TO WHOM IT MAY CONCERN

PLEASE NOTE

"Although this thesis was submitted for the degree of EngD, it was considered to be appropriate for the award of the degree of **MPhil**.

This award will be conferred at the **Graduation Ceremony** on **14 July 1999**"

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CONTINUOUS MASS FLOW MEASUREMENT OF GRANULAR MATERIALS

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"Knows he who tills this lonely field,
To reap its scanty corn,
What mystic fruits his acres yield,
At midnight and at morn."

Ralph Waldo Emerson, 1803 - 1882

ABSTRACT

Silsoe College, Cranfield University

Stuart Saunders, Engineering Doctorate - 1997

Continuous Mass Flow Measurement of Granular Materials

This thesis reports on the development of a double inclined plane (DIP) transducer system based upon the principles of force reaction. This transducer had a design specification to measure the true mass of "free" flowing granular materials, primarily agricultural crops, with an accuracy of ± 2 % on total mass flowed for flow rates between 1 and 10 kg/s. Two absolute values are used to assess accuracy in this study, (i) the total mass flowed (kg), a measure of the mass accumulation and, (ii) the mass flow rate (kg/s), a 'spot' reading of flow rate. The performance of the novel system has been evaluated through theoretical, laboratory and field studies and consideration has been given to the commercial and business aspects of the manufacture, marketing and further development of the device.

Following mathematical and laboratory studies of the sponsors current force reaction transducer – a single reaction device, angular variations were highlighted as having a significant effect upon output. A further study found that the least sensitive reaction plate angle was 55^{O}. To overcome this problem, the double inclined plane (DIP) concept was developed, 2 single reaction plates, joined along their apexes, angled at 55 degrees to the horizontal, mounted upon a horizontal strain gauged beam. Angular compensation when tilting the transducer was provided by generating a higher force from the shallower face and a lower force from the steeper face. A mathematical model of the new transducer allowed the output to be predicted to within 1.7 %. Initial calibration was undertaken in the laboratory and tested using a combine clean grain system simulation apparatus. In-situ machine studies were performed by mounting the transducer in a New Holland TF42 combine, firstly on an extended bubble up auger and finally in the drop box, between the clean grain elevator and bubble up auger.

Initial pilot studies were conducted with the combine static to calibrate the system and finally a full harvest field trial was undertaken.

Over the harvest field trial, the accuracy on accumulated mass was better than 0.9 % over 127 tonnes. Tramline effects upon transducer output were found to be self cancelling, as the resulting positive and negative ‘spikes’ in the signal, when summed over time approximated to zero. Changes in pitch angle, up to 10 degree caused between 1.5 and -2.8 % randomly distributed error. Roll angles up to 7.5 degrees, caused between -0.9 % and 1.7 % randomly distributed error in static trials. Field beans and oilseed rape required calibration constants 6.8 % and 3.1 % lower than that for 12.5 % moisture content wheat, but with adjusted calibration constants, gave excellent repeatable results. Increasing moisture contents of up to 30 % in wheat resulted in the transducer under reading by, on average, 1.6 %.

An assessment of manufacturing costs was made and the unit cost was £154.12 each for 30 units reducing to £109.59 each for 3000 units. It is recommended a pricing objective of maximising sales growth is used which will position the device at the less expensive end of the market. Due to commercial sensitivity, a draft patent has been written to protect the DIP concept. The first stages of commercial adoption already being undertaken by a major multi-national agricultural machinery company, who are evaluating a pre-production prototype.

This thesis provides the systems, data and principles required to create a novel, commercially practical transducer system, based upon the principles of force reaction. The problem of angular compensation has been overcome in a simple and effective manner offering a relatively inexpensive but accurate method of measuring mass flow rate, which has already received commercial interest.

ACKNOWLEDGEMENTS

I would like to express my gratitude to the sponsor's of this study, Griffith Elder and Co. Ltd., without whose funding, vision and encouragement this study would not have been possible.

I would also like to thank New Holland and Rycotewood College for the use of their combine harvester and in particular Michael Whitfield for his expert advice, endless patience and humour during many long hours of field trials

Finally, I would like to thank Ruth for her patience and support.

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CHAPTER 6

LIST OF PLATES

LIST OF SYMBOLS

m = mass flow rate

v = velocity

ϑ = angle

N = normal force

M = weight of material on transducer plate

g = acceleration due to gravity

s = length of transducer plate

t = time

μ = coefficient of friction

h = height of drop

K = actual calibration constant

K_t = theoretical calibration constant

K_a = experimental calibration constant

σ = stress

ε = mechanical strain

F = force

l = distance between strain gauges centres

E = Youngs modulus

I = second moment of area

b = width of transducer beam

d = depth of transducer beam

N = number of active gauges in strain gauge bridge

ΔV = variation in voltage output

ΔR = variation in resistance

V_0 = supply voltage

R = resistance

GF = gauge factor

t_R = Residence time of material on reaction plate

δ = Change in angle over the original

CHAPTER 1

INTRODUCTION

1.1 - BACKGROUND

The work reported in this thesis was undertaken as a collaborative project between Griffith Elder & Company Limited and the Department of Agricultural and Bio-Systems Engineering, Silsoe College, Cranfield University. The aim of the work was to produce a prototype transducer together with performance data which would lead to the development of a commercially practicable mass flow measurement transducer, typically for use in combine harvesters constantly monitoring any harvested crop, irrespective of type or moisture content. The transducer output when linked to field location, using a differential global positioning system, would then produce the relevant information to produce a yield map.

The measurement of crop yield mass and field location data are the critical inputs for 'yield mapping', a technique within the relatively new process of 'Precision Farming', a method to encourage maximum efficient use of the field. Traditional approaches assume a field is uniform, whereas most agricultural fields have some spatial variation in parameters such as soil type, weed population, slope, fertility and the subsequent grain yield integrates the effects of a number of these parameters (Sudduth et al, 1996). By subdividing the field into smaller components, each can receive the most suitable treatment therefore reducing overall field inputs and costs whilst maximising efficiency and outputs. Monitoring the spatial variation in yield permits a basis for developing machine control maps for implementation of spatially selective operations such as fertiliser and agrochemical applications. Such determination of local requirements allows an increase in field efficiency whilst lowering inputs, from initial seedbed preparation to crop protection. The benefits of this treatment should be seen at the following harvest through improved yields or reduced cost of production. Following harvest, further decisions on treatments can be taken, creating an iterative process where annual improvements can be seen. Obvious benefits from this process for the farmer are: (a) reduced inputs (consumables and labour) with (b) maintained or improved outputs (crop production) whilst (c) the environment gains from reduced chemical inputs (Baker et al, 1996).

It can be seen that the yield map is an essential part of the precision farming process. Many studies have been conducted in the area of field location positioning systems and sub-centimetre accuracy can be obtained (Lange, 1996) but the second important input, the yield, has had less critical review. There have been few studies conducted in the basic principles and optimisation of mass measurement systems. Most current commercial systems work on a volumetric measurement approach, which requires the use of a separate input of bulk density to allow true mass to be calculated.

Accuracy of a transducer system is commonly used as a performance indicator, this being a measure of the ability of the transducer to give a reading close to the absolute value. Two absolute values are normally used in mass flow measurement, (i) the total mass flowed (kg), a measure of the total mass accumulation and (ii) the mass flowing over time (kg/s), a 'spot' reading of flow rate. Both methods are used within this study but the distinction between them should be noted.

1.2 - AIM

The aim of this thesis is to consider the area of dynamic mass measurement using true mass as the input, from which a novel transducer offering accurate, repeatable results in a wide range of conditions can be developed.

1.3 - SPECIFICATION

An initial transducer specification was determined to define the operational range for the project for both large and small combine harvesters based upon a typical yield of ten tonnes per hectare. This allowed the maximum flow rates for each machine to be calculated, thus :

	SMALL MACHINE	LARGE MACHINE
Cut width (m)	2.0	7.0
Forward speed (m/s)	1.5	2.5
Harvesting rate (t/h)	4.0	30.0
Mass flow Rate (kg/s)	1.1	8.3

From this it can be seen that the transducer will need to cover a range of flow rates up to 10 kilograms per second with sufficient resolution to determine variances at 10% of full scale. For a typical combine grain tank of four tonnes this represents one quarter of a percent (0.25%) of the tank capacity. The transducer specification was thus:

Material to be measured	Semi-fluidic particulate mass (grains, pulses etc.)
Maximum flow rate	10 kilograms per second
Minimum flow rate	1 kilogram per second
Sensitivity	0.25 % of machine capacity
Transducer constraints :	
Accuracy	+/- 2% on total mass +/- 2% on mass flow rate
Sensitivity to installation	Minimal
Ambient conditions	-10 °C to +50 °C
Restriction to flow	Minimal
Sensing Environment:	
Weather/dust resistance	To IP 66
Electromagnetic radiation	Within legal limits
Total End user cost	£ 4000 maximum
Specific Considerations:	
Calibration interval	Annual (by customer)
Durability	10 year life
Crop damage	None

With minimal sensitivity to variations in crop type and moisture

1.4 - REVIEW OF LITERATURE

1.4.1 – Review of Technical Literature

Historically it is probably impossible to cite the first monitoring device ever associated with a combine harvester. It is recorded that the first combine harvester ever used in the USA was in 1836 (Feiffer and Feiffer, 1969) but it is very unlikely this machine was fitted with any monitors. Reed, (1978) reports that early devices such as a rag tied to the clean grain elevator drive shaft, acted as a go-no go indicator, giving the operator basic feedback upon machine operation.

Monitoring devices for combines can be classified according to their functions and three general classifications have been recognised, as follows: (a) power plant monitors (referring to engine and transmission) (b) process machinery operation monitors and (c) product control monitors (Pool and Rickerd, 1968). Whilst numerous commercial systems are available for the first two categories, product control monitors have remained largely unnoticed and are the category the sponsor requires this thesis to concentrate upon.

Early work in the UK was undertaken by Hooper et al (1973, 1974a, 1974b and 1979), following a similar study by Nolte (1970). A conical baffle was fitted inside a funnel which was supported on strain gauge links and mounted on the end of the unloading auger, allowing crop mass monitoring only when emptying the grain tank. This work was in co-operation with the Home Grown Cereals Association to assist forward selling contracts. Errors of up to 5 % for barley and 4.8 % for wheat were recorded during two harvest field trials, one very wet and one very dry. Machine vibrations were noted as being large but having no cumulative effect. Land slopes to six degrees were also included in the test variations and caused a 5% error in the signal. To remove amplifier drift when not recording, a device to re-zero the amplifier when the unloading auger was not working, was used.

An early study in the USA was undertaken by Kirk, 1977, concentrating upon the monitoring of threshing losses (grain contained in straw and chaff ejected from the rear of the combine), using an acousto-electric sensor which was fitted in the path of the ejected straw. When the ejected material struck the sensor, a wide frequency spectrum signal was produced. This signal was passed through several band pass filters, one for low frequency (0-25 kHz) and one for high frequency (25-100 kHz). A comparator was used to see whether the ratio of high to low signals fell in a predetermined range which would indicate a seed striking the sensing medium. Straw and chaff were found to have their own individual signatures when striking the medium and these could be discounted when reaching the comparator. No accuracy figures are available, but it is known that sensitivity to light crops such as oilseed rape was poor due to similarities in signature between the straw and light crop.

Work by Wang et al (1987 and 1988) at the University of Saskatchewan took Kirk's work one step further by attempting to monitor threshing losses per unit area. This work was deemed necessary due to (i) the inaccuracy of loss monitors at flow rates of 3 kg/s and above and (ii) because current loss monitors worked on a time basis which was only a relative measurement to the previous reading and not the area harvested.

Losses along a separator were approximated to a exponential function:

$$G_s = G_o \, . \, e^{-bl} \qquad \text{Equation 1.1}$$

where: G_s = Grain separation rate along separator (kg/min-m)

G_o = Analytical initial separation rate (kg/min-m)

b = Attenuation coefficient (1/m)

l = Length of separator (m.)

To predict grain separation loss, the above equation was integrated from the end of the separator to infinity. Two piezo electric sensors were used, one mounted at each end of the straw walkers. From the data provided, the above equation could be completed and a separation rate calculated. Once again this system proved to be crop sensitive, experiencing problems with barley, due to the rough nature of its husk causing separation problems and consequently fluctuating rates of separation.

Following the work on loss monitors, Pang and Zoerb (1990) saw the potential for piezo devices in yield mapping. It was recognised that the 'sounding box' type piezo sensor was only adequate for a maximum of 200 evenly spaced impacts per second. Also noted was the fact that most measuring devices were affected by grain size, moisture content, percentage of foreign material, ground slope, machine vibration and atmospheric conditions (dust and humidity). To avoid these corrupting factors, it was decided to use a high polar poly-vinylidene (PVDF) film to measure crop flow by recording each grain impact. This offered reasonable mechanical strength, wide frequency range, high output voltage wide operating temperature and low cost.

