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Field Evaluation of Hydraulic Torque Assisted Disk Implement

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Omer Ozel

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of the requirements for

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Daniel Guyer
Major professor

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FIELD EVALUATION OF HYDRAULIC TORQUE ASSISTED DISK IMPLEMENT

By

Omer Ozel

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ABSTRACT

FIELD EVALUATION OF HYDRAULIC TORQUE ASSISTED DISK IMPLEMENT

By

Omer Ozel

The performance and power requirements of the hydraulically driven soil-engaging disk are discussed. Draft, hydraulic rotary, and total powers consumed were measured at various system pressure settings and ground speeds by a microcomputer based data acquisition system.

The power disk was quantitatively compared powered vs. non-powered. The results show that applying supplemental hydraulic torque to the disk up to the breakaway torque has caused a draft reduction by up to 15 % when the torque approached the breakaway torque of 358 N-m (3168 lb-in). However, a significant reduction on total power requirement was not observed in the field tests.

Dedicated to my beloved family, Asuman, Kevser, and Yusuf.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

INTRODUCTION

1.1 Background

As primary or secondary tillage equipment, disk implements are commonly used all over the world. Such implements require a sizable amount of draft power. As the energy costs increase day by day, the efficient use or design of this type of machine plays a more important role on reducing fuel costs.

A power-driven disk could be an alternative solution to reduce the draft power. Various mechanically driven systems have been developed for better performance and power efficiency. By recent advances in the development of hydraulic power and control components, designers have had alternative opportunities for power transmission and control. One implementation of these technological developments might be hydraulic remote control and power of the active disk blade for power efficiency and safety reasons. Power can be transmitted to the disk by hydraulic hoses, instead of traditional power takeoff shafts. This type of control and power of machines could make significant contributions to farm power research and agricultural machinery safety.

On the other hand, to a farmer in a developing country, the primary source of power, a tractor, is most likely to have less than 10 kW of power and pertinent equipment are usually small category if available. Due to the depressed agricultural economy, it is not possible for such farmers to buy a large tractor or any big specific equipment for only one purpose. They usually resort to using the same implement for various farming activities, such as using a disk plow to harvest root crops, after minor modifications to meet specific operating conditions.

Previously there have been some studies on implementation and improvement of disk blades for the above purpose. Gupta, et al. (1993,1994) developed two prototype potato harvesters having mechanically driven disk blades. One of them was a one-row disk blade powered by a two-wheel walking type (single axle) tractor of 6 kW (8 Hp). The other was also a one-row disk blade with an additional separator and a single axle tractor of 8.6 kW (11.5 Hp) power.

The main idea behind Gupta's approach was to develop a cost-effective, easy to use potato harvester, which does not require great power or labor. As a result of huge population movements from rural to suburb areas in developing countries in last few decades, the need for agricultural workers increased and labor shortages occurred. Consequently, labor cost has increased and labor has been troublesome. The mechanization of agricultural production with smaller tractors, therefore, has been inevitable for farmers of small size.

1.2 Objectives

Three specific objectives of this study were:

1. To develop a hydraulic power driven soil-engaging disk system in order to reduce draft and power requirements as a function of the supplemental torque to a disk at varying ground speeds.

2. To develop a personal computer (PC) based data acquisition system to record soil-engaging disk implement performance for evaluation.
3. To measure the draft forces acting on the disk and compare the energy requirements of a disk blade as a tillage implement under powered and non-powered conditions.

Chapter 2

LITERATURE REVIEW

2.1 Principles of Disk Implement Design

There have been a number of studies on disk implements in order to determine the essential and optimum design parameters, such as disk angle, tilt angle, and other geometric properties of disks, and the effect of each parameter on power requirement of disk implements while changing other variables like ground speed, working depth and soil type of the test field. The vast amount of information and research regarding these parameters and their effects provides a very good resource for engineers and workers of disk implements to improve future designs.

A review of the literature on fundamentals of design of disk implements is necessary to fully understand the operation of the disk implement. It was also helpful in the selection of rational working ranges of the variables involved with this study. Keeping the previous knowledge in mind, the number of variables for this research were decreased to observe the main effect of the new design.

Clyde (1939) is one of the earliest workers who had reported soil forces acting on disks. He observed the effect of disk angle, vertical angle, disk diameter and moisture content of the soil and provided the guidelines for the design of disk implements and proper hitching procedures. He gave an understanding of how and where the soil forces act on disks. The observations were carried out by a basic data acquisition system due to the technology available at that time.

Gordon (1941) made significant contributions to the design of disk implements by working on a single blade disk plow under laboratory conditions. Two firmly packed different soils in soil bins were used for the test runs. The disk was placed in a framework through which the reaction of the soil on the disk was imparted to six hydraulic cells. The hydraulic cell pressures were recorded and through these records the soil reactions on the disk were resolved into three directional components; draft (horizontal force), vertical reaction force upward and downward, and side force. He noted that the largest variation in soil reactions on the disk were due to the soil types and soil properties. Other important findings of this study can be summarized briefly:

- Minimum draft was observed at a disk angle of 45 degrees. Increasing values of this angle caused steep increases in draft.
- Doubling the forward speed from 4 km/h (2.5 mph) to 8 km/h (5 mph) in sandy loam soil increased the draft by % 67.
- As the disk concavity increased, the draft and upward thrust of the soil increased.
- Increases in disk angle settings had an effect of improving soil penetration and reducing the upward thrust.

Harrison and Reed (1962) studied the forces on tillage equipment at different depths and speeds in the field and determined the power requirement for different working conditions. These data are useful in selecting and using tillage equipment in connection with different sizes of tractors.

In a study by Gill et al. (1980), the effect of geometric parameters on disk forces was investigated. They studied on three disk shapes and three sizes. The results of the work confirmed that optimum harrow design and operating conditions are influenced by disk blade geometry. Both the conical and Spherical II (a compound spherical disk with two distinct radii of curvature) had lower forces than did the more commonly used Spherical I disks. Increases in draft caused by increases in forward speed are essentially linear.

McCreery and Nichols (1956) also studied the geometry of disks and soil relationships. They reported that the convex side of the disk had created a greater soil compaction at small disk angles. Some concepts on disk implements were explained in detail. The back surface of a disk is named the bearing area of the disk which resists against penetration. For a lower draft and better penetration, the bearing area of a disk must be minimized. On the other hand, the concave side of a disk is known to be the pressure area which overcomes the soil. The application of pressure against the soil causes the soil to rupture and pulverize.

Both the bearing and pressure areas depend on disk diameter, tillage depth and disk angle. It is possible to reduce the bearing area by choosing smaller diameters, or decreasing the working depth or increasing the disk angle.

Related to this issue, Gill et al. (1981) reported the influence of disk curvature on soil penetration. Their conclusion was that increases in the radius of curvature while selecting the proper disk angle and mass had a significant effect on penetration. They found that reducing the force acting on the back surface of a disk by increasing the radius of curvature or increasing the disk angle in a range of 11.5 degrees to 20 degrees, or both at the same time, caused a reduction in the draft and vertical forces.

Improving disk penetration is an important point for developing lighter disk plows that might penetrate to the desired depths without adding weights. The lighter tillers are of particular interest from the standpoint of the development of powered disk tillers, improvement of fuel economy, reduction in soil compaction and control of depth.

Taylor (1967) also reported a study on field measurement of forces and moments on Wheatland plow disks and summarized that the performance of a plow would be radically affected by the disk angle-furrow width relationship, the selected tilt angle and the speed at which it operated.

2.2 Power Disks

Soehne (1963) studied the work quality of both conventional and powered disk plows. His observations indicated that the powered disk caused more soil pulverization where the conventional plow caused large clods in the field. While mentioning the advantage of the single pass of the powered disk, he warned of possible destruction of soil structure by rigorous action of it. In terms of power requirements, he reported that:

- Increasing the disk peripheral velocity versus ground speed with a ratio of 1.3-1.5 reduced the drawbar pull by 30% and increased total power requirement by 120%.

- Doubling the disk speed double reduced the draft to half, however, then the total power requirement increased to 170%.
- As the disk speed increases, the side and vertical forces become larger.
- When compared to the free rolling disk, the high power requirement, the relatively low reduction in draft, the difficulties involved in design and high costs, the development of the power disk could not be justified.

Abernathy (1976) also reached the same conclusion after the laboratory tests on a self-powered disk. He reported that using powered disks could reduce draft by 20%, but the total power requirement was three to six times greater than that of free rolling disks.

Tembo (1986) studied a power take-off (PTO) driven disk tiller for performance evaluation. He conducted field tests to determine the drawbar power, PTO power and total power requirements of the disk tiller. When 90% of total power was transferred through the PTO shaft and 10% of total power was obtained through the traction to the implement, a 30% savings in energy utilization was achieved at a peripheral disk velocity to ground speed (pdv/gs) ratio of 2.5. He also reported that no energy savings were observed at higher peripheral disk velocities as total specific power increased with increases in peripheral disk velocity.

The use of hydraulic power in agricultural machinery instead of mechanical power transmission has been studied by few researchers to compare the power transmission efficiency and safety of mechanical and hydraulic systems.

In this respect, Young (1975) carried out field tests to evaluate the performance of a hydraulic powered disk implement. DynaTil was a tandem disk harrow designed for only investigating the future of powering disks. The reason was that the on-the-go adjustability of gang speed and gang angle would provide farmers with greater control by allowing them to vary the degree of tillage to fit field conditions. Today, this issue is very important in terms of precision farming. As GPS (global positioning system) on machinery becomes more prevalent in agriculture, the automation and integration of such tillage equipment will be inevitable.

Input power was provided from the tractor 1000 rpm PTO drive shaft into two hydraulic pumps placed on the DynaTil. The pumps were variable displacement and pressure compensated with capabilities of 151.4 l/min (40gpm) each at 13790 kPa (2000 psi). Flow from the pumps was directed to flow dividers which divided and directed the hydraulic fluid to four hydraulic motors, one on each disk gang. The peripheral disk speed was the main test variable and was set by a flow controller located at the tractor cab. The gang angle was controlled from the tractor hydraulic system connected to a hydraulic cylinder in the gang angling mechanism.

The subjective evaluation of field performance showed more cutting and mixing of mulch with the soil, more soil pulverization, more control of degree of residue incorporation and soil pulverization by adjustments of gang angle and gang speed, the ability to work in heavy mulch residues at high gang angles. Field comparisons were also made of the DynaTil operating powered vs. non-powered. The difference between the powered and non-powered was very evident during the spring of 1975 testwork where the powered machine did a much better job of tearing apart sod. In one of the test fields he found that the horsepower requirements of the DynaTil powered were less than non-powered implements. In others, the DynaTil powered required less horsepower up to a certain forward speed. Another area of interest was the tractor slippage. Operating powered reduced the slippage 7% in one test field and 4% in another.

Shearer, et al. (1993) developed an open circuit, fluid power drive for the purpose of providing an alternative method for transmitting and controlling power by replacing the mechanical PTO drive of a large baler. They reported hydraulic drive design considerations related to this application and field trial data. Their investigation concluded that a hydraulically driven system could provide the required power up to 25 kW (34 Hp) to the baler with safety, protect the machinery against overloads and easily reverse the baler mechanisms when plugging occurs. They also mentioned that there were some inefficiencies in the hydraulic circuit sufficient to require an additional oil cooler to maintain a reasonable reservoir temperature.

2.3 Instrumentation

Measurements of the average draft required by the tillage equipment and other pertinent parameters are necessary in research in order to determine the equipment efficiency and loading, and develop more efficient machinery. The exact and simultaneous determination and the record of measurements related to a study can be achieved by only using a well adapted instrumentation.

The data acquisition systems utilized in soil-engaging implement research are usually designed to measure average draft, forward speed, disk speed, slip, engine speed, fuel consumption, working depth, etc.

Most of the instrumentation that early researchers used was mechanical and only able to monitor the variables of operation coarsely. Later some photographic means to get simultaneous readings of the pressure gauges and pen recordings were implemented for draft measurements. Clyde (1936,1939) developed and used such techniques in his tillage meter method using a hydraulic dynamometer for force determination.

For the last few decades, microcomputers have been used in agricultural machinery for the acquisition and processing of the tractor-equipment performance data. Numerous tractor monitoring and data acquisition systems have been developed and reported during the 1980 and early 1990s.

Carter (1981) developed an instrumentation system for a subsoil tool to measure average draft by implementing strain gages.

Grevis et al. (1983) developed a low-cost, versatile microcomputer based data acquisition system for tractor performance variables. The system measured drawbar pull and power, ground speed, wheel slip, fuel flow and engine speed and provided for printing these variables as well as recording on magnetic tape.

Tembo (1986) reported the use of an Apple IIe microcomputer and a 16 channel 12-bit AI13 A/D converter for the collection and analysis of data in field. The parameters measured included horizontal and vertical force components for draft power calculation, PTO speed and torque, ground speed by a radar speed sensor, right side front and rear wheel speeds for slip determination. The same PC and A/D converter was used in other research done by Mah (1990) and Mungai (1991) with some modifications depending on the variables needed.

