANSD 1" TAB(14) "TRANSD 2" TAB(28) "TRANSD 3"
TAB(42) "TRANSD 4" TAB(56) "TRANSD 5" TAB(70) "TRANSD 6"
1110 FOR Y=1 TO 60
1120 PRINT #1,"$A0 1 AR (1)
1130 INPUT #1,B$
1140 INPUT #1,R$
1150 INPUT #1,E$
1160 IF E$="E" THEN PRINT "ERROR":GOTO 1200
1170 VA(Y)=VAL(R$)
1171 IF Y=1 OR Y=7 OR Y=13 OR Y=19 OR Y=25 OR Y=31
OR Y=37 OR Y=43 OR Y=49 OR Y=55 THEN MAR=0 ELSE MAR=MAR +1
1180 PRINT TAB(MAR*14) VA(Y);
1190 GOTO 1220
1200 REM ERROR CHECKING*********************
1210 PRINT E$:GOTO 1350
1220 LSET VA$(Y)=MKI$(VA(Y))
1230 NEXT Y
1240 PUT #2,X
1250 NEXT X
1260 REM ***************************************************************
1270 REM AND RECORD LENGTHS OF 60 READINGS EACH 2 BITES LONG          **
1280 REM EACH RECORD NUMBER IS THE LOADING NUMBER.                    **
1290 REM ***************************************************************
1300 CLS
1310 PRINT " ************************* END *************************"
1320 GOTO 1390
1330 PRINT "*********ERROR********* 160"
1340 GOTO 1390
1350 PRINT "*********ERROR********* 310,1040"
1360 GOTO 1390
1370 PRINT "*********ERROR********* 570"
1380 GOTO 1390
1390 PRINT "END"
1400 CLOSE #2
```