A series of these piezo film sensors were positioned on wooden blocks and placed under the sieves, to reduce time lag between harvesting and sensing to an absolute minimum. Durability problems were encountered and the film was subsequently covered with adhesive tape to prolong its life. The sensor was set at 30^0 to the horizontal and drop height was 70 millimetres with a 0.1 millimetre clearance between the sensor and its base in an attempt to increase signal size to between 70 and 200 mV. Each signal took between 0.3 and 0.5 milliseconds, allowing a counting capacity of 2000 plus impacts per second, (approximately 56 tonnes per hour).

In practical tests the film was found to be sensitive to vibration and to infrared light, however the vibration signal was easily discernible due to its widely different amplitude. Accuracy offered was within 4.5% and by comparing the amount of grain between the front and back of the separator this method offered an ideal measurement of separation efficiency. However, wear of the PVDF strips was the main problem of this measurement technique and this was never corrected.

A more recent version of Hooper and Ambler's early UK work was researched at the University of Minnesota, which offered 'on the go' monitoring of grain mass. A conical sensor was mounted on a load cell and was positioned under the clean grain output into the grain tank. Grain was funnelled onto the point of this conical device and the signal from the supporting load cell was indicative of mass flow rate. Noise in the signal caused large errors in spot readings of mass flow rate. This noise had a wide frequency and attempts to filter were unsuccessful, (Borgelt, 1993).

Two early commercial devices were marketed which were mounted in the unloading auger to sense crop mass, similar to Hooper, Ambler and Hughes (1974b) design. The first device was the Acu-Grain BM-2 which was originally designed to inform the operator of the ground covered and crop mass harvested. A pair of strain gauged baffles were positioned on the end of the unloading auger, which were deflected by the grain leaving this auger and filling the trailer. The speed of the unloading auger needed monitoring and this was a major cause of error as the operators had difficulty holding a constant, accurate speed. At low levels of grain flow, accuracy was within 3%, (Prairie Agricultural Machinery Institute, 1984).

The second device was manufactured by Griffith Elder and Company, the sponsor's of this research work, who specialise in strain gauge based instrumentation for yield recording and weighing cells. The device known as the 'Yield per Field', was a force reaction device that was first marketed in 1977. It consisted of a single angled plate mounted on a strain gauged beam. The crop was discharged onto the edge of the plate and caused the beam to bend. This was measured by the strain gauges, their output being linear to the crop mass flow. However, re-calibration was needed for measuring widely different crops. This device was manufactured for measuring the accumulated mass of crops rather than the instantaneous flow rate needed for yield mapping purposes. Accuracy of approximately 2 % on total mass flowed could be achieved. This device can be classified as a force reaction or "F = m.a" device and several others have been researched.

Vansichen & De Baerdemaeker (1991 and 1992) also worked with force reaction sensors taking an analytical approach to the problem. Before designing a sensor, the combining process was modelled highlighting all variables and noting their effects. It was decided to develop a curved plate which changed the direction of the flowing material and measured reaction to the momentum needed to accomplish this. This change in direction was due to a combination of impact and friction and the force exerted was modelled as:

$$F = F_R \cdot v \qquad \text{Equation 1.2}$$

Where: F_R = Mass flow rate (kg/s).

F = Force (N).

v = Difference in crop speed between inlet and outlet (m/s).

From tests of this transducer the force exerted was found to be 5 Newtons for every kilogram per second flowrate, which was lost in the larger amplitude machine vibrations. To remove these a low-pass filter was used (5th. order digital Butterworth filter with a cut off frequency of 0.5 Hz.). To determine actual cutting width, an ultrasonic distance transducer was mounted on the left hand divider, to establish how much of the cutting head was actually being used. From this work, Vansichen and De Baerdemaeker (1992) concluded that on a combine with a 4.57m cut width, only 4.23m was effectively used, with a standard deviation of 0.094m. The accuracy on the total measured mass of 92 tonnes of wheat harvested using this approach was 3.5 %.

Perez-Munoz and Colvin (1994) tested a 'Yield Monitor 2000™' manufactured by Ag Leader Technology (sold by LH Agro as LH 565 in Europe), which is a strain gauged, curved plate, similar to that used by Vansichen & De Baerdemaeker. The main aim of the tests was to compare an instantaneous flow reading with actual flow, over differing run lengths of crop. It was found in laboratory experiments that the relationship between force and flow was non-linear. Although an acceptable signal was achieved, no allowance had been made for the time taken by the grain to travel through the combine to the sensor. This signal appeared heavily damped from the initial very gradual 'ramp' in recorded flow rate. This meant that the signal was not instantaneous, but took time to build and decay. Vansichen concluded that this method is suitable for yield mapping if an instantaneous signal could be provided.

Another strain gauged device was a pivoted auger developed by Wagner & Schrock (1989) and can be seen in Figure 1.1, over. This was one of the initial monitoring methods for use with precision farming systems, developed by Wagner and Schrock in 1986, but not tested until 1988.

An auger within the grain tank was pivoted at one end and had a 450N load cell at the other. As material passed along the auger, its mass was sensed by the load cell, whilst vertical acceleration was monitored by an accelerometer and charge amplifier. A computer program, leaving a reading of pure mass in a dynamic situation then compensated for this acceleration. Sampling frequency was 100 Hz, but data was averaged using a 1 second rolling average algorithm. Problems were encountered with noise sources on the combine generating a false signal. Following further testing these were found to be the auger rotation, threshing cylinder and engine. To overcome this a low-pass filter was used with a cut off frequency of 0.5 Hz, which still allowed data to be collected. Transportation delays (between grain entering the combine and reaching the sensor), were quoted as being a function of the grain flow rate. High grain flows caused a longer lag, normally between 13 and 15 seconds at 10 kg/s. For calibration it was found that true mass flow was a function of auger speed and load cell reading, offering a simple linear regression fit to the test data with an R^2 value of 0.9873. Accuracy offered was within 3% on instantaneous mass flow rates and Wagner and Schrock concluded that a pivoted auger was a viable tool to measure yield variations. However, grain moisture content was believed to affect accuracy and so Schrock developed another device, the triangular clean grain elevator.

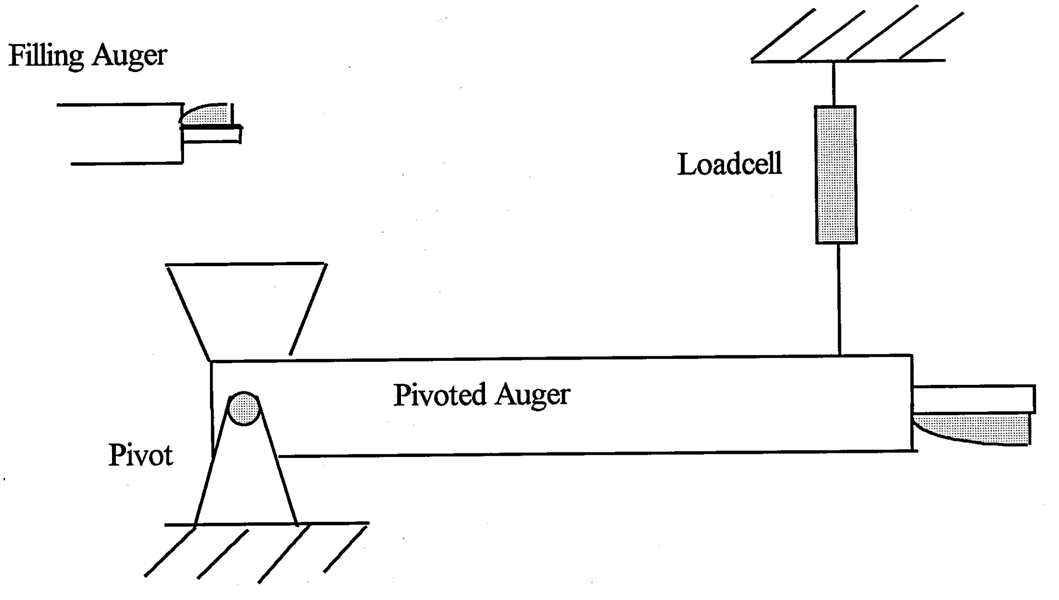


Figure 1.1 - Pivoted Auger (Wagner & Schrock, 1989)

This was achieved by adding a third sprocket to the elevator, located so as to create a horizontal section to the elevator. The housing containing the horizontal section was constructed with an 'active section' that allowed grain to be weighed as it passed through, this is illustrated in Figure 1.2. The grain entry end of the active section was supported by a simple pivot, while the grain discharge end was supported by a simple strain gauge loadcell, (Schrock et al., 1994). In laboratory tests, true flow rates could be predicted with a coefficient of determination (R^2) greater than 0.98, with the exception where crop moisture contents exceeded 24 % where R^2 dropped to 0.93. Side slopes up to 12 % were shown to have no significant effects upon the signal. In field trials 800 hectares of soybeans, grain sorghum and sunflowers were harvested. Error on total mass recorded was -0.85 %, whilst the error in instantaneous mass flow readings was 2.45 %. Problems were encountered ensuring a seal to the active section which had no effect upon the signal and it was reported that further work is intended in this area.

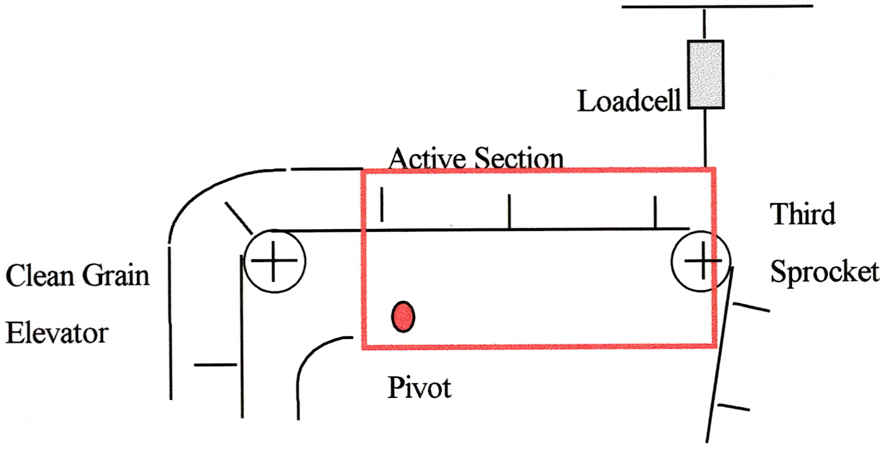


Figure 1.2 - Triangular Clean Grain Elevator (Schrock et al, 1994)

Another very simple device that reacts to the force of the crop is marketed in the USA by Microtrak. It consists of two sprung fingers which are mounted on a rotary potentiometer, the unit being fixed in the end of the bubble up auger. When crop is flowing, the fingers are forced outwards against the spring pressure, moving the potentiometer and giving a change in resistance which is interpreted as a reading of flow rate. This device is very sensitive to changes in crop particle size and density and moisture content. Claimed accuracy is 3%, (personal communications with Microtrak, 1996).

Stafford and Ambler (1992) commenced work late in 1988 after commissioning a report by Bull (1988) on the options available in mass flow measurement for the food industry. In 1992, they developed the "capacitive sensor", based upon the fact that the dielectric constant of the air/grain mixture increases with the grain concentration. The two initial design criteria were that the sensor should be non invasive, causing no blockages and that it should not be affected by machine vibration. Semi-annular capacitance plates were mounted on the discharge auger into the grain tank and a balance capacitor was used to discount any stray capacitance effects. A capacitance feedback amplifier was used to detect the difference between capacitors and following demodulation and amplification a usable signal was produced. From calibration it was found the sensor was both crop and moisture dependent, limiting its uses and demanding re-calibration with change in crop conditions. As the moisture content of grain can vary by up to 5% between the centre and headlands, there are significant disadvantages in this type of device. Accuracy offered was within 12% on total mass flowed over varying conditions but this was without correction for crop moisture content. A moisture sensor is currently being incorporated to improve accuracy of results.

Claas (Europe) launched a capacitive sensor (the CEBIS) during 1996 for their Lexion range of combines. This device also used a moisture sensor and included several pre-set calibration constants for different crops (Claas Lexion 480 product advertisements, 1996). During tests at Silsoe College errors between 2 % and 12 % (in 12 tonne loads) were experienced but it became apparent that as the loads accumulated over a day's work, the errors decreased, (Larscheid, 1996).

Several optical methods for crop measurement have been developed. Borgelt (1993) refers to the Rodvelt Agritronics system which consists of several sensors (1 - 16) mounted in the grain tank and directly linked to a series of LED's in the combine cab. It is a basic system to inform the operator of grain level and its rate of rise, but the manufacturers are showing interest at furthering it to a yield monitoring system. Also he refers to work during 1991 at South Dakota State University by Klemme, where ultrasonic distance sensors are mounted in the top of the grain tank to measure depth (and therefore volume) of grain. A moisture sensor is also used and this is combined with volume in an attempt to assess grain mass.

However unless a true density sensor is used this method will not give suitably accurate or repeatable indications of crop mass. No published papers are available for this work.

Optical methods to determine mass flow rate were also studied at the University of Illinois. A light source was mounted on one side of the clean grain elevator, with photodiodes mounted on the other. As each individual flight carried grain up the elevator, the photodiodes imaged its load and subsequently assessed the volume of grain carried. Limited tests were undertaken and research is ongoing, (Borgelt, 1993).