Watts et al. (1989) reported a mobile instrumentation and data processing system for testing cultivation equipment. The tractor three-point linkage and drawbar forces, PTO speed and torque, forward speed, wheel slip, fuel flow and depth of work were measured and then the data from the pertinent transducers were passed via a telemetry link to a location where they were recorded and processed by an on-board computer driven by specially written programs.

A portable instrumentation system developed by Thomson et al. (1989) was used to measure draft and speed when using either pull type or three point hitch mounted tillage implements. They measured horizontal and vertical draft, true ground speed and drive wheel speed. A compact and portable datalogger was utilized for data collection. It also provided strain gage load cells with 5 Vdc excitation voltage. Later the data collected was transferred to a microcomputer via a magnetic cassette tape for further processing.

Graham et al. (1990) reported an acquisition system mounted on a tractor, which was designed to measure drawbar pull, true ground speed, and wheel slippage while pulling farm implements. Major components of the system consisted of a datalogger, a hydraulic drawbar dynamometer, and a radar-based ground speed sensor.

Lackas et al. (1991) developed a portable data acquisition system using a laptop computer for monitoring the performance of pull-type soil-engaging implements during field operation. They measured the horizontal and vertical forces exerted by the implement and ground speed. A computer program written in BASIC was used to open communications between the laptop and the A/D (Analog to Digital) unit, to send commands to initiate data transfer, collection and analyze the data.

Chapter 3

EQUIPMENT

3.1 Power Disk and Hydraulic System Components:

The disk used in this study was a 660mm (26") in diameter, 6.4 mm (0.25") thick, 587 mm (23.125") in spherical radius, 102mm (4") concavity. The rotating disk mounted on a frame was attached to the tractor 3-point hitch in the normal manner.

It was designed and built as a single unit powered disk after modifying a disk plow with two disk blades. The scraper on the original disk was removed. The disk and tilt angles were kept the same. Tilt angle was not adjustable on the original plow. The disk angle and the tilt angle were measured to be 45 and 15 degrees, respectively. The disk was placed to the center line of the old frame with its original shank. The rear furrow wheel was removed for better determination of the hydraulic power effect on draft by avoiding its interference with the vertical and side forces acting on the disk equipment.

Depth of working was controlled by lowering or raising the whole frame by means of the tractor hydraulic system in position control mode. Also to give better depth control, a support wheel running on the unplowed land was mounted to the mid-left of the machine frame.

The power disk with the hydraulic system components is shown in Figure 3.1.1. Figure 3.1.2 shows field operation of the disk.

Figure 3.1.1 Hydraulic Torque Assisted Disk Implement

Figure 3.1.2 The Power Disk in Operation

The disk was powered and controlled by the hydraulic system shown in Figure 3.1.3. The flow control valve (4) and flowmeter (6) are the optional devices used in preliminary tests.

The operation and design criteria of the hydraulic torque assisted system can be explained as follows:

The desired soil displacement operation for a constant speed in powered disk equipment is based on hydraulic torque or pressure applied to the disk. The amount of torque available can be controlled by setting the relief valve.

When the pressure or torque requirement of the disk caused by soil resistance is less than the relief valve setting, the disk will be supplemented hydraulically to the required amount. While there is minimal soil resistance against the disk rotation in operation, system pressure will never reach the high relief valve settings thus providing the desired soil displacement and disk design speed.

With the relief valve set at low pressures, the torque to be applied will be limited up to the relief valve settings. If a resistance higher than the valve setting is seen, increasing pressure will be relieved by flow through the relief valve back to the reservoir.

The disk speed depends on system flow rate. Flow rate can be maintained at the desired level by providing sufficient system pressure to overcome the soil resistance. During the calibration of the disk speed sensor, flow rate was regulated

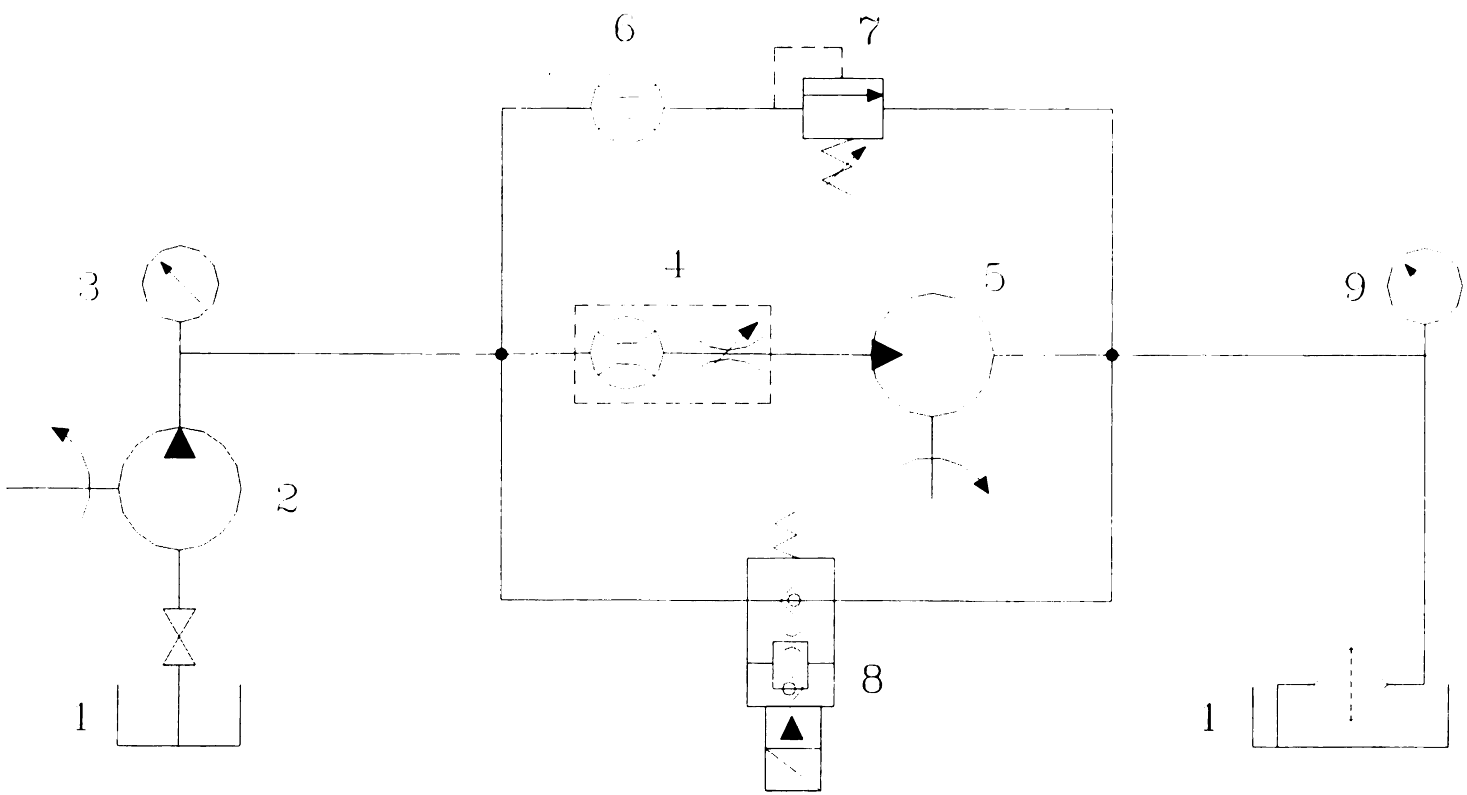

Figure 3.1.3 Hydraulic Circuit Diagram for Power Disk

by tractor engine speed so as to increase PTO pump speed and by the flow control valve located at a point before the motor in the pressure line.

To set the relief valve to a certain maximum pressure for field experiments, the flow control valve to the motor and the solenoid valve were both shut off while the PTO pump was supplying flow, then system pressure was checked by the pressure gage while turning the pressure setting screw on the relief valve. When the desired pressure setting was attained, the flow control valve was opened completely and the solenoid valve was opened or closed based on operation mode selection and the test run was started.

Four maximum pressure settings of 2758, 4137, 6205, and 8274 kPa (400, 600, 900, 1200 psi) were selected to observe the effect of supplemental torque on potential draft reduction. The relief valve was set approximately according to glycerin filled pressure gage readings assuming that they indicate true values.

The detailed information about the hydraulic system components shown in Figure 3.1.3 is given below.

Pump (2)

In the early stages of the research, the tractor's own hydraulic pump was used to power the disk. In preliminary field tests, it was observed that the disk hydraulic system was interrupted by the tractor's hydraulic system while controlling the working depth. Also the tractor hydraulics were not sufficient enough to provide large powers. Therefore, a **Prince HC-PTO Pump** (Model: HC-PTO-2A) was selected as the primary power source, independent from the tractor's hydraulic system.

It was a hydraulic gear pump, specifically designed for PTO drive operation at 540 rpm (design rpm) on agricultural tractors. It provides a flow rate of 43.2 lpm (11.4 gpm) and an input power of 13.5 kW(18.1 Hp) at design rpm. These numbers are based on an operating pressure of 13790 kPa (2000 psi). The required shaft type is 35 mm (1.375") in diameter, 6 tooth. (ASAE S203.13 MAR94)

Suction and return line sizes were 25.4 mm (1") and 12.7 mm (0.5"), respectively. A 100 mesh suction strainer and a 10 micron return line filter were placed in the hydraulic circuit for both proper flow and filtering. Though the minimum recommended reservoir size for the pump was 57 l (15 gal) a 10-gallon size reservoir with 19 l (5 gal) of oil was implemented.

A 280 mm (11") long torque arm and 3.56 kN (800 lb) minimum working strength chain were used as torque arm kit as described in the manual. The chain was fixed to the tractor chassis with two bolts perpendicular to the torque arm.

Disk Drive Motor (5)

To drive the disk, a low speed-high torque **Ross** brand hydraulic wheel motor having a displacement of 327.8 cm^3 (20 in^3) was attached directly to the back of the disk with a custom flange and tang drive. And a custom made coupling was used to couple the motor's shaft to the disk shaft. The support wheel was adjusted to such a level that the motor could not touch the ground surface in the field when in operation.

Relief Valve (7)

A pilot operated relief valve by **Sun Hydraulics** was used to regulate maximum system pressure and limit pressure in the system. A leakproof screw adjusts relief settings between 690 and 20684 kPa (100 and 3000 psi). Care was taken not to overload the hydraulic system beyond 13789 kPa (2000 psi) because the pump used required a relief valve set at or below rated pressure of 15513 kPa (2250 psi). The relief valve was designed for flow rates of up to 94.6 lpm (25 gpm).

Solenoid Valve (8)

A **Parker** brand (Model: DS091ND012LP) cartridge style solenoid valve with a base (Parker model: B09-2-6P) allowing for individual piping of the valve was selected for the hydraulic circuit. This valve was used to pressurize or depressurize the system, for powered and non-powered cases. It is a normally open DC solenoid valve. When the valve is energized, there would be no flow through the valve to the return line and all flow would run through the motor up to the preset system pressure.

3.2 Tractor

The towing tractor used for the power disk was a 1982 Ford model 7610. The maximum net power and maximum PTO power of the tractor are 72.3kW (97 Hp) and 64.2 kW (86 Hp), respectively. The transmission system offered a variety of speeds to meet most working requirements. All speed categories were attained easily by selecting the matching gear for a certain engine speed based on

4-wheel drive. The rear and front tire sizes were 18.4-34.6 and 13.6-24, respectively.

3.3 Instrumentation-Data Acquisition System

Each component of a PC-based data acquisition system is essential for obtaining proper results. Basically, every PC based data acquisition system consists of the elements listed below and illustrated in Figure 3.3.1.

1. Transducers (Sensors)
2. Signal Conditioning Modules
3. Data Acquisition Hardware
4. Data Acquisition Software or Driver
5. The Personal Computer

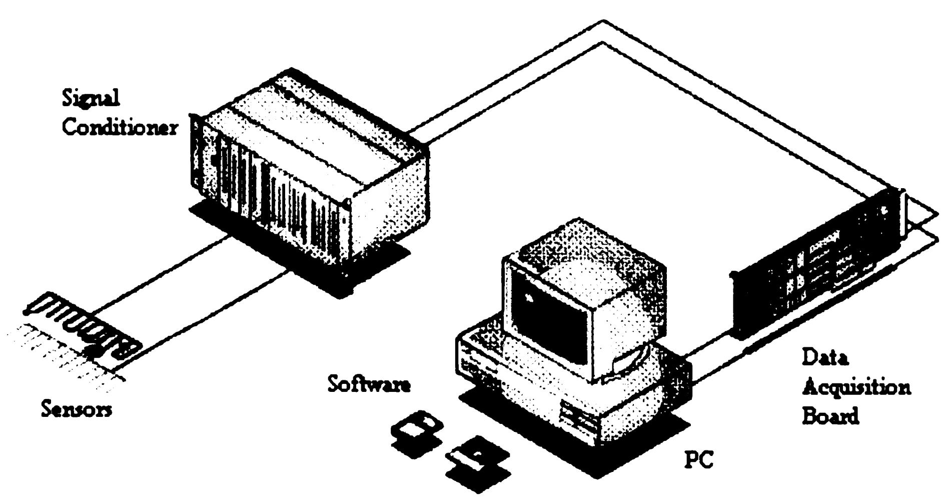

Figure 3.3.1 Elements of a PC-Based Data Acquisition System

The instrumentation system used in this study included an IBM compatible PC, a data acquisition board with 8 channels connected to one of the PC's buses, a signal conditioner chassis with various modules and power supply, two separate individual signal conditioning modules for the pressure sensors, various transducers, a DC to AC voltage converter to energize the PC and signal conditioner, an accessory battery, and different size cables and wires. All of these components, except the sensors, were placed inside the tractor cab, paying attention not to disturb the tractor driver during operation.