RDS are a UK company who also use photodiodes in the clean grain elevator with their current Ceres 2 yield monitor. Several additional inputs have been included since the system was launched, to improve accuracy. Firstly, because the transducer makes no compensation for variations in crop bulk density (only the crop shadow being used to determine mass), a moisture sensor in conjunction with pre-set calibration constants for different crops has been included. Also because the shadow of the crop on the elevator paddle will change with slopes, an inclinometer has been tested and will possibly be used on the production version. During tests at Silsoe College errors varied between 0.3 % and 12 % (on 12 tonne loads) and once again errors decreased as loads were totalled over a days work, (Larscheid, 1996). These units were recommended by John Deere and New Holland although were only retrofit items, (RDS, 1996). Bashford et al (1993) tested this system in Canada and were concerned by the need for regular calibration and lag between the crop entering the machine and reaching the transducer.

Launched in 1988, the 'Claydon Yieldometer' is illustrated in Figure 1.3. This device consisted of a pelton wheel mounted on the end of the clean grain auger. By using a level sensor to only make the wheel turn when each paddle becomes full, it is ensured each paddle carries the same volume of crop. As the grain approached the level sensor, an electromagnetic clutch was engaged via a relay which resulted in a turning of the wheel of which each half revolution was measured and displayed in the cab. This system does not compensate for variations in bulk density and only offers a volumetric measurement. If true mass is to be found, bushel weight needs to be regularly taken and compensated for. It was an exclusive fitment to Claas combines until 1995 and claimed accuracy was within 1% on total mass harvested.

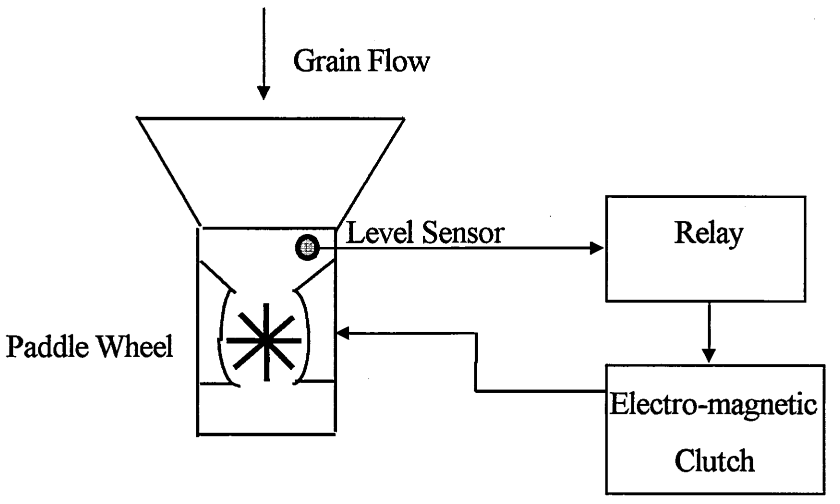


Figure 1.3 - Pelton Wheel Device (Claydon Yieldometer)

Searcy et al (1989) found that this device suffered from inadvertent wheel turning when there was inadequate grain level for complete filling of the paddle wheel. Also classical digital filtering techniques could not be used as the signal was not evenly spaced, so a filtering algorithm was constructed based on arithmetic averaging, a clear source of inaccuracies. No raw data was available but it was concluded that the flow meter required modification to perform adequately.

Bull (1988) discusses the Compton effect using gamma or x-rays. They were emitted into the crop flow, and the scattered radiation was collected by a wide angle energy sensitive detector. When a photon is scattered by a particle it loses a proportion of its energy related to the angle at which it is scattered. By counting the number of photons of a given (lower) energy, the density of the conveyed material can be found. Massey Ferguson developed this gamma absorption method to monitor crop mass flow in the clean grain elevator on their Dronninborg manufactured combines. The radioactive isotope used is Americium 241, a low level gamma emitter of energy 35 mega Bequels, (MF press launch and personal communications, 1993 - 1995). Although this is a very low level of radiation (approximately half the output of the luminous hands on a 1950's watch), problems have been encountered in several countries where radiation is a sensitive issue.

Borgelt & Sudduth (1992) report that studies have been conducted at the University of Idaho by Petermen using a 12 volt DC motor to drive the clean grain elevator. A shunt was placed in the power line and by measuring the voltage across it, current was calculated. It was proved that current was linearly related to quantity of grain in the clean grain system. No further information was available.

Several potential methods are recognised by Bull (1988) and Scott (1993), both identify the classes of measurement as divisible into two categories :

1. True mass which uses a single transducer taking a direct mass measurement
2. Inferential mass incorporating grain velocity and concentration to calculate mass flow

Only two methods of direct mass measurement are detailed, these being the coriolis force and gyroscopic force :

(a) Coriolis mass flow meters use a horizontal U-tube which carries the flowing material and is oscillated in the vertical plane about a horizontal axis. As the particles move along the inlet pipe they experience increasing vertical velocity due to the pipe oscillations. Similarly, the particles in the outlet pipe have reducing vertical velocity. The coriolis force is equal in magnitude but opposite in direction in each leg of the pipe, so causing the tube to twist. This torque can be directly related to the mass flow rate, (Bull, 1988), (Dimaczek et al, 1994).

(b) Gyroscopic Mass Flow Meters use the gyroscopic effect by passing the conveyed material around a tube bent into a circular loop, which rotates around the axis of the inlet/outlet tubes. The material rotating around the loop couples with the perpendicular rotation of the pipe and causes the system to rotate about a third axis. This movement exerts a force on the input bearings which is directly proportional to the mass flow rate, (Bull, 1988).

The main problem with inferential flow measurement is ensuring that the same time window (and hence crop) is sampled for the solids velocity and concentration. Bull (1988) recognises two potential methods for velocity measurement:

(a) Doppler Methods use the principle of 'Doppler Shift'. Energy (laser light or microwaves) is transmitted into the grain flow at a constant frequency (f_T). Some of this energy is reflected back to a receiver at a frequency (f_R). The difference in frequency is related to the velocity by the equation.:

$$f_R - f_T = \frac{2v \cdot \cos\theta \cdot f_T}{C} \qquad \text{Equation 1.3}$$

where: C = Velocity of transmitted energy.

θ = Angle made between transmitted energy and the flow.

v = Grain flow velocity

(b) Tracer Methods involve injecting markers into the solids and monitoring their progress over time. Suitable markers must have particle size and mass similar to the conveyed material. To overcome this problem, radioactive markers have been used, measuring their progress with scintillation devices. Another solution is to use phosphorescent markers and monitor their passage with photo-multiplier tubes. A major problem with both these methods is that they contaminate the conveyed material, which is highly undesirable. There may be a case for investigating other tracers such as electrostatic or ultrasonic.

To measure the solids concentration, several additional methods were identified by Bull (1988):

(a) Electrostatic methods pass particles through an electrostatic chamber, where they have an electrostatic charge 'injected'. This charge is then induced onto the walls of the pipe and is directly proportional to the mass flow rate. Unfortunately, velocity has unknown effects on this method as does the fact that a particle flowing in a pipe creates its own electrostatic charge. Also the electrostatic charge is dependant upon moisture content, the effects of which are currently unknown.

(b) Microwave Doppler methods use the same principle as discussed in the section on Doppler effects above, where the density of the flowing material can be determined from the RMS of the Doppler signal. However, this method is only reliable when particle size and moisture content are relatively stable.

(c) Nuclear Magnetic Resonance Principle (NMR) conveys the material through a strong magnetic field, where the nuclei of the particles are magnetised. This lifts the degeneracy of the energy levels with respect to the orientation of their nuclear spins. The splitting in energy levels is detected further downstream by observing the absorption of radio waves at a frequency equal to the gap between the levels. The magnitude of NMR is proportional to the number of appropriate nuclei and hence material concentration. A very expensive method which has had some successful applications in monitoring coal dust.

1.4.2 REVIEW OF ALTERNATIVE MEASURING TECHNIQUES

Weighing measurements (such as the pivoted auger) offer the advantage of a direct reading of mass, are non-intrusive and the performance of the combine is not affected if the transducer fails. However there is a need to measure vertical acceleration so that it can be removed from the signal. Accuracy on previous work is stated at 3% on total mass flow.

Pelton wheels offer a very dubious accuracy of 0.5% on total mass flowed. If the device fails the combine is stopped and (in the commercial model currently available) only a volumetric measurement is made. To calculate mass flow rate the bulk density of crop is needed and this is constantly changing with moisture content.

Force reaction devices offer accuracy to within the limits of the project specification, few or no moving parts, low cost, are non-intrusive and in-sensitive to crop type. They can however, be affected by vibration and dynamic effects. Previously this has been cancelled by the use of an accelerometer and comparator.

Gamma absorption devices offer a non-intrusive method not restricted by crop type. Already in commercial use these devices have not been allowed into several European Countries and American States due to the use of gamma ray emitters.

True mass flow measurement such as the coriolis mass flow meter offer an accurate reading which is in-sensitive to crop type. However they are precise and sensitive devices which require laboratory conditions to work correctly and are very expensive.

Capacitive based methods are non-intrusive and relatively accurate with a comparatively low cost. Nevertheless, they are very sensitive to moisture content necessitating a separate moisture sensor.

Piezo methods have only one advantage that of being non-intrusive. An accuracy of 4.5% is claimed but wear resistance and reliability of piezo film is dubious.

Optical methods give only a volumetric measurement and require a bulk density input for true mass calculation. Several researchers are already optimising this method and one successful system is available for commercial use.

Nuclear Magnetic Resonance is an extremely expensive measurement method which although highly accurate is only suited to a clean dry laboratory and not the rigours of a combine in operation.

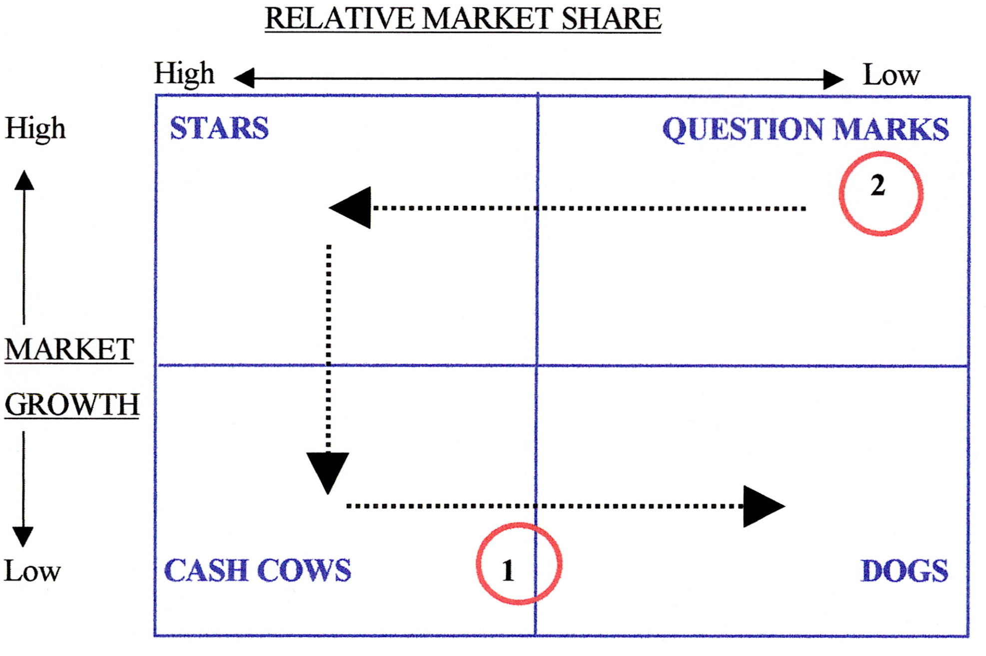
Microwave Doppler techniques prove sensitive to variations in particle size and moisture content. They are unsuitable for applications where several different crop types are harvested.

Electrostatics are very difficult to use for sensing crop flow due to their moisture sensitivity. Also the extra static generated by flowing crops cannot be compensated for.

1.4.3 – Review of Management Literature

'Given the intense competition in most markets today, companies that fail to develop new products are exposing themselves to great risk. Their existing products are vulnerable to changing customer needs and tastes, new technologies, shortened product life cycles and increased domestic and foreign competition.' (Kotler, 1994)

This is exactly the position the sponsoring company found itself in when deciding to commission this study. Their current crop mass measuring system was becoming outdated, unsuitable for adaptation to precision farming which although still in its infancy was recognised as an area of high growth. By constructing a Boston Consulting Group (BCG) matrix, Figure 1.4, the relative position of each can be clearly seen.



1. Current grain mass measurement system - 'Grain Brain'
2. Possible positioning of novel precision farming based grain mass flow rate transducer

▶ Normal product movement with time

Figure 1.4 - BCG Matrix for Current and Planned Product

The arrows on Figure 1.4 dictates the normal progression with time of a successful product in an emerging market. Generally new products in an emerging market are classified as high risk and normally requiring high investment, but may have the potential of a high market share and a good return on investment. As market share increases and the market continues growing, the product becomes a star and as market growth slows the product becomes a cash cow, being milked for all it is worth with minimal investment before the possibility of losing market share and becoming a dog. Position one on Figure 1.4 shows the placement of the sponsor's current product with a falling share of a relatively stagnant market. If a new precision farming based product is introduced, it would start at position two with the potential to move quickly to a star with suitable marketing management.

To assess the potential market for a mass flow rate transducer, an analysis of the market is needed to assess the current and potential demand. Demand estimates are affected by three main factors, the area of sales (USA, Europe, UK etc.), the time (short, medium or long term) and the sales type (industry sales, company sales, product item etc.). For this study, the area visualised by the sponsor is initially the UK with possibilities of future expansion to Europe, the time-scale is short to medium term and the sales type could be either (a) direct to the customer as a retro-fit item or, (b) to a combine manufacturer for use as a factory fitted item.

'Total market potential' is the maximum amount of potential sales of a product available within a given period. A common way to estimate this is

$$Q = n \cdot q \cdot p \qquad \text{Equation 1.4}$$

where :
- Q = Total market potential
- n = Number of buyers in potential market
- q = Quantity purchased by potential buyer
- p = Price of an average unit

Marketing figures were obtained from AEA statistics but in such an infantile market, 'n' and 'p' values are constantly changing. Using annual values for the 1996/97 season, the total UK combine sales was 1573 of which it is estimated that 15 % had yield mapping capability. Using an average unit cost of three thousand pounds this results in a total potential market value of

$$Q = 1573 \times 1 \times 3000$$
$$Q = £\,4.75 \text{ million}$$

That is to say, if every customer bought a yield mapping system with their new combine the total UK potential market value for yield mapping systems in 1996/97 is estimated at four and three quarter million pounds.

However it is estimated that the three major players in the combine market (New Holland, Claas and Massey Ferguson) each have a twenty percent market share (three hundred and fifteen units). If the system was sold to one of these as a factory fit unit, the potential market value would be nine hundred thousand pounds.

If however the target market segment is individual farmers who have purchased a combine within the past three years with no precision farming system currently fitted, the market is estimated at 3540 units, which results in a potential market value of one million pounds.

Very few products lend themselves to easy forecasting of future market demand, and precision farming products are a prime example. It is common to use a three stage approach, firstly preparing a macroeconomic forecast, followed by an industry forecast and finally a company sales forecast.

A confidential industry forecast for combine sales has been conducted by the AEA which shows that despite a steady 20 % growth over the past 3 years in combine sales, the market will drop from 1573 to approximately 1000 units over the next 2 years.

However there has been a 110 % growth in sales of machines with yield mapping capabilities over the past 3 years and this is predicted to continue, resulting in a projected 1998 sales figure of approximately 250 units.

At company level, several sources of information on potential demand can be investigated. Firstly the opinion of the company sales force, in terms of sales to current and prospective customers, can be sought. Although these employees may not be aware of larger economic developments, they are aware of customers needs and opinions and have good insight into any developing trends. This is difficult to apply to this study, as the sponsor's current sales are mainly to farmers who will not adopt precision farming technology in the near future. During trade shows and exhibitions, the sponsor has received numerous enquiries concerning yield mapping but no record of numbers has been kept.

Expert advice can be sought from marketing consultants, trade associations, dealers, distributors and suppliers. However, in this case, the product will be offered directly to the manufacturer or customer and marketing consultants cannot be justified within the sponsor's budget.

As the sponsor has not previously sold a similar product, the prediction of future demand has to be a subjective one, made as a combination of current sales, market growth and estimated market share, thus

Current UK market	= 1573 units
Current market potential value	= £ 4179000
Predicted 1998 market	= 1000 units
Predicted 1998 market potential value	= £ 3000000
Estimated market share - year 1	= 5 %
Resulting market share	= 50 units
Resulting market share value	= £150000

If the correct marketing and pricing policy is used and the 5 % market share realised, the demand is estimated at 50 units for the first year. This figure will be amplified in further years if more market share is gained or the market expands.

Although this is a subjective assessment, the potential of the precision farming market is clearly visible. To benefit from this, care is needed in the pricing policy and marketing approach, , ensuring penetration into this potentially profitable market.

To guide the development of the new transducer system, the process of new product development (NPD) was used. This allowed each stage of the research work to be identified and commercial influence to be included into what was considered a mainly technical study. The process of new product development is represented in Figure 1.5 showing the complete process in flow chart form, from corporate strategy to launch. For this study, the process will be followed down to the business analysis stage, with recommendations for further stages being made.

The starting point of the NPD process is corporate strategy linked to core skills and business scope. The company should have a clear direction for research and development, linked to its core skills. In this study, the sponsor's core skills are centred around low volume production of measurement devices for agriculture. Through this product they can maintain their position as innovators of these devices.

The generation of ideas can come from many quarters, employees, research and development, customers, competitors and distributors. In this study, research and development will play a pivotal role in idea generation. Although customer input is vital, this avoids the myopic view of customers or distributors, who cannot express the need for a product they have never envisaged. The objective of idea generation is to maximise the number of ideas, the purpose of exploration and analysis is to select the few with the most potential for success considering the market need. This potential depends upon, (i) The ideas compatibility with the companies corporate strategy, (ii) the potential demand for the product, and (iii) the firms capability to exploit the product opportunity. In this study, a weighted scoring system based upon experience and knowledge of competitor products was used.

Once a concept is selected, it requires development and testing, whether in the field or against potential customers. In a study such as this one which is mainly technical, concept testing is the key stage in this development process.

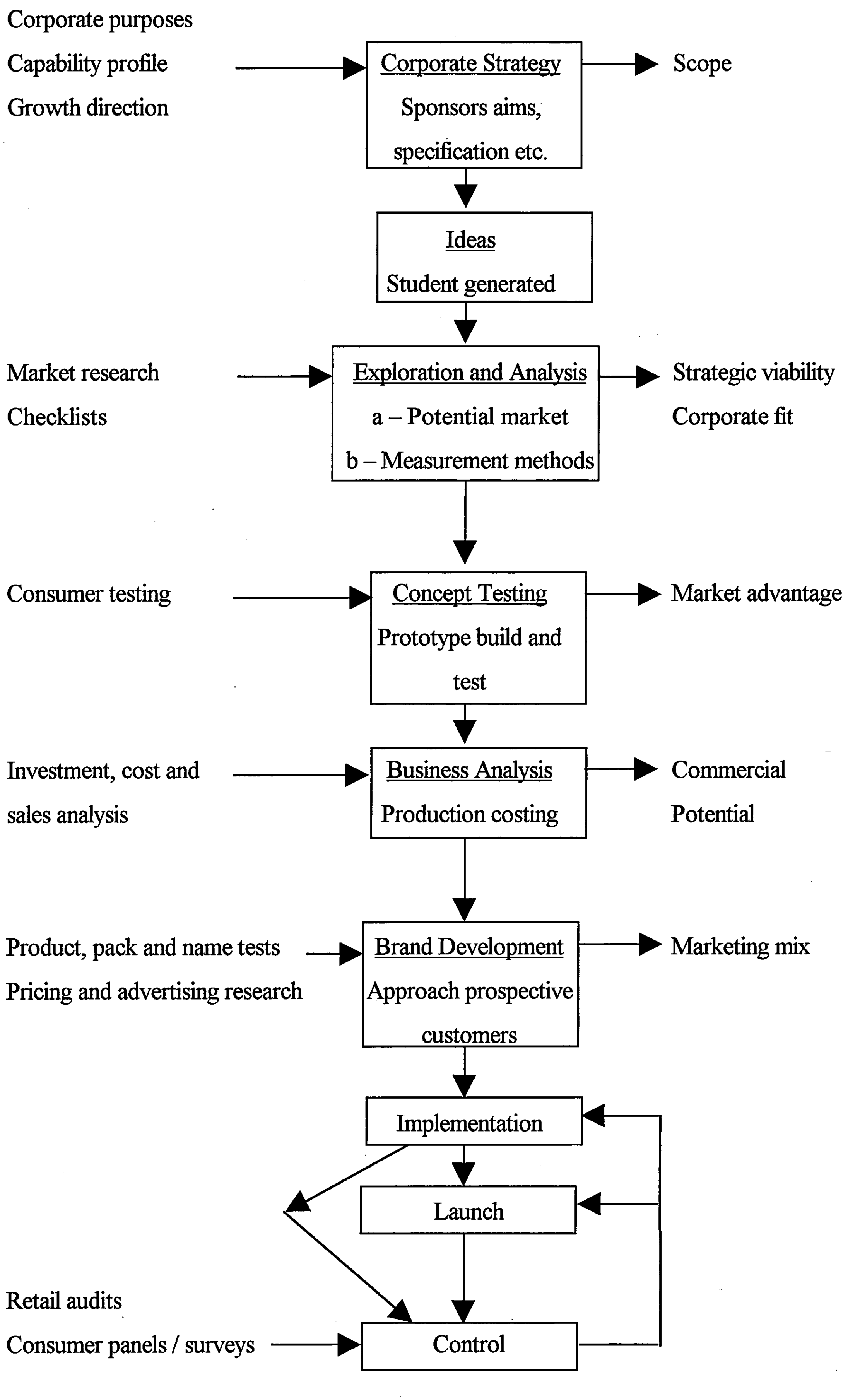


Figure 1.5 - The Process of New Product Development (after Kotler, 1994)

The business analysis will be the final contribution of this study to the NPD process. Although this analysis is mainly financial, it can be a mistake to base any decision purely upon this, as the product may be the key to maintaining a market presence and future profits. This may not be in the short term interests of the shareholders, but can be used in the long term to preserve jobs and demonstrate the company's commitment to the community.

Brand development can be viewed as an extension of the concept testing stage, developing the product and ensuring the marketing mix (name, price, distribution and promotion) are correct through customer pilot tests.

If the brand development tests are encouraging, implementation will be the next process. This can take the form of test marketing, regional roll outs or a full national launch. Test marketing involves launching the product in one or more parts of the country and determining how the product would fare in realistic conditions. Regional roll outs are a natural progression from the test marketing, allowing the marketing process to be fine tuned in each region depending upon customer reaction in previous regions. The national launch is used if the company aims to pre-empt the competition, providing it has the resources. Followers find it much more difficult to achieve market share, having to convince the consumer that there product is even better than the original.

Complimentary to a review of relevant literature and NPD, a brief review of currently available commercial models was undertaken. Since the advent of precision farming in the late 1980's, very few commercial systems have appeared on the market. Table 1.1 is a review of the systems, their advantages and disadvantages, end user cost and an assessment of cost per hectare per year.

Table 1.1 - Assessment of Commercially Available Systems

SYSTEM	MEASUREMENT METHOD	COST (£)	COST (£/Ha/Yr)	CLAIMED ACCURACY	ADVANTAGES	DISADVANTAGES
RDS Ceres 2	Optical	4350	2.17	2 %	Well researched, good dealer network, part of a larger package - expandable.	Expensive, many extras needed, regular calibration needed.
Claas CEBIS	Capacitive	3800	1.9	3 %	Factory fitted with technical backup, handles high flow rates.	Inaccurate, unreliable, very moisture sensitive.
Griffith Elder Grain Brain	Force reaction	1200	0.6	1.50 %	Accurate, robust, simple and low cost.	Only for unloading auger so no mapping capability.
Claydon Yieldometer	Pelton Wheel	3500	1.75	1 %		Dubious accuracy, not fail-safe, only volumetric measurement.
Ag-Leader YM2000	Force reaction	3900	1.95	2.50 %	Accurate, robust, simple.	Poor in wet crops, expensive.
Microtrack	Force Reaction	1500	0.60	4 %	Simple, easily fitted	Inaccurate, moisture content and crop sensitive
Dronninborg Flowcontrol (MF)	Gamma absorption	3500	1.75	1 %	Simple, robust, not moisture sensitive.	Radioactive source causes concern, not available as retrofit.

NB - Prices do not include DGPS positioning system

1.5 - EVALUATION OF CONCEPTS

To investigate the most suitable methods of mass measurement for further investigation an design technique - value analysis (Dyson, 1991) was used. The methods of measurement reviewed, were categorised and a marking criteria set. Each marking criteria was weighted according to importance and each category of measurement method awarded marks in each criteria. From the total of these an overall score for each category was found.

Table 1.2 - Marking Criteria and Weightings

MARKING CRITERIA	WEIGHTING /10
Accuracy	9
Simplicity	7
Cost	6
Durability	8
Fail-safe (will the combine stop if transducer fails)	8
Sensitivity (to vibration, ambient conditions and installation)	5
Flow restriction	6
Need for calibration/Bushel weight	4
TOTAL	53

Each marking criteria and overall total for each measuring technique are shown in Table 1.1, Appendix 1, and Figure 1.6. From this figure, it can be clearly seen that force reaction devices appear most suitable to the design criteria, with a score of 80%. Gamma absorption methods offer a second choice with 76%. Other categories considered scored considerably lower marks, with the pelton wheel the lowest at 36%. Therefore, force reaction measurement techniques appear to offer a sensible starting point for this study.