The instrumentation system was reassembled first in the Fall of 1996 after Mungai (1991) and finalized in the Summer 1997 following some modifications to the disk speed sensor. The same signal conditioner, rear wheel speed sensor and strain gages were utilized and tested in other studies in conjunction with Tembo (1986) and Mah (1990). Since the earlier strain gage circuits were designed to measure horizontal and vertical components of draft and moments, the strain gage covers were removed to find out which ones measured the horizontal draft component.

After the inspection of the circuits, the bridges intended for the measurement of horizontal force components were also verified during the calibration of sensors. The front wheel speed sensor used before was removed and mounted to the back of the disk as the disk speed sensor.

The instrumentation system will be described in two sections, sensors and data acquisition hardware. Calibration of the sensors will also be explained under sensors.

3.3.1 Transducers (Sensors)

Main parameters needed for the performance evaluation of the power disk were hydraulic pressure drop, draft, ground speed and disk speed. Therefore, strain gages, pressure, and speed sensors were used to quantify these variables. Each transducer sensed the related physical phenomena and produced electrical signals that the data acquisition hardware could accept. The electrical signals produced were inherently proportional to the physical parameter monitored. Draft forces, speeds of the disk and rear wheel, and in and out pressures were converted into analog signals that an A/D converter can measure. Then, the calibration response equations were developed by performing linear regression procedure. The resulting calibration equations and coefficients of determination for the sensors are shown in Table 3.3.1.

Each of the transducers will be described as follows.

3.3.1.1 Pressure Sensors for Measurement of Hydraulic Pressure Drop

The hydraulic system used two pressure-to-voltage transducers for measuring both the pressure line pressure and return line pressure to determine the pressure drop across the disk motor. The transducers (3 and 9) are located in the hydraulic system as shown in Figure 3.1.3.

Channel Number	Variable	Calibration Response Equation	r^2
1	Top Link Force (lbs)	mV = 18.473 + 0.624 * Force	0.9998
2	Right Link Force (lbs)	mV = 49.534 + 0.457 * Force	0.9947
3	Left Link Force (lbs)	mV = 37.730 + 0.499 * Force	0.9982
4	Tractor Rear Wheel Speed as Ground Speed (rpm)	mV = 14.885 + 59.724 * rpm	0.9996
5	Disk Speed (rpm)	mV = 25.772 + 23.908 * rpm	0.9995
6	Pressure In (psi)	mV = (Pressure / 0.3) + 200	-
7	Pressure Out (psi)	mV = (Pressure / 0.3) + 200	-

Table 3.3.1 Calibration Response Equations and Coefficients of Determination

In terms of calibration of these two sensors, since both had already been calibrated and used before in other studies in the Agricultural Engineering laboratory, the calibration equations obtained previously were accepted as they were. The calibration equations for the pressure transducers are given in Table 3.3.1 and specifications of the transducers are presented in Appendix B. As mentioned previously, two glycerin filled pressure gages were also added to the system so that it would be possible to set the relief valve to any desired pressure and directly monitor the operation.

3.3.1.2 Draft Measurement

Determination of draft is the most important part for the evaluation of the power disk as well as of other soil-engaging implements. Draft components are defined to be horizontal forces acting on two lower links and the top link. Draft power for a certain case was then calculated by multiplying the forward speed by draft. Measurement of vertical forces on lower links was neglected in this study.

The strain gages were utilized to quantify the above draft force components on the three point links. The application of strain gages was performed and described by Tembo (1986) as follows:

The lower link ends which were custom made hitching members bolted to the original lower links were machined to uniform thickness and width at the hitch points to facilitate the application of strain gages. Strain gages were cemented on the machined surfaces. The top link was cleaned at mid-position and strain gages were placed to respond to compressive and tensile forces only.

Certainly a great care was taken while installing these transducers to eliminate possible damages and to maximize sensitivity, direction and location of gages.

Four strain gages (Micro Measurement, EA-XX-125PC-350) with 350 Ohm resistance established the Wheatstone bridge circuit for each of the draft components measured. The Wheatstone bridge and its connection to the signal conditioner module are illustrated in Figure 3.3.1.2.1. Excitation voltage was 10 volts and provided by the signal conditioner power supply. The special protective coating system was preserved to avoid physical damages and water penetration. The low level signals from the strain gages were transmitted to the M1060 signal conditioning module through a five-conductor shielded cable.

Since the true and exact determination of draft depends on the true calibration of strain gages, great care must be taken during the calibration. The calibration of strain gages was carried out twice, one in the Fall of 1996 and the other in the Summer of 1997. The latter was considered the final calibration and the data taken were used to develop the regression equations for force determination. However, the data collected in both calibrations were very close to each other. A detailed description of calibration process is given as follows:

During calibrations, known longitudinal forces were applied on each link on which strain gages were placed. Tembo (1986) reported that the maximum allowable tensile load on each of the links was found to be 20 kN (4500 lbs), which had been determined from the geometry and material properties of the machined lower links. Considering this finding and expecting maximum working

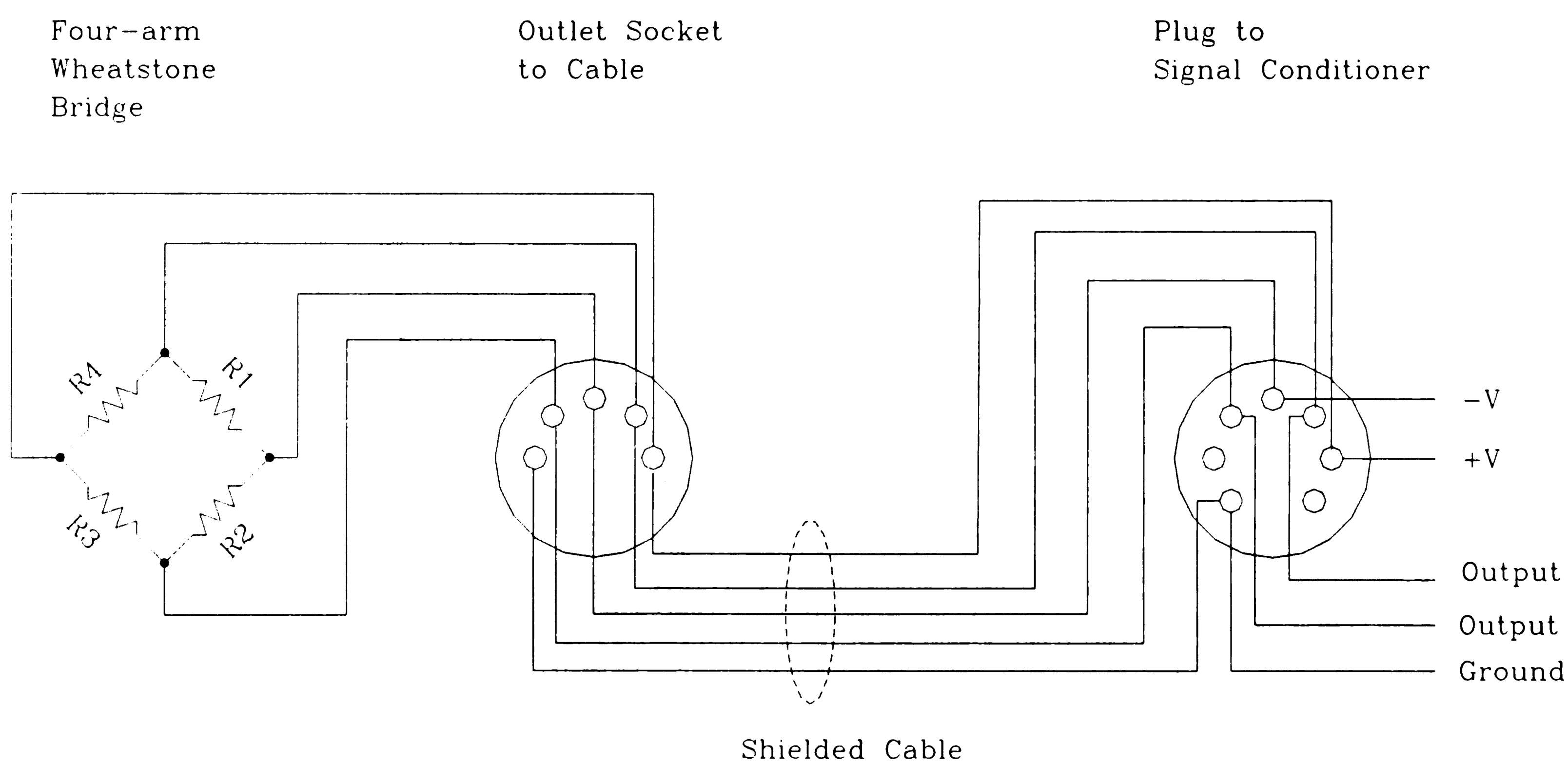

Figure 3.3.1.2.1 Wheatstone Bridge Circuit for Strain Gages

force of 17.8 kN (4000 lbs), lower links were loaded up to 17.8 kN (4000 lbs) in tension with 2.22 kN (500 lbs) increments. The top link was loaded up to 13.3 kN (3000 lbs) in tension with the above increments The force was applied by retracting a double acting hydraulic cylinder with a load capacity of 45 kN (10116 lbs). A hydraulic tensiometer (by John Chatillon & Sons) with a maximum load of 44.5 kN(10000 lbs) was used to measure the applied force. It was connected in line, between the link and the hydraulic loading unit.

For each loading or known force, the data were taken and saved immediately by means of the data acquisition system. Later, a standard regression analysis of the data was carried out to obtain a linear regression equation that predicts the output response voltage at each loading. The calibration equations developed are presented in Table 3.3.1.

After all transducers had been determined to be linear in their response, strain gage response under compressive loading was assumed to be as linear as in tensile loading.

3.3.1.3 Disk Speed Measurement

The sensor was to be capable of withstanding exposure to oil, dust and rough handling because of its location. Therefore, a magnetic pickup sensor (inductive proximity switch) manufactured by **Wabash Inc.** was selected and used to measure the instantaneous rotational speed of the disk.

A custom-made sprocket having 30 teeth was implemented to generate frequency output proportional to the disk speed. The frequency signals produced were sent to the frequency to voltage (F/V) converter module of the signal conditioner. The reason for conversion was that the software driver of the data acquisition board, which was a built-in function created by a driver setup program inside an Excel spreadsheet, could only handle analog signals.

A number of disk speeds were set either by regulating the engine speed so as to increase pump flow or by metering the flow control valve to the hydraulic disk motor. When a certain disk speed was set and verified by tachometer, the data acquisition system was initiated to sample the sensor. The sensor was sampled for each speed setting and the data collected were recorded for the regression analysis of the sensor output. Then, a calibration response equation was developed as shown in Table 3.3.1.

3.3.1.4 Ground Speed Measurement

To measure the rear wheel speed as a base for ground speed determination, a cylindrical magnetic pickup (**Wabash Inc.**) was mounted on a bracket and positioned near the periphery of the sprocket. The sprocket mounted on the axle hub just inside the right rear wheel. A 1.3mm (0.05") gap was left between the pickup and sprocket teeth surfaces. As the wheel turned, the passing of the sprocket teeth and gaps past the magnetic pickup generated an alternating signal with a frequency proportional to the wheel speed.

The frequency signal produced was sent to the signal conditioner and processed by the M1080 Frequency to Voltage (F/V) module, and the analog voltage obtained was supplied to the related channel of the A/D converter located in the PC bay.

3.3.2 Signal Conditioning Modules

The electrical signals generated by the transducers must be converted into a form that the data acquisition board can accept. Amplification is the most common signal conditioning process. Low-level strain gage or pressure transducer signals should be amplified to increase the measurement resolution. For the best resolution. the signal should be amplified so that the maximum voltage swing equals the maximum input range of the A/D converter.

In addition, by placing the amplifier close to the transducer, interference from noise picked up on the lines between the transducer and the computer is minimized. This minimization occurs because the signal has already been amplified before it travels across the lines to the computer. However, in mobile applications like in this research, signal conditioners need to be kept in tractor cabs due to harsh working conditions.