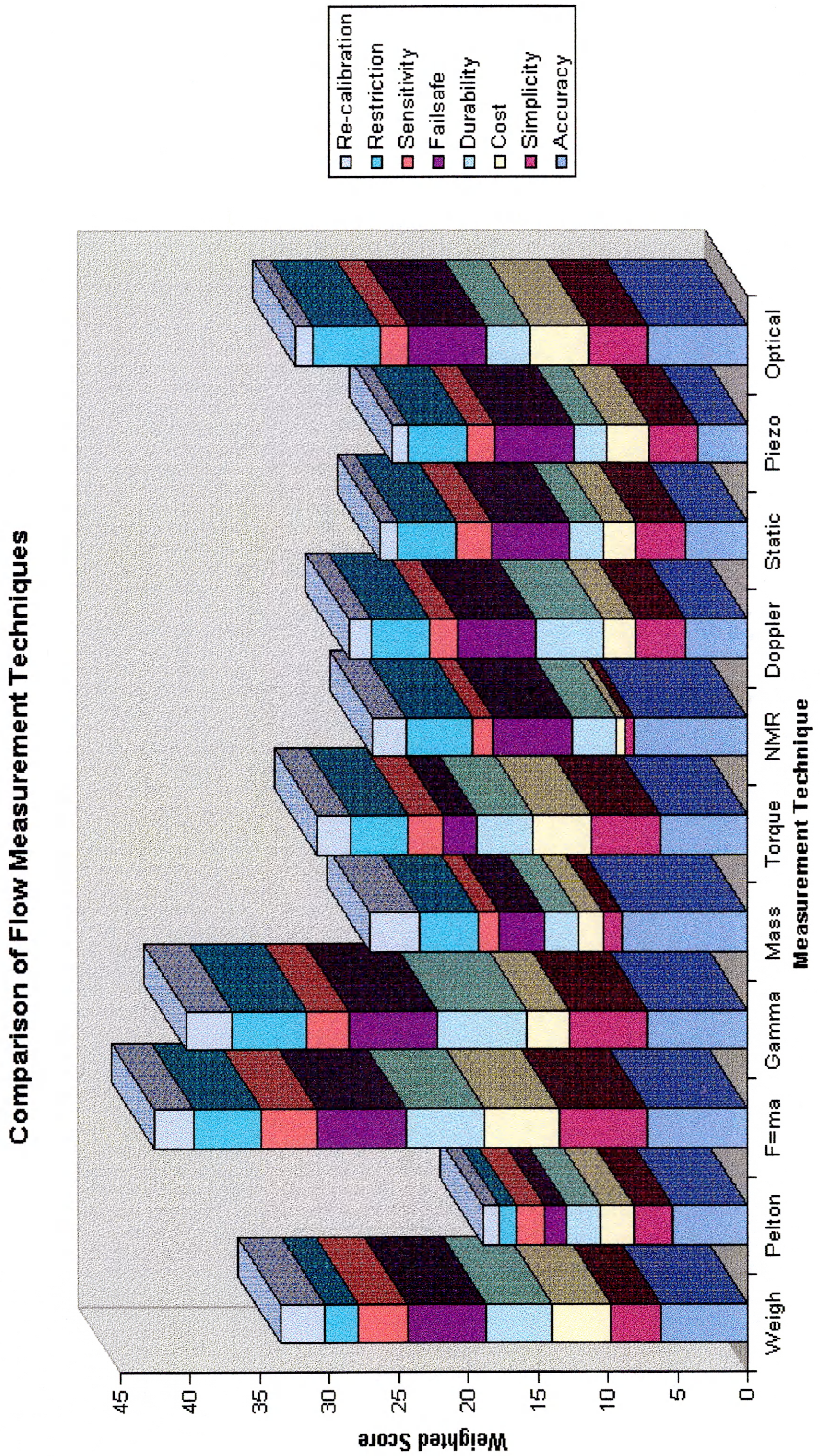


Figure 1.6 - Comparison of Flow Measurement Techniques

1.6 - OBJECTIVES

The objectives of this study are

1. To select the design parameters for a novel mass flow measurement system for "free" flowing granular materials, regardless of moisture content or material characteristics, using the principles of force reaction.

2. To design transducer systems capable of measurements within 1.5 % accuracy on accumulated mass, and 2 % on 'spot' flow rate readings.

3. To evaluate the performance of the system via theoretical, laboratory and field studies.

4. To identify the commercial potential for the device, its manufacture and its potential for further development.

CHAPTER 2

THEORETICAL MODELLING AND SENSITIVITY ANALYSIS

2.1 - INTRODUCTION

Initial studies have identified the force reaction type transducer as being the most suitable for further development in this study. The object of this work was to predict the behaviour of the sponsor's current force reaction transducer, for varying plate angles (as would happen when harvesting on a hill) and when monitoring different crops. This was achieved by formulating a mathematical simulation of the device and using this to conduct a sensitivity analysis.

This work increased understanding of transducer and crop behaviour using the sponsor's current transducer, making it a natural extension of the idea generation element of the new product development process.

2.2 - SYSTEM DESCRIPTION

The sponsor's of this thesis use strain gauge technology in their current force reaction transducer, the 'Grain Brain', a device for measuring crop mass flows from the combine unloading auger, consisting of a reaction plate mounted upon a strain gauge beam, the complete unit being referred to as the transducer. This is pictured in Plate 2.1, with each component labelled.

The Griffith Elder force reaction transducer is available in two models. The earlier 'Yield per Field' model, hereafter referred to as a type 1, uses a 1 millimetre thick 280 millimetres square mild steel type 1 reaction plate. The type 1 strain gauge beam uses four strain gauges; mounted on two opposed flats milled onto a round section cantilever beam, which are wired as a four arm active bridge. The later 'Grain Brain' model, hereafter referred to as type 2, uses a larger type 2 reaction plate of 320 millimetres by 300 millimetres, made of half hard aluminium (NS4), has the advantage of less weight.

The type 2 strain gauge beam is also constructed from aluminium and is rectangular in section with a slot milled along the centreline. The two external faces accommodate six strain gauges, again wired as a four arm active bridge but using two gauges for temperature compensation. Due to the thinner sectional area where the gauges are mounted and the material from which the beam is made, sensitivity in comparison with the type 1 is greatly improved. Plate 2.2 shows details of both transducers.

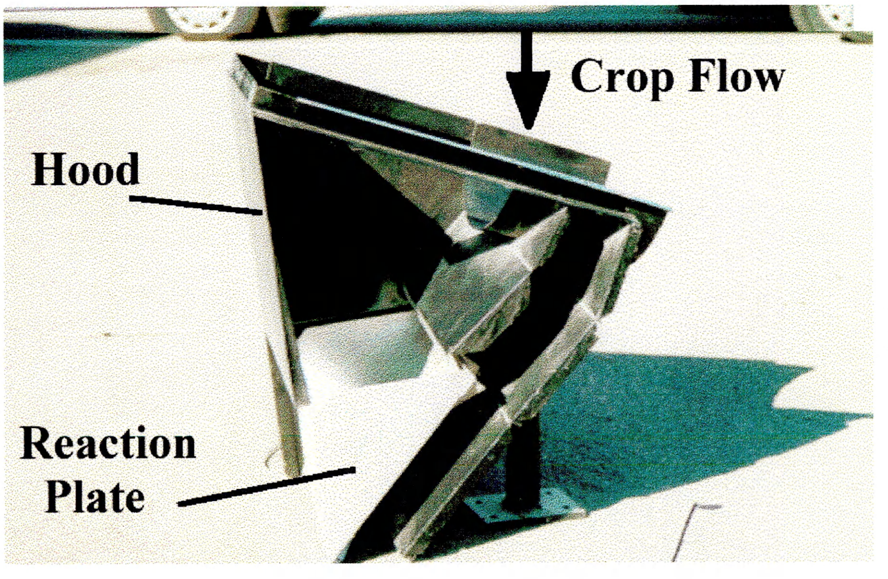


Plate 2.1 - Section of 'Grain Brain' Unit, Detailing Components

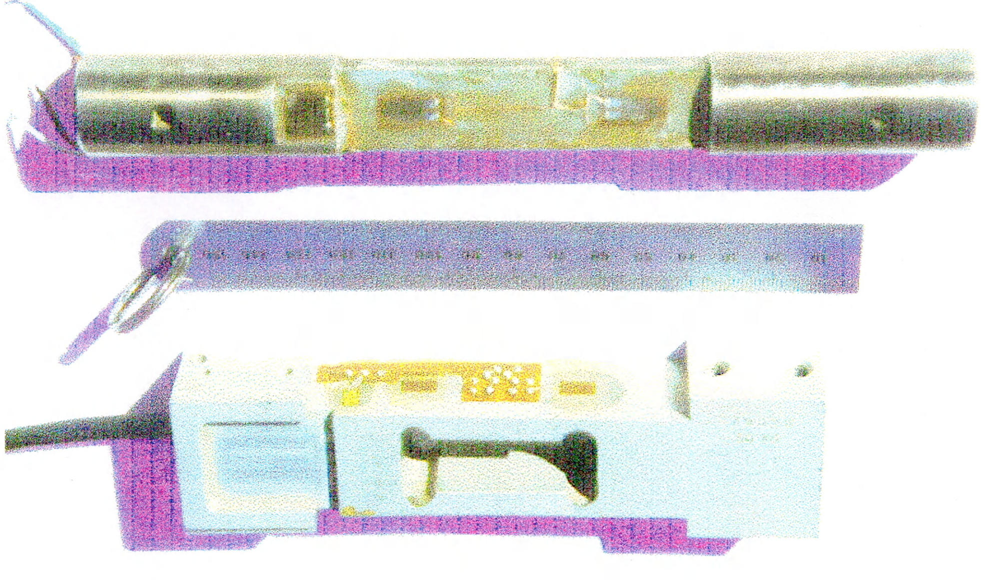


Plate 2.2 -Strain Gauged Beams Used on Griffith Elder Transducers

2.3 - DEVELOPMENT OF MODEL

Before developing a force reaction model the following assumptions about the behaviour of flowing material and plate/material interactions were made:

1. The falling crop does not experience drag due to air friction or any particle interactions, i.e. it flows as a slug of material.
2. The movement of each particle has no effect on any others.
3. Every particle impacts the plate.
4. Every particle is in direct contact with the plate when sliding down, i.e. there are no multi-layer flows.
5. Every particle slides down the plate, i.e. there is no rolling or bouncing.
6. Every particle is identical with the same coefficient of friction.
7. Coefficient of friction only affects residence time.
8. Every particle travels the same distance directly down the plate with no sideways movement.
9. When the crop hits the plate, the momentum giving rise to impulsive forces normal to the plate is destroyed.
10. The total force acting on the plate due to crop flow consists of two components, (i) The impulsive force of material striking the plate, and (ii) The weight of material as it travels down the plate.

For prediction purposes, the total force 'F' had to be determined. A simple diagram, Figure 2.1, shows the two components of total force.

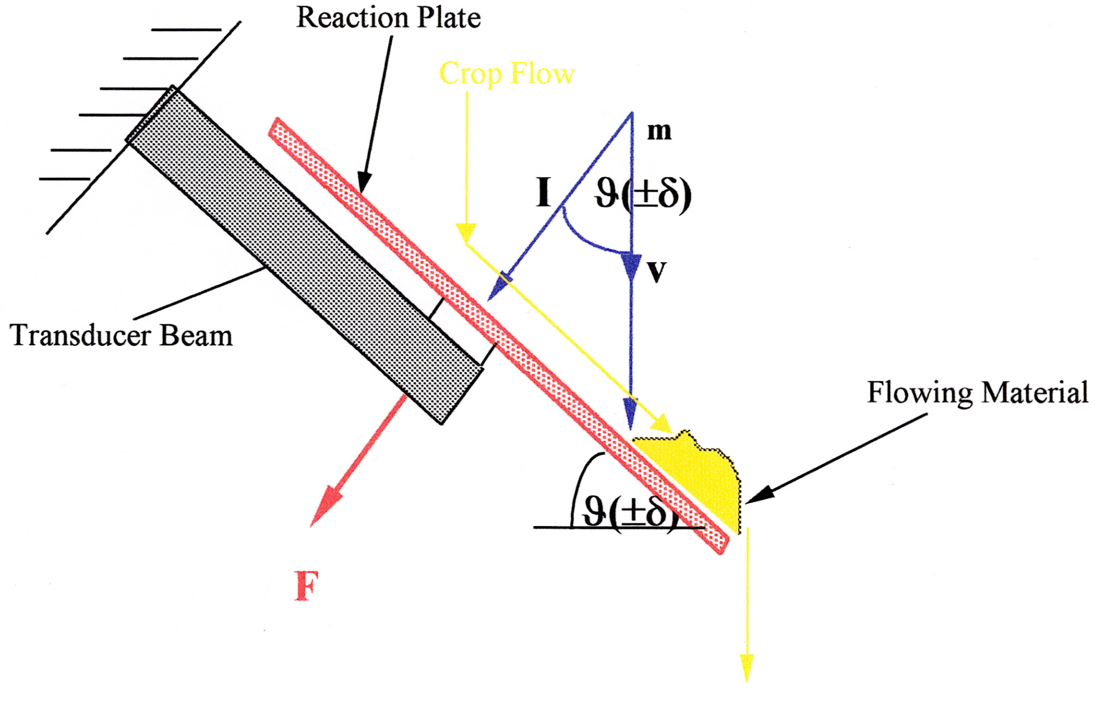


Figure 2.1 - Schematic Layout of Flowing Material Detailing Forces

When the material strikes the plate, all velocity normal to the plate is destroyed, hence the impulse force, I, is equal to the rate of change of momentum normal to the plate, hence :

$$I = m \cdot v \cdot \cos(\vartheta \pm \delta) \qquad \text{Equation 2.1}$$

where :

I	= impulse force	(N)
m	= mass flow rate	(kg/s)
v	= velocity of material	(m/s)

(where $v = \sqrt{2.g.h}$, where h is the material drop height)

ϑ	= plate angle	(degrees)
δ	= small variations in plate angle (offering simulation of roll effects)	(degrees)

M is the mass of material on the plate at any one time and is the result of mass flow rate (m) and residence time (t_R). This weight exerts a force, N, normal to the plate of:

$$N = m \cdot t_R \cdot g \cdot \cos(\vartheta \pm \delta) \qquad \text{Equation 2.2}$$

Hence the total force normal to the plate, F, is given by:

$$F = m \cdot v \cdot \cos(\vartheta \pm \delta) + m \cdot t_R \cdot g \cdot \cos(\vartheta \pm \delta) \qquad \text{Equation 2.3}$$

$$\therefore \Rightarrow F = m\,(v + g \cdot t_R) \cdot \cos(\vartheta \pm \delta) \qquad \text{Equation 2.4}$$

2.4 - MATHEMATICAL PREDICTION OF BEAM SENSITIVITIES

Using the previously developed model, the force 'F' exerted upon the transducer over a range of flow rates can be predicted. From this, if the characteristics of the strain gauge beam and excitation voltage are known, the beam output can also be predicted. It will then be possible to derive the calibration constant 'K' to express the beam signal (mV) in terms of flow rate (kg/s). This will have units of volts per kilogram per second.