Two different signal conditioning modules were used for analog signal amplifications. Since the pressure transducers had come with their pre-established signal conditioning modules, only three modules of the 24-channel signal conditioner were used for strain gage signal amplifications. Signal conditioning modules also produced excitation for strain gages and pressure transducers, which require external signal sources.

3.3.3 Data Acquisition (Computer Interface) Hardware

A data acquisition or computer interface system is a device that allows the user to feed data from the real world to a computer. In this research, a PC-based data acquisition system was used to monitor and record the signals produced by the sensors. The data acquisition system utilized had only 8 channel inputs. There were 7 sensors used on the power disk system to monitor the required variables mentioned earlier. The signal from each sensor was sent to one of the 8 channels of the A/D converter after signal conditioning or frequency to analog converting processes.

The A/D converter was a plug-in computer data acquisition card, the PIE-137 system (by **P. I. Engineering Inc.**, Williamston, Michigan). It was installed directly on one of the PC's serial buses within the computer case. Advantages of such cards are speed and cost because they are connected directly to the bus, and they do not need extra packaging and external power.

It uses a 12-bit converter with a maximum conversion rate of 66 000 conversions per second. It features 8 channel analog inputs with software selectable ranges between ±0.2 V and ±200 V, and on-board timing.

The plug-in card is designed for the IBM compatible PCs and has a terminal board (a panel named Smart-bay) that attaches it, and that is where all the connections for sensors are made. The Smart-bay panel wired to the plug-in card allows easy access to all 8 channels of input. Each Smart-bay has an onboard microprocessor with its own RAM to handle data acquisition and control functions and RISC processors with two FIFOs to handle the communication to the computer. These processors are used to eliminate the time conflicts and to handle high speed data transfer easily. The standard system connection panel is also a P. I. Engineering product with 8 standard 6 wire RJ11 (modular telephone style) sockets.

Each socket has :

1. One Analog line (+)
2. One Analog Return line(-)
3. One Control and Power Ground line (fused ground)
4. One diode protected and current limited Power line
5. One Digital Input line (IN)
6. One Digital Control line (OUT)

The PIE-137 system is supplied with driver software that works under Windows, providing the user with the options needed for basic applications. The details of the software will be explained in Section 3.3.4.

The sampling rate was selected at 25 Hz (samples per second) after considering the test run lengths and data accumulation during each run. This selection was in a range that most tillage research had been done. This rate was also considered to be enough for the representation of the field work because the field conditions and other measured variables do not change rapidly within the selected working ranges.

The theoretical resolution of a A/D converter is equal to the size of the Least Significant Bit (LSB) of the converter. This is the smallest quantity of voltage that the A/D converter can detect. It is determined by dividing the full scale range by 2 raised to the power which equals the number of bits in the A/D converter.

The full scale ranges used in this study were ±6 V (12 V) for strain gages and speed sensors, and ±10 V (20 V) for the pressure transducers. These ranges were chosen in order to match the input signal's range to the board's signal range to take best advantage of the resolution available to accurately measure the signal. The theoretical resolutions with the 12-bit converter used were 2.93 mV and 4.88 mV for the ±6 V and ±10 V ranges, respectively. These resolutions were considered to be offering very accurate digital representation of the analog signals interested. Information lost in the conversions was also considered negligible for this type of research.

3.3.4 Data Acquisition Software for Analysis and Monitoring

Software is one of the PC-based data acquisition elements that must be examined closely. Because plug-in data acquisition boards do not have displays, the software is the only interface the user has to the system. The software is the component that controls the system. The software integrates the transducers, signal conditioning, and data acquisition hardware into a complete, functional data acquisition system. Therefore, before developing a data acquisition system, the software must be evaluated completely.

The driver software provided by the data acquisition board manufacturer (**P. I. Engineering**) included:

- Simple functions under Visual Basic for Windows with example programs for the user's needs,
- Simple functions as add-ins to the Excel through the Menu bar,
- A voltmeter displaying the analog input of the selected channel,
- A multi channel monitoring utility displaying results after scanning all channels.

From these options, the **Multipoint Voltage** add-in function in the Excel environment was selected for the 7 channel data acquisition in the field. Using Excel for multipoint measurements, up to 8 channels with selectable ranges is very convenient and easy for further analysis of data. During data acquisition, the data is imported directly from the data acquisition hardware to an Excel spreadsheet through special communication software that links the data acquisition card with Excel. No programming skills are required for the control of data acquisition system when the **Multipoint Voltage** add-in function in Excel is used. This function is enough for every application unless a digital input is measured. If there are any frequency or digital inputs to measure, these signals must be converted to analog signals by means of a signal conditioning module then directed to the computer interface sockets.

Alternatively, some simple functions provided by the manufacturer for any control program which might be developed under Visual Basic would be used to control the data acquisition process. For such custom applications, users have to write their own software in standard programming languages. The programming language that is used must be able to write to and read data from the data acquisition board plugged into the computer.

Data acquisition software provided removed the low-level hardware programming details and gave the user high-level function calls that could be used with conventional programming languages.

3.3.5 Personal Computer (PC)

The data acquisition computer was an IBM compatible, 486-DX2/66-MHz computer with a user-friendly Windows3.1 interface. Microsoft Office's Excel, Visual Basic and the data acquisition board driver were already set up and ready to use for a complete data collection and analysis.

The A/D system was a 12-bit system as described in detail in Section 3.3.3. The same computer was used during the calibration of the sensors. The power source for the PC was a 12 Vdc-120Vac, 60Hz, 500 Watt voltage converter (**Venner Corp.**, Ohio, Model: 20-500).

Generally, the processing capabilities of the PCs have increased to a level at which they have plenty of computational power for most data acquisition and analysis applications. The PC microprocessor used was also capable of processing data fast enough to respond to the real-world signals.

While working with a PC based data acquisition system, the limiting factor for collecting large amounts of data is often the hard disk. Therefore, it was ensured that there was sufficient free disk space to hold the data before performing any acquisition.

Chapter 4

FIELD PROCEDURES

4.1 Test Field and Soil Properties

The tests were conducted on a Michigan State University farm, in the field adjacent to the Clinical Center. All data from tests were taken on the same day, July 28,1997. The soil on the test site was Metea loamy-sand. The field was nearly level and fallow with clover cover. A few lines of compaction were observed in the field probably caused during field operations.

Measurement of soil cone index (index of soil strength) was carried out after considering the ASAE Standard S.313.2. A nonstandard penetrometer (manufactured by **Soil Instruments**, Chicago) was used based on complete depth-penetration relationship, and measurements were made to a depth of 127 mm (5") in the test area of the field. The default rod length of the penetrometer was a limiting factor on the penetrations. A depth of 127 mm (5") was considered sufficient enough to represent the soil property. The diameter and base area of the penetrometer were 9.2 mm (0.362") and 67 mm^2 (0.1 in^2), respectively. Forty cone index measurements were taken randomly across the field to determine the average cone index value of the soil.

Soil samples were also collected for the determination of soil moisture content on the test day. Twenty samples were taken randomly to a depth of 203 mm (8") and immediately put into sealed plastic containers to avoid any moisture loss. The soil moisture samples were weighed before drying. They were dried in an oven at 105 °C for 24 hours and the moisture content was determined after measuring each dried soil sample weight.

The average values, standard deviations, maximum values, and minimum values of both cone index and moisture content are presented in Table 4.1.1.

Table 4.1.1 Soil Properties of Test Field for Power Disk Study

Soil Property	**Average**	**Std. Dev.**	**Maximum**	**Minimum**
Cone Index (kPa)	4920	1410	7580	2410
Moisture Content (%, dry base)	10.4	1.2	12.3	8.2

There are several consequences of both the variability and the method of the above measurements. First, the cone index and the soil moisture content were assumed to be the average value representing the whole field. Second, the maximum value of force during penetration of the instrument was recorded regardless of whether that maximum value was reached at the top, middle, or bottom of the 127 mm (5") stroke.

In addition to the 7 variables monitored by the data acquisition system, the average tillage width and depth of the randomly selected furrows were measured and determined to be 438 mm (17.25") and 197 mm (7.75"), respectively. They were approximately fixed all over the field because the depth of working was controlled by the support wheel running on the unplowed ground and the disk angle was kept the same during the test runs.

4.2 Method of Data Collection in the Field

This section describes the procedures used in the field to collect data.

4.2.1 Repetitions

Each test run required approximately 120 seconds to complete the data set. Three repetitions of each variation under power or unpower conditions were recorded.

The tractor driver initiated the data collection once a steady-state was reached at the start of each run. Another individual switched the solenoid valve on and off for 20 second periods to simulate power-unpower conditions. During the data acquisition, the process was also monitored by the tractor driver for any possible errors that might occur.

4.2.2 Varying Ground Speeds

To observe the effect of different forward speeds, three different speeds were used. The ground speeds under test were approximately 0.5, 1.0, and 1.5 m/sec (1.12, 2.24, and 3.36 mph). The respective gears were Low1, Low2, and Low3. The selected speeds were established based on 4-wheel drive at 2100 rpm tractor engine speed.

4.2.3 Varying Pressure Relief Valve Settings

Four different relief valve pressure settings, 2758, 4137, 6205, and 8274 kPa (400, 600, 900 and 1200 psi), were accommodated by adjusting the hexagonal screw and verifying them by looking at the pressure gages. Once a pressure level was set up, it was kept constant for different ground speeds.

4.2.4 Data Acquisition and Sampling Frequency

As mentioned in detail earlier, a program provided by the data acquisition card manufacturer, which is an add-ins function inside Excel, was directly used in the data acquisition. With this version of Excel, it was possible to store 16384 rows of data for each run. Considering sampling rate (frequency) of the system, it was a very good data storage environment as well as a proper place for signal processing.

The program, **Multi-Point Voltage** function under Excel, was activated by selecting this function under the **Signal + Control** menu. Then, the channels for the sensors and their bipolar voltage ranges were selected appropriately as well as the data acquisition frequency and the required time for sampling.

As soon as the system was ready for data collection, the test run was started. When steady-state was reached after a buffer zone, the Enter key was depressed to run the whole data acquisition system. The screen was updated by selected periods for checking the system operation by a cell in the upper left corner of spreadsheet updating the data quantity.

A sampling frequency of 25 Hz was selected because it was sufficient for tillage data collection and proper for storing data. This frequency provided good resolution of data points per distance traveled in the field, especially at slow speeds.

4.2.5 Data Storage

After each test run in the field, the data collected was immediately stored in individual Excel files on the hard drive of the PC along with the information related to the settings of variables and the field conditions. The data files were also copied on floppy disks for any unexpected failure of the hard disk drive and for further analysis of the data in higher technology computers in the office (off-line).

Chapter 5

RESULTS AND DISCUSSION

A power (hydraulic assisted) disk implement with a single disk was designed and fabricated in order to conduct experimental studies in the field. A PC based data acquisition system having sensors was implemented to measure and record the pertinent variables instantaneously. The influence of hydraulic torque assist to the disk on draft requirements was determined from the data obtained.

Experiments to determine the effects of this new approach were carried out in an MSU farm field whose properties are presented in Chapter 4. Data specific to the given conditions, settings and situation were obtained and later statistically analyzed for a proper presentation of the research results.

There are some special considerations related to the results of field experiments. These have to be summarized before reporting and interpreting the research results.

1. From the review of literature, it is understood that there are various settings or mechanical design factors affecting draft requirements, such as angle settings of disks, disk dimensions, and the geometry of the tractor-implement attachment. The dimension and angle settings of the disk were considered to be in the optimum range. These geometric settings were kept the same during

the experiments so that it could be possible to highlight only the effect of powering the disk and to eliminate the effect of other factors as much as possible.

2. To be able to apply more hydraulic torque and to observe the effect of it on draft requirements in a broader range, the maximum possible working depth and cutting width were set based on the geometry of the disk and the attached disk motor. Therefore, this application might not be an actual practice performed by farmers.
3. Since the lower links and top link between the tractor and the implement were approximately in parallel with each other and the ground surface while traveling, all strain gage measurements were considered to be due to pure longitudinal forces. The cross sensitivity of the vertical forces on the longitudinal forces was neglected. The calibration response equations of the horizontal forces did not include the vertical axis response voltages (cross sensitivity).
4. The forward speed of the tractor was measured only by means of the speed sensor-sprocket system placed on the right rear wheel. Slip was assumed to be negligible for this tractor-disk implement match because of the ratio of available power by tractor and the draft power required by the disk.
5. System flow rate used in hydraulic power calculations was determined based on the motor displacement and disk speed measured by the speed sensor.

6. In terms of soil condition, the average field cone index was found to be relatively high and it varied a lot even in a very short distance over the field.

5.1 Power Disk

The powered disk implement was designed only to test some concepts regarding hydraulic power applications on agricultural machines. It was intended that a basic disk implement would be fabricated only for experiments in the field and then the possibility of applying this technique on other disk equipment would be sought if significant improvements were achieved. Because of conflicts and doubts about the justification of powered disks from the previous studies on powering disk implements, this concept had to be verified whether the powered system works and it is practical.

Some shortcomings regarding only the hydraulic components and body of the machine were observed during preliminary experiments in the field and later they were modified step by step for more reliable performance, as mentioned previously.

The hydraulic pressure relief valve was very helpful while regulating system pressure and provided the desired pressure settings. It was capable of adjusting system pressure up to 20680 kPa (3000 psi) with 690 kPa (100 psi) increments. However, the maximum system pressure required in the field was determined to be around 6900 kPa (1000 psi).

The solenoid valve was activated manually by an on-off switch for certain periods of time. The line on which the solenoid valve was placed was used to bypass flow so that the disk could be set to nonpowered. This method was an easy way of controlling or directing fluid flow to obtain the power and non-powered modes.

No leakage or contamination was observed from the hydraulic system components under very harsh and dirty field conditions. It can be stated that it is technically feasible to apply hydraulic power and control techniques on soil-engaging agricultural implements with safety.

5.2 Data Acquisition System and Sensors

Accuracy in measurements is very important in any research since every finding or conclusion depends on the data obtained by the data acquisition system. Each variable must be measured with acceptable accuracy and reliability. Therefore, the sensors used in this study, except the two pressure transducers, were subjected to certain calibration procedures under laboratory conditions and their accuracy was determined. For the pressure transducers, the previous calibration response equations determined by the Agricultural Engineering Department were used.

One of the proximity sensors used to determine the disk speed malfunctioned. After a long inspection of connections to that sensor considering the other potential noise sources, it was detected that the sensor was producing weak signals. This problem was eliminated after replacing that sensor by another sensor producing stronger signals.

The calibration response equations developed and the coefficient of determination (r^2) values of the measured parameters are listed in Table 3.3.1. The measured load exhibited excellent agreement with the applied load for each sensor. The coefficient of determination (r^2) approached 1.000 for all calibration equations.

All sensors were essentially found to be linear in their responses to known applied loads under laboratory conditions. The hysteresis effect on the strain gages while loading and unloading was found insignificant for all three strain gage bridges on the links.

The PC with the data acquisition card in the tractor cab was able to monitor and record the conditioned analog voltages generated by sensors. While performing each test run, the data being collected was monitored for any possible failure. Despite the harsh and dusty environment in the field, neither the PC with data acquisition board nor the signal conditioner failed during operation.

The data acquisition system developed can be considered a portable system because it can be easily moved to other tractors. As the microcomputer technology improves quickly, new and affordable laptop computers will become available in the market. The use of laptops will soon replace the cumbersome PCs with monitors and the required power converters.

5.3 Main Concepts for Evaluation of Hydraulic Torque Assisted Disk

The detailed evaluation of main concepts are based on average values of measured variables. The complete statistical analysis of data sets for each run are shown in Appendix C. Equations for the calculation of parameters, such as disk speed, draft power, hydraulic rotary power, are listed in Appendix A. Two sample graphs prepared from the conditioned raw voltage data are shown as in Appendix D.

The main concepts analyzed are 1) Draft Ratio versus Hydraulic Torque Assist, 2) Ratio of Disk Speed-Ground Speed versus Torque, 3) Specific Power Requirements of the Disk Implement.

5.3.1 Draft Ratio versus Hydraulic Torque Assist

The most important objective of this research was to determine the real effect of powering the disk implement on draft requirements. All energy saving related studies regarding soil-engaging implements were concerned about reducing the draft. For this purpose, most workers tried to implement rotary power by mechanical means or to apply vibration to the active working blade. The previous papers reported conflicting results regarding the draft reduction when disks were powered.

In this study, a hydraulic power transmission technique that provides the required supplemental hydraulic torque was studied. The amount of torque available to the disk was set as a variable and limited by the relief valve at low pressure settings. In previous experiments reviewed in Chapter 2, the speed of disks were controlled by means of gear reduction units for a constant disk speed. Therefore, the disks were rotating at a prefixed RPM and the torque to be applied was dependent on the soil resistance against the machine during forward motion.

In this research the PTO pump provided flow depending on the preset engine speed. The relief valve was on standby and it was bypassing overflow when needed by reducing excessive system pressure down to the preset pressure settings. Meanwhile, there was some loss in the disk speed because the bypassed flow rate reduced the flow rate passing through the motor. Therefore, there was always fluctuations on the disk motor speed at low relief valve settings.

When the relief valve was set to 8274 kPa (1200 psi), the system pressure on average never reached that value. All flow was passing through the disk motor providing quite constant disk speed. Such high pressure relief valve setting is the design working setting for maintaining constant disk speed and avoiding the inefficiency due to relieved flow rate through the relief valve.

Each test run included both powered and non-powered working conditions for comparison of the two operation modes. The hydraulic system was alternately powered and unpowered every 20 seconds for 3 replications. The experimental data was collected for 3 different ground speeds at 4 various pressure relief valve settings and the draft ratios were obtained after the draft calculations. The term of draft ratio is defined as the draft measured in powered mode divided by the draft measured in non-powered mode. The draft ratios indicated how much draft power reduction was achieved for the selected variable settings.

The acquired data sets showing the relationship between the draft ratio and hydraulic torque occurring for the three forward speeds are presented in Figure 5.3.1.1.

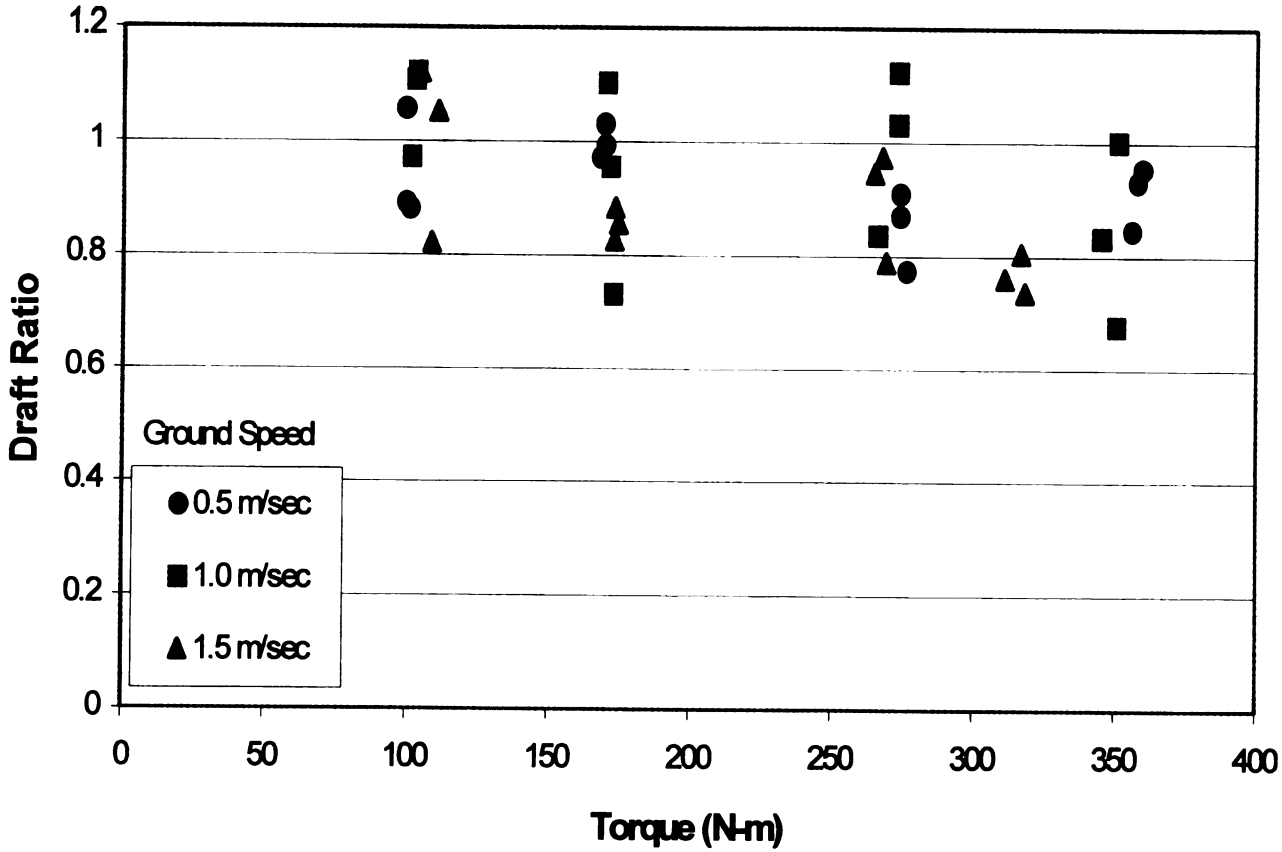

Figure 5.3.1.1 Draft Ratio versus Torque for Different Ground Speeds

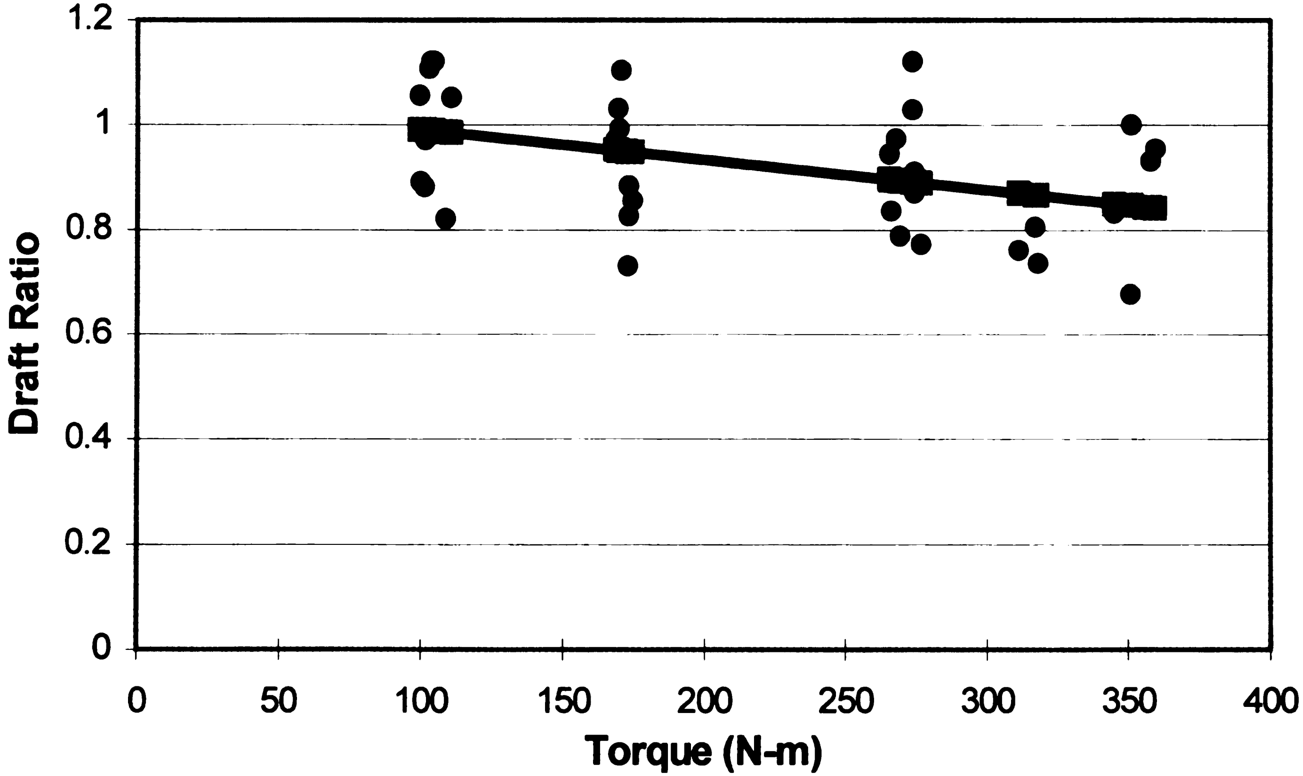

Figure 5.3.1.2 Best-Fit Line of Draft Ratio versus Torque

Ideally when no hydraulic torque is applied to the disk motor, the draft ratios of powered and non-powered modes must be 1 or unity. This means that no pressure drop occurs and the disk is free rolling in either case. As the torque (pressure drop) being applied increases, the draft ratio is expected to change somewhat. Figure 5.3.1.2 illustrates that there is certainly draft reduction with increasing pressure drop. The maximum draft reduction attained in this research was around 15 % and it occurred at the maximum torque or pressure drop. The maximum draft reduction of 15 % is based upon the best fit line shown in Figure 5.3.1.2.

The regression line in Figure 5.3.1.2 has a very poor coefficient of determination (r^2) of 0.18 with scattered data sets of ratios. The scattered data, pointing to a poor relationship, can be explained by the changes in soil resistance during operation. This is because other variables which might affect the ratios, such as ground speed, working depth and width, were determined to be quite constant for all test runs. A more reliable regression line to predict the draft reduction versus hydraulic torque or rotary power could have been established in a test field with more uniform soil properties or in more controlled soil bins under laboratory conditions.