All factors except drop height and material mass on plate are known. For these calculations a drop height of 0.45 metres is used, representing a typical free-fall height available in a combine. To calculate the sliding mass on the plate, firstly the residence time of the material on the plate (t_R) is calculated:

Using the equation

$$s = (u \cdot t) + (1/2 \cdot a \cdot t^2) \qquad \text{Equation 2.5}$$

where : s = distance down plate (m)

u = initial velocity (m/s)

t = time for crop to slide down plate (s)

a = acceleration down plate (m/s^2)

Assuming initial velocity as the component of the vertical velocity (during free-fall) which acts parallel to the plate upon impact :

Initial velocity (u)	$= v \, . \, \sin \vartheta$	Equation 2.6
Acceleration down the plate (a)	$= g \, (\sin \vartheta - \mu \, . \, \cos \vartheta)$	Equation 2.7

Therefore :

$$s = ((v \, . \, \sin \vartheta) \, t) + (^1/_2 \, (g \, (\sin \vartheta - \mu \, . \, \cos \vartheta)) \, t^2)$$

or in quadratic form : Equation 2.8

$$0 = \{(^1/_2 \, (g \, (\sin \vartheta - \mu \, . \, \cos \vartheta)) \, t^2) + ((v \, . \, \sin \vartheta) \, t) - s$$

Therefore : Equation 2.9

$$t = \frac{-(v \, . \, \sin \vartheta) \pm \sqrt{(v^2 \, . \, \sin^2 . \, \vartheta) + (2 \, . \, g \, . \, (\sin \vartheta - \mu \, . \, \cos \vartheta)) \, s}}{g \, (\sin \vartheta - \mu \, . \, \cos \vartheta)}$$

However, of the 2 solutions to this quadratic equation, only one can be correct as the grain only flows down the plate, therefore:

$$t = \frac{-(v \, . \, \sin \vartheta) + (v \, . \, \sin \vartheta) \sqrt{1 + \frac{2g}{(v^2 \, . \, \sin^2 \vartheta)} \, . \, (\sin \vartheta - \mu \, . \, \cos \vartheta) \, . \, s}}{g \, (\sin \vartheta - \mu \, . \, \cos \vartheta)}$$

Equation 2.10

$$\therefore \Rightarrow \quad t = v \, \frac{\left[\sqrt{(1 + \frac{2g}{v^2 \, . \, \sin \vartheta} \, . \, (1 - \mu \, . \, \cot \vartheta) \, s\}} - 1 \right]}{g \, (1 - \mu \, . \, \cot \vartheta)}$$

Simplifying :

$$\Rightarrow \quad t = \frac{v\left[\sqrt{1 + \frac{2\,s\,.\,A}{v^2\,.\,\sin\vartheta}} - 1\right]}{A} \qquad \text{Equation 2.11}$$

$$\text{where :} \quad A = g\,(1 - \mu\,.\,\cot\vartheta) \qquad \text{Equation 2.12}$$

Using values of :

$v = \sqrt{2\,.\,g\,.\,h} = \sqrt{2 \times 9.81 \times 0.45}$ = 2.97 m/s

μ (12.5 % moisture content wheat on steel) = 0.45

ϑ = 45^0

$A = 9.81\,(1 - (0.45 \times \cot 45))$ = 5.39

For a type 1 plate, where s = 0.21m, using Equations 2.11 and 2.12 :

$$\Rightarrow \quad t_R = \frac{2.97\left[\sqrt{1 + \frac{2 \times 0.21 \times 5.39}{6.24}} - 1\right]}{5.39}$$

$$\Rightarrow \quad t_R = \frac{2.97\,.\{1.167 - 1\}}{5.39}$$

$$\Rightarrow \quad t_R = 0.092 \text{ seconds}$$

For a type 2 plate, where s = 0.23m, using Equations 2.11 and 2.12:

$$\Rightarrow \quad t_R = \frac{2.97\left[\sqrt{1 + \frac{2 \times 0.23 \times 5.39}{6.24}} - 1\right]}{5.39}$$

$$\Rightarrow \quad t_R = \frac{2.97\,\{1.182 - 1\}}{5.39}$$

$$\Rightarrow \quad t_R = 0.1 \text{ seconds}$$

These times can be used to calculate the sliding mass on the plate at any flow rate, i.e. at 10 kg/s, a mass of 1 kilogram will be on a type 2 plate at any one time.

Using this information it is now possible to calculate the total force (F) on the plate at a variety of flow rates using Equation 2.4. For example, at 5 kg/s, using a type 2 plate :

$$F = m\,(v + g\,.\,t_R)\,.\,\cos(\vartheta \pm \delta)$$
$$F = 5\ (2.97 + 9.81\ .\ 0.1)\,.\,\cos 45$$
$$F = 17.79\ N$$

If the voltage output of each transducer beam relative to force is known, and the force for each transducer type relative to flow rate calculated, the relationship between flow rate and transducer voltage ($V.kg^{-1}.s$) can be found, this is the calibration constant. Figure 2.1, Appendix 2, shows the range of flow rates and resultant predicted forces. From these the slopes of the lines can be seen as

Type 1   2.7 $N\,.\,kg^{-1}.s$

Type 2   2.8 $N\,.\,kg^{-1}.s$

To relate these forces to a voltage output from the transducer beam, two methods were used.

1. Knowing the dimensions, material characteristics, gauge characteristics and electrical input of the type 1 transducer, the voltage output over a range of forces could be calculated. The type 2 beam was not subjected to this calculation due to its complex construction.
2. Each was calibrated by static loading, using 12 volts excitation and recording the resultant signal changes with a computer adapted for data acquisition. The results are plotted in Figure 2.2, Appendix 2.

To theoretically derive strain gauge bridge output for a 4-arm active differential bridge arrangement, the strain at any gauge position for a rectangular section cantilever beam is given by:

$$\varepsilon = \frac{6 \cdot F \cdot a}{E \cdot b \cdot d^2} \qquad \text{Equation 2.13}$$

where : ε = mechanical strain

F = Force applied to cantilever beam (N)

a = Distance of line of action of force F from gauge centres (m)

E = Youngs modulus (N/m^2)

b = width of transducer beam (m)

d = depth of transducer beam (m)

The change in voltage output from the bridge can be expressed as

$$\Delta V = \frac{V_0}{4} \cdot \left[\frac{\Delta R_1}{R} - \frac{\Delta R_2}{R} + \frac{\Delta R_3}{R} - \frac{\Delta R_4}{R} \right] \qquad \text{Equation 2.14}$$

where : ΔV = variation in bridge output (V)

ΔR = change in gauge resistance (Ω)

V_0 = bridge supply voltage (V)

The resistance ratio can be expressed as a function of gauge factor (k) and strain

$$\frac{\Delta R}{R} = k \cdot \varepsilon \qquad \text{Equation 2.15}$$

The sensitivity of this system, in terms of volts per Newton, is therefore given by

$$\frac{\Delta V}{F} = \frac{V_0}{2} \cdot \frac{6 \cdot k}{E \cdot b \cdot d^2} \cdot l \qquad \text{Equation 2.16}$$

where : l = distance between the pairs of strain gauge centres for a differential arrangement (m)

Applying Equation 2.16 to the type 1 transducer beam:

$$\frac{\Delta V}{W} = \frac{12}{2} \cdot \frac{6 \times 2.1}{200 \times 10^9 \times 0.016 \times 0.008^2} \times 0.06 \qquad = 21.2\ \mu V/N$$

Therefore, beam output = 21.2 $\mu V/N$ $\times$ 2.7 N . $kg^{-1}.s$ = 59 $\mu V.kg.s^{-1}$

This theoretically derived beam output can be compared with the static calibration shown in Figure 2.2, the beam output being the slope of the line. It can be seen that for the type 1 beam, both outputs are 0.00059 volts per kilogram per second, highlighting the predictability of the analytical model. The static calibration of the type 2 beam shows an output of 0.022 volts per kilogram per second.

2.5 - SENSITIVITY ANALYSIS ON VARIABLES

Using the equations derived, it became possible to determine the effect of differing crops and hence coefficient of friction (μ) and differing plate angles ($\vartheta \pm \delta$) upon the transducer. From these calculations it was possible to discover if any of these factors required special attention during practical testing and subsequent novel transducer development.

2.5.1 -Effect of Varying Coefficient of Friction

The coefficient of friction (μ) between reaction plate and crop will affect the amount of sliding material on the plate and hence the overall signal produced. It may vary with each crop type harvested, the variety, the ripeness, the moisture content, the amount of trash in the sample and the material and condition of the reaction plate. As these factors may vary across each field the variations in coefficient of friction are unpredictable. Ideally, the transducer needs to be relatively insensitive to these changes, which are in the range of 0.3 to 0.6 (Clarke, 1984).

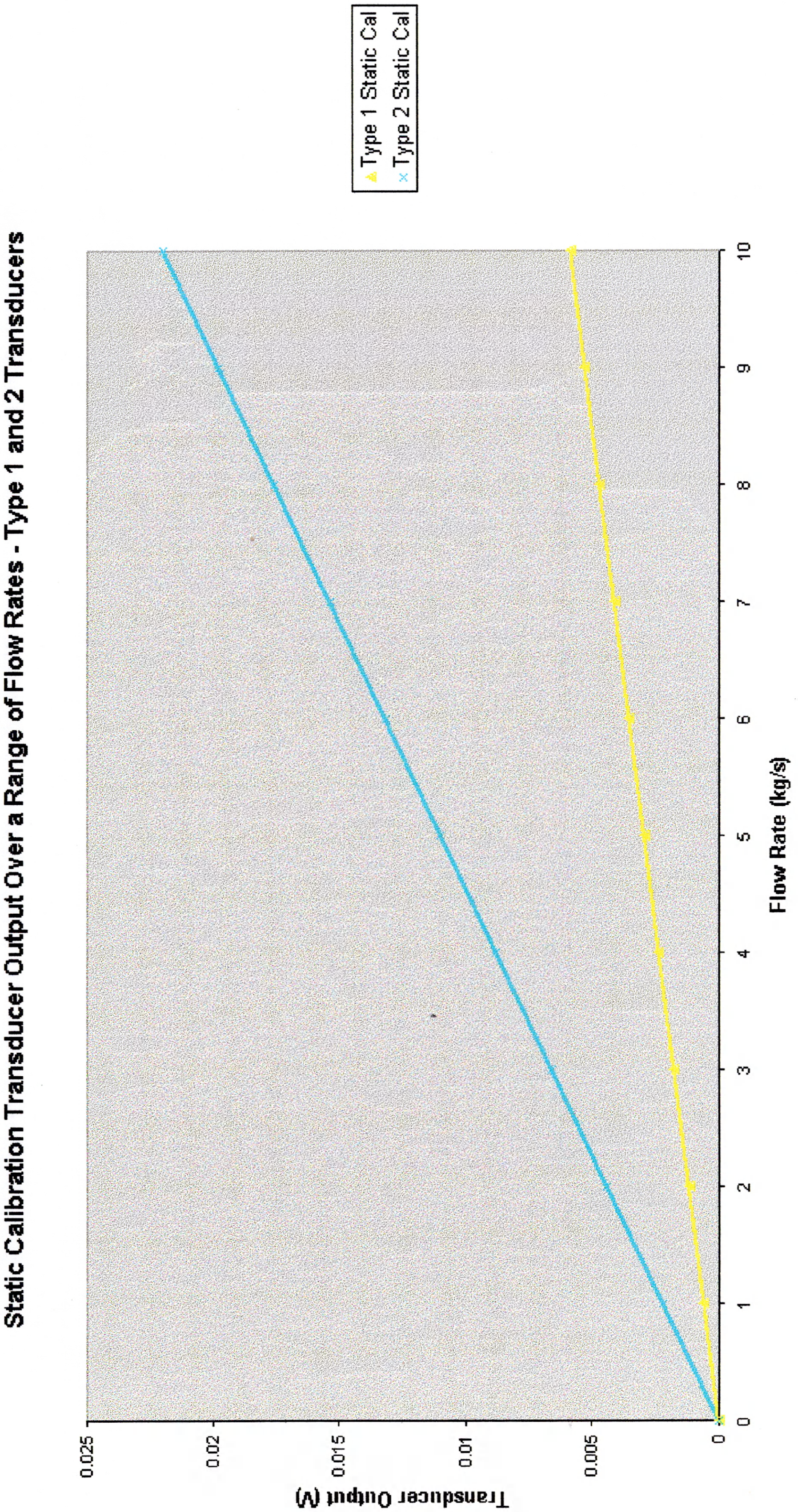


Figure 2.2 - Static Calibration Transducer Beam Output Over a Range of Forces Type 1 and 2 Beams

Using Equation 2.11 and 2.12, it is possible to predict the time each particle will be on the reaction plate and from this calculate the sliding mass at any given flow rate. Equation 2.4 can then be used to predict the force generated normal to the reaction plate.