It can be summarized that powering a single disk implement slightly reduces the required draft power but it also often increases the total power required due to supplemental rotary power to the disk. For example, Table 5.3.1.1 shows the total power requirements of powered and non-powered modes for

Table 5.3.1.1 Power Requirements (kW) for Different Ground Speeds at Relief Valve Setting of 8274 kPa (1200 psi)

Operation Mode	Power Component	Ground Speed		
		0.5 m/sec	1 m/sec	1.5 m/sec
Non-powered	Draft	3.62	9.00	13.76
	Rotary	0.07	0.08	0.08
	Total	3.69	9.08	13.84
Powered	Draft	3.73	7.66	10.42
	Rotary	1.22	1.92	2.21
	Total	4.95	9.58	12.63

different ground speeds at the pressure valve setting of 8274 kPa (1200 psi). Total power requirements for 0.5 m/sec (1.12 mph) and 1 m/sec (2.24 mph) increased when the disk was powered. For the ground speed of 1.5 m/sec (3.36 mph), the total power required decreased, but when the relief valve was set to 900 psi at the same ground speed, the total requirement increased. Therefore, as a soil working implement it is impossible to justify powering the disk implement studied in terms of energy savings. If the powered disk is considered to be a potential root crop harvester for the farmers of developing countries, it might perform the required function providing the desired operating speeds and the rotary power.

5.3.2 Ratio of Disk Speed-Ground Speed versus Torque

Change in the ratio of disk peripheral speed and ground speed (V_d/V_{gr}) against the supplemental hydraulic torque applied was another important concept under test. The resulting data for three different ground speeds when the disk was powered are presented in Figure 5.3.2.1, where each data point represents the average of three replications.

The maximum torque occurring during all test runs was found in the neighborhood of 360 N-m (3200 lb-in). The effect of lower torque values on speed ratio might be proportioned to that of the maximum torque applied so that it can be general rule applicable to hydraulically driven disks.

Figure 5.3.2.1 shows that there is almost a linear relationship between speed ratio and supplemental torque applied. Non-powered data sets indicated a speed ratio of approximately 1 for all forward speeds. Therefore, it is expected

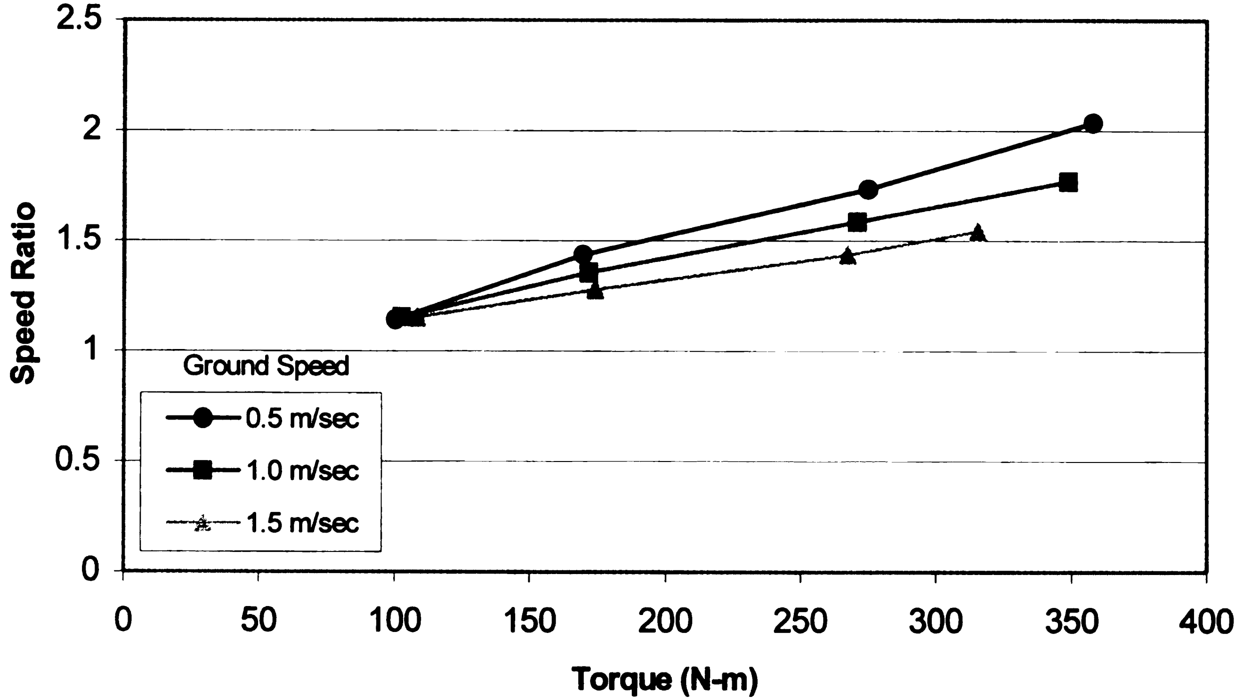

Figure 5.3.2.1 Ratio of Disk Speed-Ground Speed versus Torque

that all speed ratios for different ground speeds converge at 1 when no supplemental torque is applied. In Figure 5.3.2.1, all speed ratios converge at a value of 1.15 when a torque of 100 N-m (888 lb-in) is applied and increase up to the values of 1.54 and 2.04 depending on the forward speeds at the torque values of 316 N-m (2792 lb-in) and 358 N-m (3168 lb-in), respectively. The speed ratios increased linearly for each ground speed depending on the torque applied. At low relief valve settings, load inertia or soil resistance made it impossible to accelerate to full disk speed, so part of the pump output bypassed over the relief valve. Therefore, there had always been power losses at the relief valve settings of 2758, 4137 and 6205 kPa (400, 600, 900 psi).

5.3.3 Specific Power Requirements of the Disk Implement

The performance of disk implements is usually measured in terms of draft, specific draft, power requirements, and depth. In order to provide some practical data for those who are interested in disk implement design, the power requirements of the powered disk used were calculated and discussed below.

Specific draft power for tillage equipment is defined as the power required to manipulate the soil per unit area at a given ground speed. Total specific power for a powered equipment includes both specific draft power and specific rotary power required to displace the soil per unit area. These are the important criteria while comparing different powered disks.

The draft power, rotary power and total power requirements of the disk used in this study are tabulated for different forward speeds and system pressure settings in Appendix C. Using these tables, specific power requirements of the disk implement for each case can be found by dividing the resultant power values by the average cross section of the furrows, which was determined to be approximately 716 cm^2 (111 in^2). This provides a means to compare or estimate the power requirements of such disk implements under different working conditions.

The forward speed is the most influential factor on draft requirements. The tabulated data indicate that as the forward speed increases, the total specific power requirement also increases.

Chapter 6

CONCLUSIONS

The following conclusions were drawn from the results of the research:

1. Disk implement draft as a function of supplemental hydraulic torque changing with the pressure drop across the hydraulic motor can be determined by a PC based data acquisition system.
2. There is a slight relationship between the ratio of power and non-power drafts and the torque applied. The ratios of powered and non-powered drafts were related statistically to the torque required to rotate the disk blade by using the regression analysis in Excel. 75% of the draft ratio data points are observed less than 1, that is, the draft forces become smaller when the disk system is powered. Once the supplemental torque increased to the breakaway torque value, the maximum draft power reduction was achieved by about 15 percent based on the best fit line of regression. However, the supplemental hydraulic power requirements often cancelled the savings of draft reduction.
3. The PC based data acquisition system performed the data collection and storing procedures without any loss or damage despite the harsh and dirty environment. An effective method of measuring rotational speed of the disk was developed using a proximity switch and a custom-made sprocket placed around the disk flange at the back. This might provide a basis for a better understanding of soil handling by disks.

4. The results also show that there is a strong influence of soil variability on the draft data as mentioned in previous studies. Therefore, the test of such disk implements for performance evaluation must be conducted in laboratory soil bins for more reliable results.
5. The nature of the ratio of disk peripheral speed and forward speed, for a powered disk was determined as a function of hydraulic torque in various forward speeds. This parameter was observed to be about 1 when the disk was free rolling without supplemental hydraulic torque.

Chapter 7

RECOMMENDATIONS FOR FUTURE RESEARCH

1. Since the results from the study are not encouraging in terms of savings in energy utilization, the application of vibration techniques together with powering disks might be investigated for much more potential reduction in draft with rational savings.
2. A more reliable comparison method of the disk implement powered and non-powered can be achieved when the disk is powered and non-powered for shorter time intervals. For example, 5 or 10 second interval instead of 20 seconds for each mode can be conducted in order to reduce the influence of soil variation on implement draft.
3. Photographic means to record the work done by the equipment can be implemented for the subjective evaluation of the degree of pulverization and soil displacement. Using these visual records along with the numerical data can provide more reliable interpretation of the machine performance.
4. The influence of the powered disk implement on soil compaction can be determined for a complete evaluation of the powered system.
5. To be able to set more uniform soil conditions by selecting the most appropriate test routes, cone index measurements can be made in the test site before test day.

APPENDICES

APPENDIX A

APPENDIX A

POWERED DISK IMPLEMENT PERFORMANCE EQUATIONS

This appendix presents the performance equations used in calculations and the pertinent dimensions of the powered disk and tractor right rear wheel. All calculations were performed in Excel. The raw voltage data were converted to actual values of the related variables based on the calibration equations developed. Then, statistical analysis of the data was performed and printed in tabular form as shown in Appendix C.

PERFORMANCE EQUATIONS NOMENCLATURE

R	:	Right Link Horizontal Force
L	:	Left Link Horizontal Force
T	:	Top Link Horizontal Force
F_{Net}	:	Net Draft Force
D	:	Disk Diameter
V_{gr}	:	Ground Speed
V_d	:	Peripheral Disk Speed
π	:	3.141592654
V_d/V_{gr}	:	Peripheral Disk Speed to Ground Speed
P_{In}	:	Pressure In to Hydraulic Motor
P_{Out}	:	Pressure Out from Hydraulic Motor
ΔP	:	Pressure Drop across Hydraulic Motor

1. IMPLEMENT DRAFT REQUIREMENT (N):

   DRAFT (kN) $= R\ (i) + L\ (i) + T\ (i)$

   $= F_{Net}$

2. DRAFT POWER (kW):

   DRAFT POWER (kW) $= F_{Net} * V_{gr}$

   $= (\ kN * m/s)$

3. HYDRAULIC ROTARY POWER (kW):

ROTARY POWER (kW) = $[(P_{In} - P_{Out}) * Q] / 60000$

$= (\Delta P * Q) / 60000$

= (kPa * l/min) / 60000

4. TOTAL POWER (kW):

TOTAL POWER (kW) = DRAFT POWER + ROTARY POWER

= (kW)

5. POWERED DISK:

DISK DIAMETER = 660mm

DISK PERIPHERAL SPEED (m/s) = $[RPM * (\pi * D)] / (60*1000)$

$= (rpm*\pi*mm) / (60*1000)$

APPENDIX B

APPENDIX B

SPECIFICATIONS OF SENSORS

Appendix B.1 : Strain Gages for Determination of Draft Forces

Sensor Origin : Micro Measurements (MM) Inc., (EA-XX-125PC-350)

Specification : Four arm 350 Ω full bridge assembly, bonded onto the right and left sides of the lower drawbar links, and at the mid-point of the top link.

Excitation Voltage : 10 volts-dc

Calibration Range for Static Loading:

Right Link Force : 0 to 17.8 kN (4000 lb) with increments of 2.2 kN (500 lb)

Left Link Force : 0 to 17.8 kN (4000 lb) with increments of 2.2 kN (500 lb)

Top Link Force : 0 to 13.3 kN (3000 lb) with increments of 2.2 kN (500 lb)

Appendix B.2 : Strain Gage Amplifier (Signal Conditioner)

Origin : Data Capture Technology Inc.

Specifications :

Input Configuration : High Gain Differential

Input Impedance : 1 MΩ Differential

Input Mode : Resistive bridge in 1, 2 or 4 arm connection with internal bridge completion.

Input Range : Up to 500 mV

Noise : Less than 5 μV r.m.s. at maximum gain

Drift : Less than 2 μV at maximum gain

Bandwidth : DC – 10 kHz

20 – 5000 in switched steps with interpolate control

Voltage Output : Up to ± 2 Vdc

Voltage Output Impedance: 0.5 Ω

Appendix B. 3 : Pressure Transducers for Determination of Pressure Drop

Origin : Basingstoke, England

Series 2000, Transinstruments

Model : 2000 G G H30 02 A10A H04

Range : 20680 kPa (3000 psi)

Output : 0 -10 Vdc

Excitation Voltage : 12.5 - 30 Vdc

3 Cables to transducers : Power(+), Ground (-), Analog Signal (volt)

Appendix B. 4 : Speed Sensors for Determination of Disk and Ground Speeds

Origin : Wabash Inc.

Model : 60-0198"G", Magnetic Pickup (cylindrical pole piece, 2.5 inches reach

Specification : 14 V_{p-p} at 30 inches /sec, 1.3 mm (0.05") air gap

Kernko (Japan) RPM Speed Indicator with special adapters was used as tachometer while calibrating the disk and ground speed sensors. The indicator had a range of 100 - 1000 rpm. For slower tractor rear wheel speeds, a stopwatch was used.

APPENDIX C

APPENDIX C

RESULTS FROM STATISTICAL ANALYSIS

Excel was used for the statistical analysis of the data collected. First, raw voltage values of each variable were converted to actual values. Second, the pertinent conversions required for SI units were performed. Third, the data were statistically analyzed. Last, the results of the statistical analysis were arranged and presented in tabular form on the following pages.

The tractor engine speed for all tests was set to be 2100 rpm. The disk implement was operated in the position control of the tractor hydraulic system.

The headline at each table lists: Test Number, Tractor Gear Selected, Mode (Powered, Non-powered), Relief Valve Pressure Setting.

Test 1-N, Low1, Non-Powered, NA

11-U	AVG	MAX	MIN	ST DEV
Top Compression (kN)	8303.01	14038.96	4059.02	1791.72
Right Draft (kN)	10934.11	16389.22	6360.79	1814.96
Left Draft (kN)	4583.38	8658.93	1203.40	1331.45
Ground Speed (m/sec)	0.58	0.65	0.52	0.03
Disk Speed (m/sec)	0.57	1.96	0.39	0.21
Pressure Drop (kPa)	669.97	806.68	537.79	40.29
Flowrate (l/min)	5.41	18.59	3.72	1.97
Net Draft (kN)	7214.48	11612.31	2895.00	1452.76
Vd/Vgr	0.98	3.32	0.73	0.36
Draft power (kW)	4.20	6.97	1.64	0.88
Rotary power (kW)	0.06	0.21	0.04	0.02
Total power (kW)	4.26	7.04	1.69	0.87

Test 1-P, Low1, Powered, 2758 kPa (400 psi)

11-P	AVG	MAX	MIN	ST DEV
Top Compression (kN)	7153.89	12332.43	3043.75	1578.04
Right Draft (kN)	10319.61	16861.15	6183.82	1781.90
Left Draft (kN)	3691.15	7470.37	203.92	1274.79
Ground Speed (m/sec)	0.58	0.65	0.52	0.03
Disk Speed (m/sec)	0.61	0.98	0.48	0.06
Pressure Drop (kPa)	2582.79	3061.25	2223.54	149.95
Flowrate (l/min)	5.83	9.24	4.59	0.59
Net Draft (kN)	6856.87	11269.92	2927.13	1626.83
Vd/Vgr	1.05	1.61	0.88	0.10
Draft power (kW)	4.00	6.85	1.63	0.98
Rotary power (kW)	0.25	0.40	0.18	0.03
Total power (kW)	4.25	7.13	1.87	0.98

Test 2-N, Low1, Non-Powered, NA

12-U	AVG	MAX	MIN	ST DEV
Top Compression (kN)	7264.07	12526.85	3735.00	1700.68
Right Draft (kN)	8897.20	14000.10	4827.03	1745.73
Left Draft (kN)	2967.40	7119.20	-39.19	1393.47
Ground Speed (m/sec)	0.54	0.62	0.47	0.03
Disk Speed (m/sec)	0.56	0.83	0.41	0.07
Pressure Drop (kPa)	609.04	754.97	496.42	39.82
Flowrate (l/min)	5.26	7.87	3.88	0.67
Net Draft (kN)	4600.52	8748.03	729.81	1538.36
Vd/Vgr	1.04	1.61	0.80	0.12
Draft power (kW)	2.46	4.76	0.39	0.82
Rotary power (kW)	0.05	0.08	0.04	0.01
Total power (kW)	2.52	4.82	0.46	0.82

Test 2-P, Low1, Powered, 4137kPa (600 psi)

12-P	AVG	MAX	MIN	ST DEV
Top Compression (kN)	7073.46	15162.24	3259.76	1623.67
Right Draft (kN)	8751.68	16595.69	5682.40	1756.81
Left Draft (kN)	2653.26	7497.38	-39.19	1093.44
Ground Speed (m/sec)	0.54	0.63	0.46	0.03
Disk Speed (m/sec)	0.71	0.87	0.59	0.04
Pressure Drop (kPa)	3841.69	4550.50	3092.27	293.67
Flowrate (l/min)	6.76	8.20	5.63	0.39
Net Draft (kN)	4331.48	9141.06	1503.49	1397.94
Vd/Vgr	1.33	1.57	1.16	0.06
Draft power (kW)	2.33	5.35	0.80	0.77
Rotary power (kW)	0.43	0.58	0.34	0.04
Total power (kW)	2.76	5.88	1.21	0.77

Test 3-N, Low 1, Non-Powered, NA

13-U	AVG	MAX	MIN	ST DEV
Top Compression (kN)	8999.86	15723.88	4685.47	1953.91
Right Draft (kN)	11320.49	20607.07	7865.06	1990.45
Left Draft (kN)	4602.22	9037.11	176.91	1457.57
Ground Speed (m/sec)	0.55	0.63	0.48	0.03
Disk Speed (m/sec)	0.62	0.81	0.48	0.05
Pressure Drop (kPa)	677.91	1975.33	506.76	94.88
Flowrate (l/min)	5.87	7.66	4.59	0.52
Net Draft (kN)	6922.86	14388.73	2217.57	1618.05
Vd/Vgr	1.12	1.46	0.93	0.09
Draft power (kW)	3.84	7.83	1.30	0.91
Rotary power (kW)	0.07	0.22	0.05	0.01
Total power (kW)	3.90	7.89	1.37	0.91

Test 3-P, Low1, Powered, 6205 kPa (900 psi)

13-P	AVG	MAX	MIN	ST DEV
Top Compression (kN)	7019.88	12159.62	3691.80	1743.28
Right Draft (kN)	9613.16	14265.56	5800.38	1751.60
Left Draft (kN)	3339.29	7632.45	-201.27	1521.61
Ground Speed (m/sec)	0.55	0.63	0.48	0.03
Disk Speed (m/sec)	0.88	1.15	0.68	0.07
Pressure Drop (kPa)	5922.30	8976.90	4498.79	486.17
Flowrate (l/min)	8.35	10.86	6.46	0.68
Net Draft (kN)	5932.57	10497.77	1108.05	1744.94
Vd/Vgr	1.61	2.12	1.34	0.13
Draft power (kW)	3.27	5.96	0.59	0.99
Rotary power (kW)	0.82	1.21	0.57	0.09
Total power (kW)	4.09	6.83	1.47	0.97

Test 4-N, Low1, Non-Powered, NA

14-U	AVG	MAX	MIN	ST DEV
Top Compression (kN)	8378.15	12397.24	5527.93	1118.50
Right Draft (kN)	10805.65	14649.00	8101.02	971.68
Left Draft (kN)	4197.96	6930.11	2256.90	795.12
Ground Speed (m/sec)	0.55	0.63	0.47	0.03
Disk Speed (m/sec)	0.61	0.83	0.48	0.05
Pressure Drop (kPa)	691.35	837.71	558.47	50.15
Flowrate (l/min)	5.74	7.87	4.51	0.49
Net Draft (kN)	6625.46	9596.10	3794.64	941.93
Vd/Vgr	1.11	1.51	0.94	0.07
Draft power (kW)	3.62	5.47	2.08	0.55
Rotary power (kW)	0.07	0.10	0.05	0.01
Total power (kW)	3.69	5.53	2.16	0.55

Test 4-P, Low1, Powered, 8274 kPa (1200 psi)

14-P	AVG	MAX	MIN	ST DEV
Top Compression (kN)	6807.38	18402.48	602.77	2281.12
Right Draft (kN)	10230.57	19486.24	2939.33	2208.22
Left Draft (kN)	3390.33	11171.12	-1903.08	1606.29
Ground Speed (m/sec)	0.55	0.61	0.48	0.03
Disk Speed (m/sec)	1.03	2.96	0.68	0.31
Pressure Drop (kPa)	7517.52	9080.32	5894.97	573.63
Flowrate (l/min)	9.75	28.06	6.42	2.95
Net Draft (kN)	6813.52	12254.89	207.08	1690.70
Vd/Vgr	1.89	5.77	1.28	0.57
Draft power (kW)	3.73	6.64	0.10	0.95
Rotary power (kW)	1.22	4.02	0.74	0.38
Total power (kW)	4.95	9.33	2.02	0.92

Test 5-N, Low 2, Non-Powered, NA

21-U	AVG	MAX	MIN	ST DEV
Top Compression (kN)	8774.87	17257.60	192.34	2236.26
Right Draft (kN)	12232.96	21255.97	2319.92	2606.83
Left Draft (kN)	5276.68	12008.52	-1281.78	1588.06
Ground Speed (m/sec)	1.13	1.21	1.07	0.03
Disk Speed (m/sec)	1.04	1.53	0.86	0.09
Pressure Drop (kPa)	515.14	682.58	372.31	49.57
Flowrate (l/min)	9.84	14.52	8.12	0.87
Net Draft (kN)	8734.76	16627.06	845.80	2043.54
Vd/Vgr	0.92	1.39	0.80	0.08
Draft power (kW)	9.86	18.24	0.94	2.30
Rotary power (kW)	0.08	0.14	0.06	0.01
Total power (kW)	9.94	18.33	1.07	2.30

Test 5-P, Low 2, Powered, 2758 kPa (400 psi)

21-P	AVG	MAX	MIN	ST DEV
Top Compression (kN)	9174.80	20778.66	2417.30	2293.32
Right Draft (kN)	13224.86	22376.79	6213.32	2836.80
Left Draft (kN)	5560.98	13089.03	284.96	1526.71
Ground Speed (m/sec)	1.12	1.19	1.04	0.03
Disk Speed (m/sec)	1.19	2.02	0.91	0.16
Pressure Drop (kPa)	2478.09	2937.14	2120.12	154.37
Flowrate (l/min)	11.30	19.13	8.66	1.54
Net Draft (kN)	9611.04	16866.78	4108.64	2194.90
Vd/Vgr	1.07	1.81	0.84	0.14
Draft power (kW)	10.76	18.79	4.72	2.46
Rotary power (kW)	0.47	0.83	0.33	0.07
Total power (kW)	11.22	19.19	5.11	2.46

Test 6-N, Low 2, Non-Powered, NA

22-U	AVG	MAX	MIN	ST DEV
Top Compression (kN)	9046.34	16458.34	5095.90	1735.23
Right Draft (kN)	11095.15	17775.51	6360.79	2009.84
Left Draft (kN)	4185.61	9172.18	1041.32	1209.47
Ground Speed (m/sec)	1.08	1.17	1.00	0.03
Disk Speed (m/sec)	1.05	1.22	0.88	0.06
Pressure Drop (kPa)	429.09	703.26	289.58	56.24
Flowrate (l/min)	9.96	11.53	8.33	0.56
Net Draft (kN)	6234.41	10489.35	1379.08	1609.75
Vd/Vgr	0.97	1.11	0.84	0.05
Draft power (kW)	6.73	11.55	1.56	1.72
Rotary power (kW)	0.07	0.11	0.05	0.01
Total power (kW)	6.80	11.62	1.64	1.72

Test 6-P, Low 2, Powered, 4137 kPa (600 psi)

22-P	AVG	MAX	MIN	ST DEV
Top Compression (kN)	7823.04	13066.89	3864.61	1587.90
Right Draft (kN)	10125.29	15858.31	6567.26	1688.46
Left Draft (kN)	3387.61	7254.27	420.02	1245.94
Ground Speed (m/sec)	1.07	1.16	1.01	0.03
Disk Speed (m/sec)	1.34	1.51	1.12	0.07
Pressure Drop (kPa)	3708.10	4333.32	2999.19	299.89
Flowrate (l/min)	12.74	14.35	10.57	0.64
Net Draft (kN)	5689.86	9731.66	1832.38	1464.07
Vd/Vgr	1.25	1.40	1.07	0.06
Draft power (kW)	6.10	10.80	1.92	1.58
Rotary power (kW)	0.79	1.01	0.60	0.07
Total power (kW)	6.89	11.60	2.63	1.57

Test 7-N, Low2, Non-Powered, NA

23-U	AVG	MAX	MIN	ST DEV
Top Compression (kN)	8256.24	18056.86	2395.70	2153.27
Right Draft (kN)	10833.70	17451.06	2791.85	2299.08
Left Draft (kN)	4360.96	15790.32	-66.21	1654.57
Ground Speed (m/sec)	1.08	1.17	0.99	0.03
Disk Speed (m/sec)	1.13	2.41	0.91	0.17
Pressure Drop (kPa)	470.24	713.60	330.95	45.75
Flowrate (l/min)	10.73	22.87	8.66	1.65
Net Draft (kN)	6938.43	14417.64	329.94	1979.96
Vd/Vgr	1.05	2.20	0.86	0.16
Draft power (kW)	7.47	15.76	0.37	2.14
Rotary power (kW)	0.08	0.27	0.06	0.02
Total power (kW)	7.56	16.03	0.53	2.14