A range of coefficient of friction values are considered in Table 2.1, assuming a maximum flow rate of 10 kg/s and a type 2 transducer.

Table 2.1 - Predicted Friction Effects Upon Total Transducer Force (mass flow rate 10 kg/s)

Coefficient of friction (μ)	Time on Plate (s)	Force on Beam (N)	% Deviation from 12.5 % m.c. wheat ($\mu = 0.45$)
0.3	0.098	27.8	-0.3
0.35	0.099	27.8	-0.3
0.4	0.1	27.9	0.0
0.45	0.1	27.9	0.0
0.5	0.101	28.0	0.3
0.55	0.102	28.0	0.3
0.6	0.102	28.1	0.7

Considering a typical 12.5 % moisture content winter wheat where $\mu = 0.45$ (Clark, 1984), it is shown that the signal variation due to changes in coefficient of friction will be a predicted maximum of +0.7 % ($\mu = 0.6$). This variation is very low because friction only has a small effect upon the sliding mass on the reaction plate, which in turn contributes only approximately one third of the overall force.

Theoretically, friction has a minimal effect upon force and hence on the transducer signal. However practical tests should include test materials with a wide range of coefficient of friction values to substantiate these calculations.

2.5.2 -Effect of Varying Plate Angle

When harvesting on a slope, the reaction plate will be subjected to this slope. Very few fields are completely flat and therefore the effects of slope are important. Ideally the transducer should be insensitive to these. Using Equation 2.4, the total force (F) for a type 2 reaction plate can be calculated at various plate angles, for a 10 kg/s flow rate, as in Figure 2.3 over.

This Figure shows that as the plate angle reduces, the force upon the plate increases. This is due to two factors :

1. The sliding mass takes longer to flow the length of the plate.
2. The impact force acts more directly upon the beam.

The plate angle therefore has a much larger influence on the magnitude of the signal than friction and requires practical evaluation and suitable design to provide subsequent compensation.

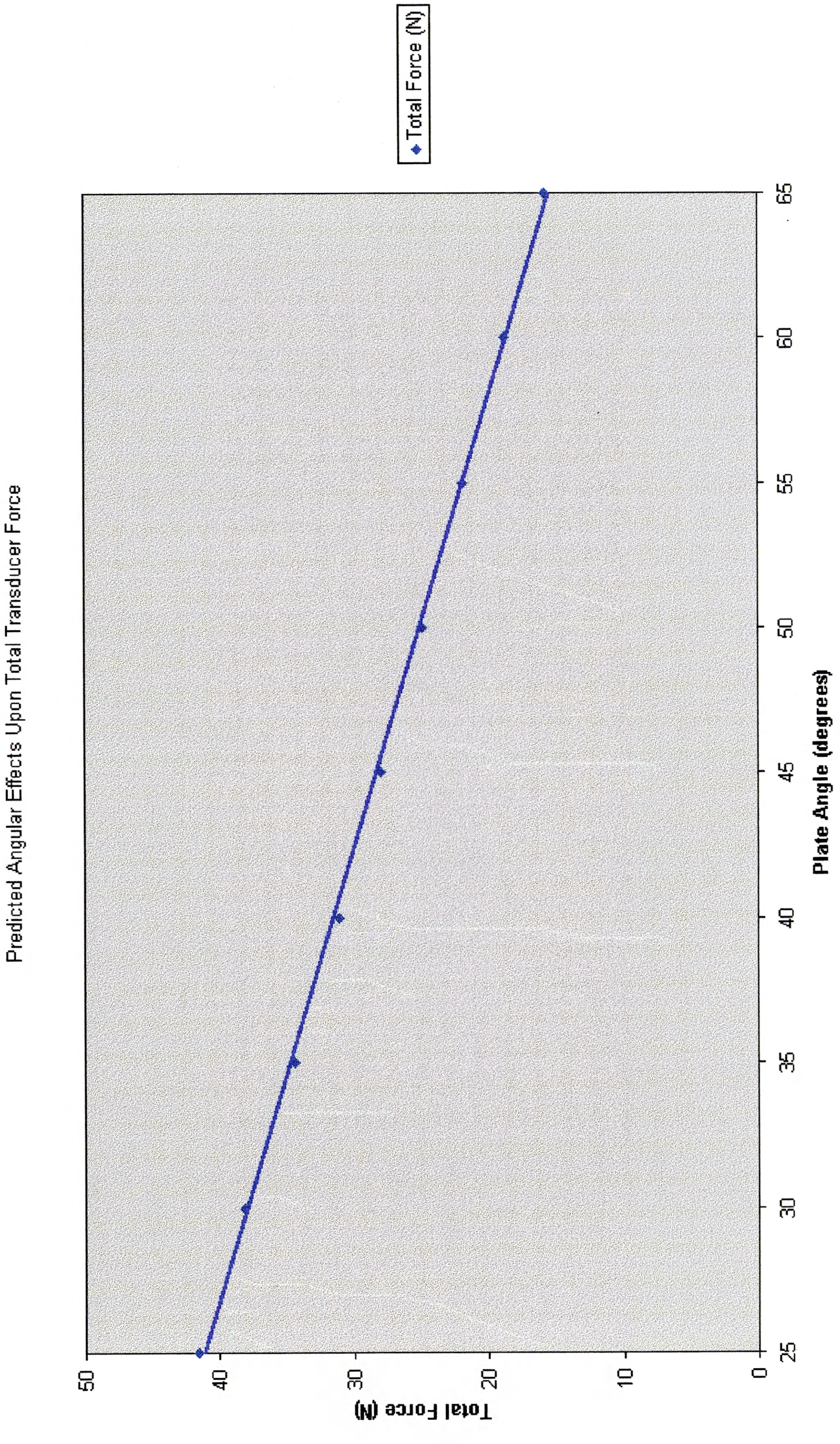


Figure 2.3 – Predicted Angular Effects Upon Total Transducer Force

2.6 - CONCLUSION

Using basic mathematical and dynamic principles a simple model applicable to the force reaction transducer studied was developed. The resulting voltage output was predicted using a static calibration and confirmed using a simple beam equation. This allowed prediction of the effect of roll angle and coefficient of friction on the transducer output.

Material type (and related coefficient of friction), was determined as having a minimal effect upon the transducer's output, the friction range for agricultural crops causing a variation in the worst case of +0.7 % when compared with 12.5 % moisture content winter wheat. This will be investigated further experimentally.

From the model, it was possible to predict the effect of varying plate angles (such as when harvesting across a slope). This was found to have a significant effect with a 20 degree reduction in plate angle from the standard 45 degrees causing a 49 % increase in signal; and a 20 degree increase causing a 44 % reduction in signal.

Having theoretically estimated the sensitivities and characteristics of the force reaction transducer, the results needed substantiating experimentally, using a range of biological and mineral particulates in laboratory tests.

CHAPTER 3
EXPERIMENTAL EVALUATION OF THE MODEL, ITS SENSITIVITY TO THE EFFECT OF MATERIAL FRICTION AND ANGULAR EFFECTS

3.1 - INTRODUCTION

The aim of this work was to provide a valid experimental background to, (i) evaluate the accuracy of the model previously developed, (ii) determine the effect of grain type, moisture content and coefficient of friction, (iii) determine the significance of slope effects and (iv) determine the linearity and repeatability of the transducer system.

To perform these studies, a standard laboratory procedure was established using apparatus constructed to allow a range of systems to be compared. Using these procedures, the signal linearity and repeatability of the force reaction transducer using differing crops at varying moisture contents and angles were assessed together with an understanding of the behaviour of crop flow.

During this study two methods of measuring accuracy were used

1. Total mass flowed, i.e. a measure of the accumulation of grain, being found by integrating the transducer signal with respect to time.
2. A spot reading of flow rate, found from multiplying the transducer signal and calibration constant.

This stage of the study was considered to be the "exploration and analysis of ideas" element of the new product development process. By practically operating a measurement system, a valuable insight was achieved into the mechanics of flowing materials as well as highlighting any problems with the current system.

3.2 - DESIGN AND CONSTRUCTION OF TEST APPARATUS

Before the test apparatus was designed its function and therefore desired features (specification) had to be decided. The following design criteria were set :

- The apparatus should be versatile enough to support any transducer system at angles up to 15^{O} in pitch and roll.
- It must be suitable for use both in the laboratory and possibly upon a combine.
- The flow rate should be controllable up to 10 kg/s, for any granular material.
- A constant head of material should be kept above this transducer.
- It should allow suitable instrumentation for monitoring transducer performance.

A frame structure, 2 metre high by 1 metre square was constructed from 25 millimetre angle section. It was intended to sit the transducer under test in the bottom section with the test material storage reservoir and flow controller mounted directly above it, as illustrated in Figure 3.1. In the top of this frame a $3m^3$ conical plastic hopper was mounted and acted as a reservoir for the test grain. A slider was fitted at the bottom of this to control grain flow. The reservoir fed into a funnel mounted directly beneath it, the top of which was higher than the bottom of the reservoir, this served to keep a constant head of test material above the transducer. Mounted on the bottom of the funnel, a graduated slider provided a variable aperture to control flow rate.

Directly below the funnel, the transducer was mounted. It fed the test material into a $4m^3$ catch bin, mounted upon a 10 tonne extended octagonal ring transducer, EORT (Godwin 1975). This allowed measurement of the accumulated mass of flowing crop to within $\pm0.01\%$ (full scale) which equates to ±1 kilogram.

The output from the test transducer and the EORT, which was amplified, was recorded during the study on a *Campbell 21X* datalogger, offering a resolution of 166 micro volts and an accuracy of ±0.01% (full scale). This was unloaded via an SC232A interface to a laptop computer with dedicated *Campbell* software.

Once construction was complete, the EORT was statically calibrated. This was accomplished by placing and removing a series of weights on the transducer and recording the signal. Figure 3.1, Appendix 3 illustrates the results of this calibration.

A *Panasonic* video camera was positioned 0.5 metres above the plate to examine grain to plate interactions during each test.