Test 7-P, Low 2, Powered, 6205 kPa (900 psi)

23-P	AVG	MAX	MIN	ST DEV
Top Compression (kN)	7456.98	14362.98	3713.40	1650.17
Right Draft (kN)	11048.99	18807.85	7363.64	1858.70
Left Draft (kN)	3953.95	9631.39	474.05	1433.85
Ground Speed (m/sec)	1.08	1.16	1.01	0.03
Disk Speed (m/sec)	1.59	1.91	1.36	0.12
Pressure Drop (kPa)	5638.73	6918.83	4374.69	454.99
Flowrate (l/min)	15.03	18.09	12.86	1.14
Net Draft (kN)	7545.96	13829.81	3717.69	1834.73
Vd/Vgr	1.47	1.76	1.27	0.11
Draft power (kW)	8.15	15.05	3.97	2.00
Rotary power (kW)	1.41	1.90	1.11	0.15
Total power (kW)	9.56	16.38	5.38	1.95

Test 8-N, Low 2, Non-Powered, NA

24-U	AVG	MAX	MIN	ST DEV
Top Compression (kN)	9793.54	17127.99	5398.32	1858.57
Right Draft (kN)	12809.70	22022.85	7806.07	2223.53
Left Draft (kN)	5573.34	10198.66	2337.93	1256.40
Ground Speed (m/sec)	1.05	1.14	0.97	0.03
Disk Speed (m/sec)	1.08	1.28	0.88	0.05
Pressure Drop (kPa)	491.65	703.26	72.39	64.24
Flowrate (l/min)	10.24	12.11	8.33	0.50
Net Draft (kN)	8589.50	15341.74	3768.59	1664.48
Vd/Vgr	1.03	1.19	0.88	0.04
Draft power (kW)	9.00	15.92	3.94	1.75
Rotary power (kW)	0.08	0.12	0.01	0.01
Total power (kW)	9.08	16.00	4.04	1.74

Test 8-P, Low 2, Powered, 8274 kPa (1200 psi)

24-P	AVG	MAX	MIN	ST DEV
Top Compression (kN)	7328.64	13974.15	3778.20	1841.41
Right Draft (kN)	10719.12	18276.93	6213.32	2128.52
Left Draft (kN)	3999.78	8280.75	690.15	1456.31
Ground Speed (m/sec)	1.04	1.13	0.96	0.03
Disk Speed (m/sec)	1.70	2.08	1.39	0.15
Pressure Drop (kPa)	7148.09	9080.32	5584.71	530.05
Flowrate (l/min)	16.10	19.75	13.15	1.43
Net Draft (kN)	7390.26	14508.97	2590.64	1902.00
Vd/Vgr	1.64	2.01	1.37	0.14
Draft power (kW)	7.66	14.87	2.52	1.95
Rotary power (kW)	1.92	2.53	1.36	0.21
Total power (kW)	9.58	16.67	4.57	1.88

Test 9-N, Low 3, Non-Powered, NA

31-U	AVG	MAX	MIN	ST DEV
Top Compression (kN)	9029.69	15378.26	3065.35	1460.28
Right Draft (kN)	11436.94	18040.97	5770.88	1525.95
Left Draft (kN)	5330.01	9280.23	1149.37	1021.40
Ground Speed (m/sec)	1.60	1.68	1.51	0.03
Disk Speed (m/sec)	1.50	1.76	1.27	0.11
Pressure Drop (kPa)	366.48	537.79	206.84	58.71
Flowrate (l/min)	14.21	16.72	12.03	1.04
Net Draft (kN)	7737.27	13156.91	3050.26	1245.21
Vd/Vgr	0.93	1.09	0.81	0.07
Draft power (kW)	12.41	20.64	4.72	2.00
Rotary power (kW)	0.09	0.12	0.05	0.01
Total power (kW)	12.50	20.72	4.81	2.00

Test 9-P, Low 3, Powered, 2758 kPa (400 psi)

31-P	AVG	MAX	MIN	ST DEV
Top Compression (kN)	8705.45	19849.79	84.33	1940.62
Right Draft (kN)	11520.75	20754.54	3912.68	2084.77
Left Draft (kN)	5175.36	16357.58	-822.56	1424.16
Ground Speed (m/sec)	1.60	1.68	1.53	0.03
Disk Speed (m/sec)	1.71	2.11	1.54	0.08
Pressure Drop (kPa)	2430.46	3050.90	2078.75	183.67
Flowrate (l/min)	16.19	20.04	14.56	0.76
Net Draft (kN)	7990.66	17262.34	3005.78	1767.03
Vd/Vgr	1.07	1.31	0.97	0.05
Draft power (kW)	12.81	28.26	4.87	2.88
Rotary power (kW)	0.66	0.90	0.53	0.06
Total power (kW)	13.47	28.84	5.45	2.87

Test 10-N, Low3, Non-Powered, NA

32-U	AVG	MAX	MIN	ST DEV
Top Compression (kN)	10138.47	17948.85	3432.58	1898.15
Right Draft (kN)	13348.03	21314.96	7422.63	2056.98
Left Draft (kN)	5359.00	11036.06	1122.36	1219.19
Ground Speed (m/sec)	1.54	1.65	1.44	0.03
Disk Speed (m/sec)	1.52	1.75	1.33	0.07
Pressure Drop (kPa)	284.13	455.05	155.13	46.18
Flowrate (l/min)	14.38	16.55	12.65	0.70
Net Draft (kN)	8568.56	13055.33	4466.80	1536.01
Vd/Vgr	0.98	1.09	0.90	0.04
Draft power (kW)	13.21	19.87	6.90	2.39
Rotary power (kW)	0.07	0.11	0.04	0.01
Total power (kW)	13.28	19.94	6.97	2.39

Test 10-P, Low 3, Powered, 4137 kPa (600 psi)

32-P	AVG	MAX	MIN	ST DEV
Top Compression (kN)	8211.86	16436.74	4210.23	1678.28
Right Draft (kN)	11540.88	19279.77	7304.64	1816.50
Left Draft (kN)	4285.49	9631.39	474.05	1274.44
Ground Speed (m/sec)	1.54	1.63	1.46	0.03
Disk Speed (m/sec)	1.82	2.19	1.58	0.12
Pressure Drop (kPa)	3601.60	4354.00	2906.12	305.44
Flowrate (l/min)	17.27	20.79	14.93	1.13
Net Draft (kN)	7614.50	11861.34	3494.05	1534.34
Vd/Vgr	1.18	1.43	1.05	0.07
Draft power (kW)	11.76	18.86	5.32	2.37
Rotary power (kW)	1.04	1.38	0.75	0.11
Total power (kW)	12.79	20.09	6.36	2.36

Test 11-N, Low 3, Non-Powered, NA

33-U	AVG	MAX	MIN	ST DEV
Top Compression (kN)	9696.01	19568.97	5225.51	1984.11
Right Draft (kN)	13145.88	26447.15	8130.52	2567.15
Left Draft (kN)	5214.78	10928.01	1500.54	1437.02
Ground Speed (m/sec)	1.56	1.65	1.42	0.03
Disk Speed (m/sec)	1.56	1.77	1.29	0.08
Pressure Drop (kPa)	312.25	506.76	175.81	54.23
Flowrate (l/min)	14.77	16.80	12.19	0.76
Net Draft (kN)	8664.65	18532.32	3390.62	2127.90
Vd/Vgr	1.00	1.17	0.84	0.05
Draft power (kW)	13.49	29.00	5.31	3.38
Rotary power (kW)	0.08	0.13	0.05	0.01
Total power (kW)	13.57	29.07	5.37	3.38

Test 11-P, Low 3, Powered, 6205 kPa (900 psi)

33-P	AVG	MAX	MIN	ST DEV
Top Compression (kN)	8175.55	15140.64	3432.58	1891.65
Right Draft (kN)	11913.80	18365.42	7127.67	2046.25
Left Draft (kN)	4322.82	9820.48	366.00	1495.85
Ground Speed (m/sec)	1.55	1.70	1.42	0.04
Disk Speed (m/sec)	2.06	2.40	1.78	0.13
Pressure Drop (kPa)	5412.33	6701.65	3805.87	444.62
Flowrate (l/min)	19.56	22.70	16.89	1.27
Net Draft (kN)	8061.07	13642.27	3694.39	1889.15
Vd/Vgr	1.33	1.53	1.18	0.08
Draft power (kW)	12.53	21.29	5.72	2.95
Rotary power (kW)	1.76	2.33	1.30	0.18
Total power (kW)	14.30	22.85	7.24	2.93

Test 12-N, Low 3, Non-Powered,

34-U	AVG	MAX	MIN	ST DEV
Top Compression (kN)	10078.00	21599.52	2892.54	1736.94
Right Draft (kN)	13334.25	22966.70	4296.12	1864.13
Left Draft (kN)	5609.06	14385.65	-687.50	1348.16
Ground Speed (m/sec)	1.55	1.63	1.46	0.03
Disk Speed (m/sec)	1.54	1.69	1.35	0.06
Pressure Drop (kPa)	333.11	599.84	103.42	58.58
Flowrate (l/min)	14.61	16.01	12.82	0.59
Net Draft (kN)	8865.31	14983.14	716.08	1701.10
Vd/Vgr	0.99	1.08	0.90	0.03
Draft power (kW)	13.76	23.19	1.09	2.63
Rotary power (kW)	0.08	0.15	0.02	0.01
Total power (kW)	13.84	23.30	1.20	2.63

Test 12-P, Low3, Powered, 8274 kPa (1200 psi)

34-P	AVG	MAX	MIN	ST DEV
Top Compression (kN)	6761.06	20260.22	1812.46	1824.35
Right Draft (kN)	10196.14	27803.94	5475.93	1720.97
Left Draft (kN)	3313.75	11873.46	-930.62	1448.62
Ground Speed (m/sec)	1.54	1.66	1.46	0.03
Disk Speed (m/sec)	2.20	2.86	1.94	0.14
Pressure Drop (kPa)	6349.30	8842.45	4581.53	635.32
Flowrate (l/min)	20.88	27.11	18.38	1.37
Net Draft (kN)	6748.82	17391.22	2013.86	1605.78
Vd/Vgr	1.43	1.84	1.31	0.09
Draft power (kW)	10.42	27.80	3.24	2.48
Rotary power (kW)	2.21	3.59	1.57	0.26
Total power (kW)	12.63	30.53	5.38	2.53

APPENDIX D

APPENDIX D

SAMPLE CONDITIONED RAW VOLTAGE DATA GRAPHS

The printouts show the raw voltage data of the pertinent parameters measured. These analog voltage values were converted to the actual data by using the calibration equations developed earlier.

In the printouts :

Channel 1	Top Link Force
Channel 2	Right Link Force
Channel 3	Left Link Force
Channel 4	Ground Speed
Channel 5	Disk Speed
Channel 6	Pressure In
Channel 7	Pressure Out

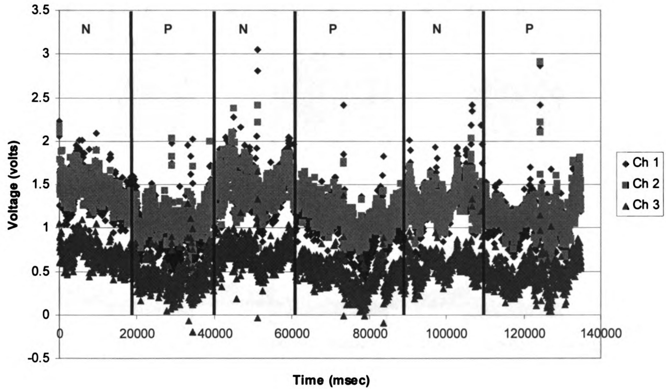

Figure DF1 Sample Conditioned Raw Voltage Data from Top, Right, and Left Link Strain Gages

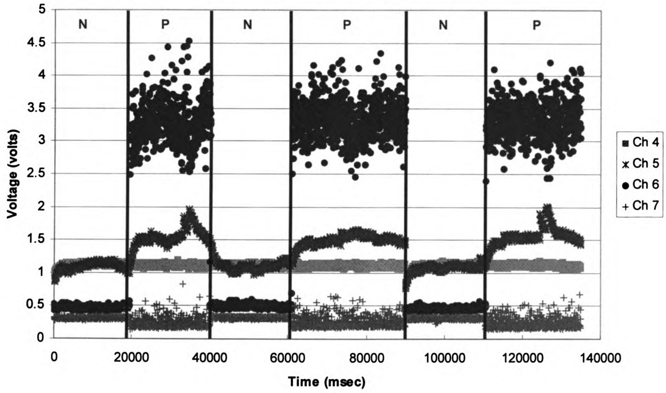

Figure DF2 Sample Conditioned Raw Voltage Data from Pressure Sensors, Disk and Ground Speed Sensors

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