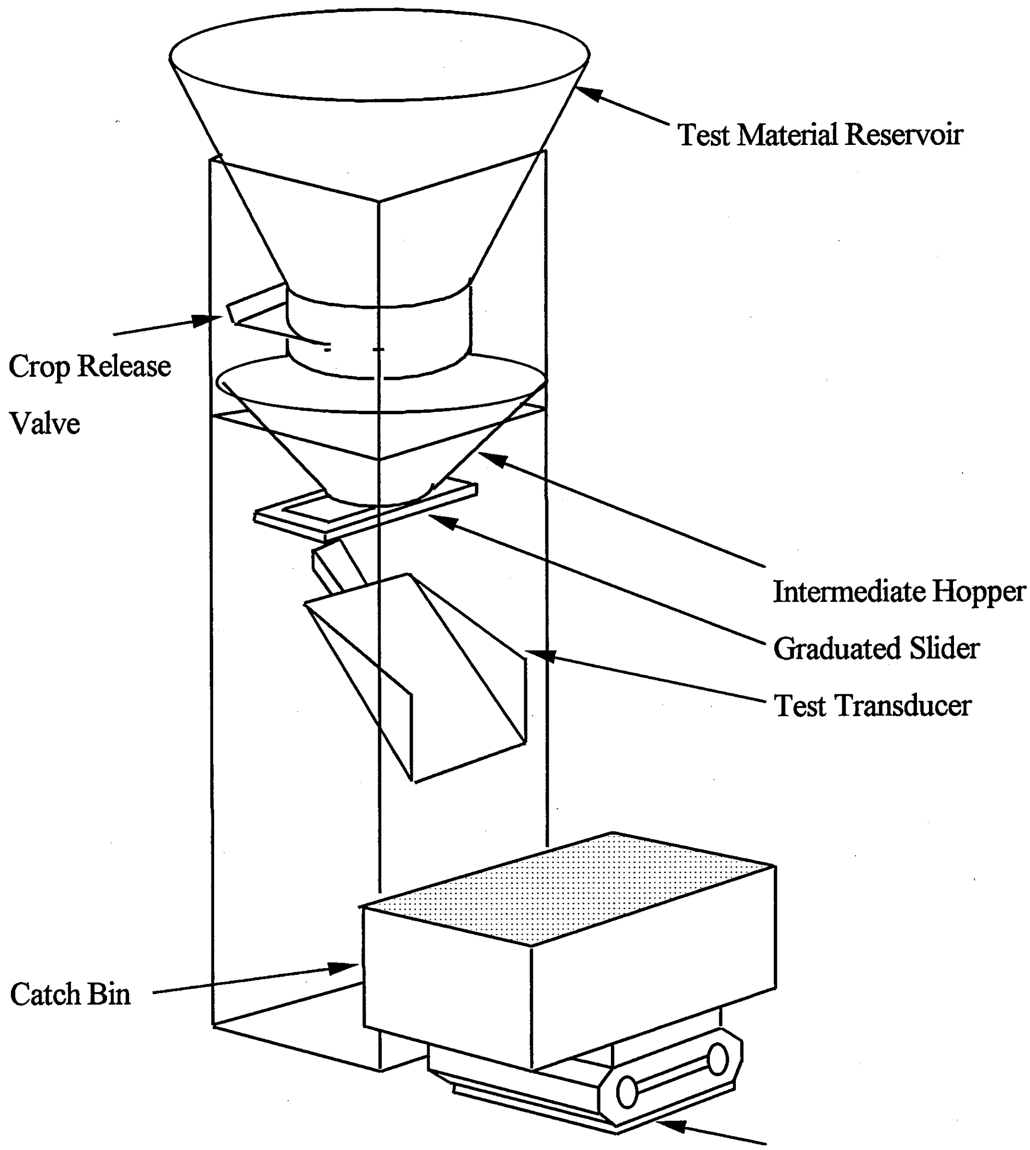


Figure 3.1 - Basic Layout of Test Apparatus

3.3 - MATERIAL FRICTION EFFECTS

3.3.1 - Test Materials

A range of biological and mineral particulates were chosen for their contrasting size, friction, density and shape, each with a different characteristic. Table 3.1 details the materials and their properties, which were determined by standard laboratory experiments.

Table 3.1 - Test Material Properties

Material	Moisture Content (% wb)	Bulk Density (kg.m^{-3})	Coefficient of Friction (μ)
Dry Wheat	12.5 %	762	0.4
Medium Wheat	23 %	700	0.58
Wet Wheat	31 %	688	0.74
Barley	12.5 %	618	0.4
Oats	12 %	412	0.43
Oilseed Rape	12 %	753	0.25
Coarse Sand	n/a	1000	0.5
Gravel	n/a	930	0.6

The range of wheat moisture contents cover the range that may be encountered in the field. The 12.5% figure is the lowest figure usually encountered in an ideal harvest, the 23% being the normal cut off point for harvesting. However, in regions where wet autumn weather is forcing a harvest, figures as high as 31% can occasionally be encountered, this is not normally financially viable due to the cost of post harvest crop drying. To achieve these moisture contents, grain wetting and drying equipment was used.

3.3.2 - Methodology

A standard procedure was adopted to use in every test run, this ensured consistency in operation and results. The crop reservoir was filled with the relevant test material and the graduated slider adjusted to an aperture suitable for the desired flow rate. The video and data recording equipment was started and the material released and allowed to flow freely over the transducer, the signal from the transducer and EORT were recorded. The crop reservoir was then reloaded and the test repeated. At least three replications were performed with each material.

Using the theoretical K_t value derived in Chapter 2, the transducer signal could be converted to flow rate and plotted over time. By differentiating the EORT signal, the actual flow rate could also be plotted on the same graph, allowing a comparison of the 2 flow rate signals. Mass accumulation could also be plotted, by integrating the transducer signal with respect to time and recording this on the same graph as the EORT signal. Typical examples of these are illustrated in Figures 3.2 and 3.3 respectively. A time lag of approximately 3 seconds, between the crop registering on the transducer and accumulating in the catch bin is clearly visible.

To assess the effectiveness of the K_t value, the final catch bin mass was compared to the total integrated transducer mass. From this the error in K_t could be found and an adjusted actual calibration constant, K_a, calculated.

Initial tests were conducted with wheat at 12.5 % moisture content using both type 1 and 2 transducers. Once confidence in the methodology had been gained, all other materials were tested. The type 1 transducer was only tested with wheat in early parts of the study, as it was decided to be of an outdated design, the type 2 offering much higher sensitivity

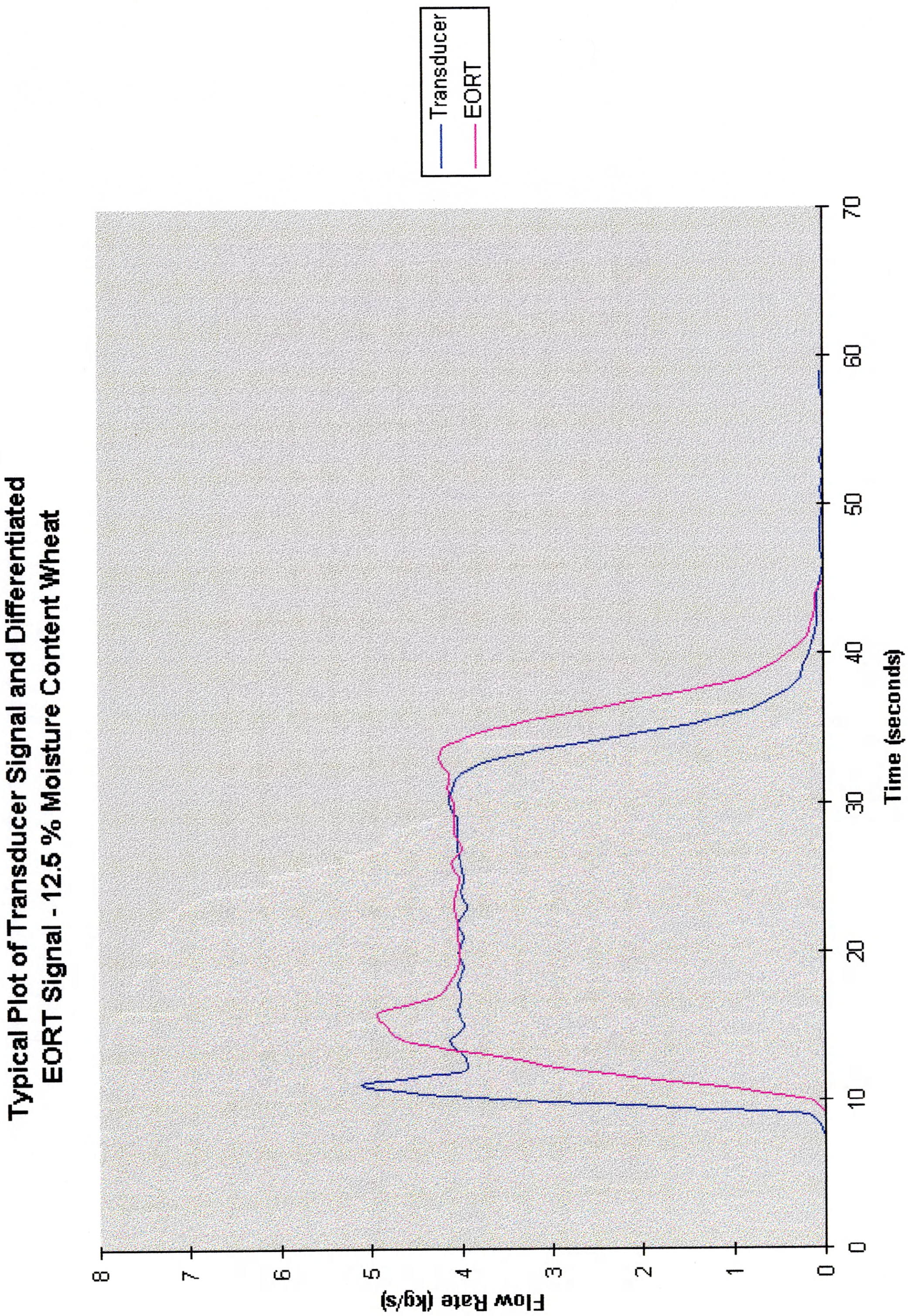


Figure 3.2 - Typical Plot of Transducer Signal and Differentiated EORT Signal
12.5 % Moisture Content Wheat

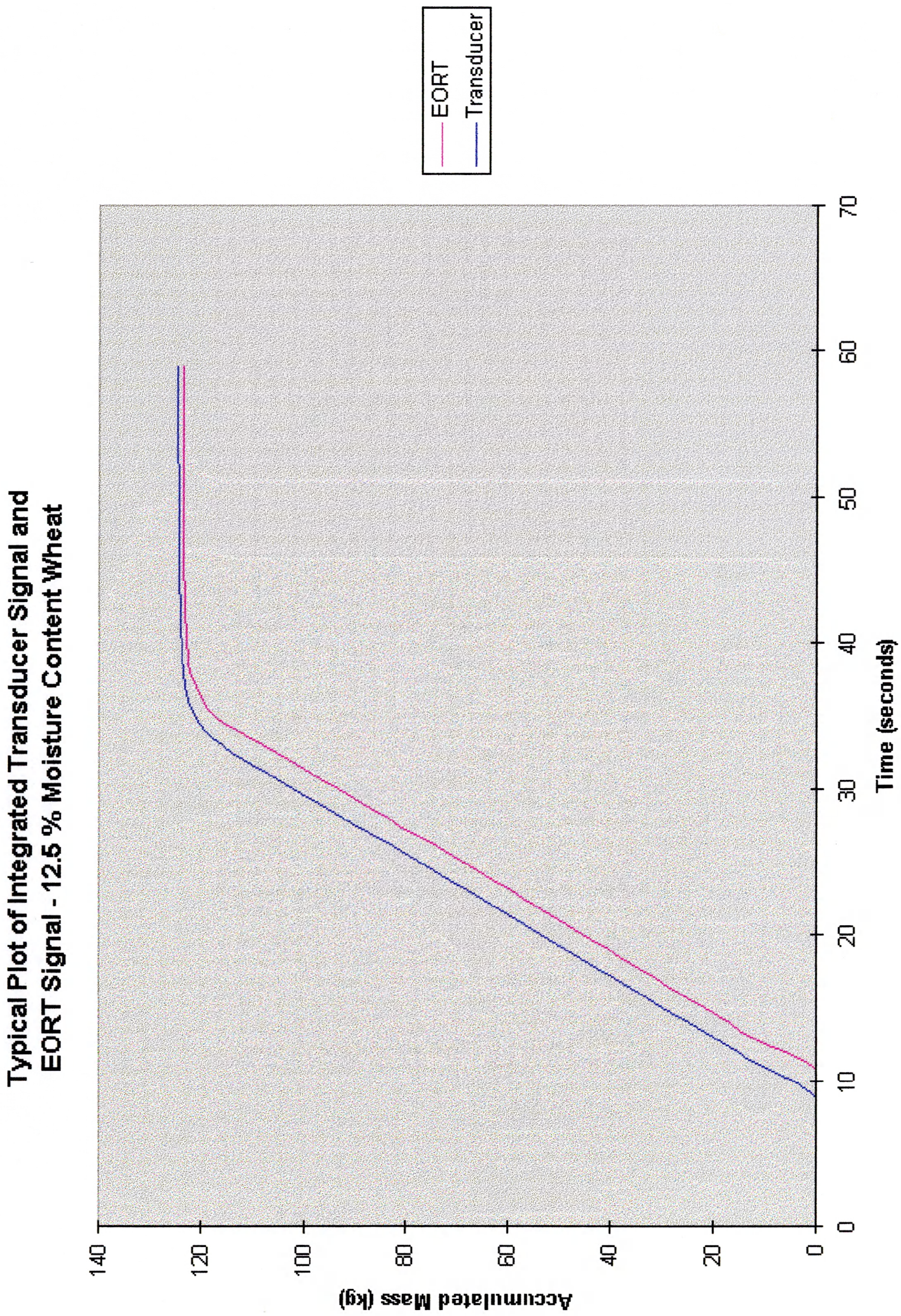


Figure 3.3 - Typical Plot of EORT Signal and Integrated Transducer Signal
12.5 % Moisture Content Wheat

3.3.3 - RESULTS AND DISCUSSION

3.3.3.1 - Type 1 Transducer

Twenty four tests were conducted over a range of flow rates using 12.5 % moisture content wheat. Two problems were observed, (i) the variation in steady state flow rate between tests using the same aperture. This was acceptable because in every test, the true mass flow rate was measured with the catch bin. (ii) The poor quality of the video, each grain appearing as a streak on every frame. This was due to the relatively slow frame speed of 25 frames per second. High speed video equipment was investigated, the costs associated with it were prohibitive therefore this approach was discontinued.

By plotting the steady state flow rates against transducer signal as in Figure 3.4, the calibration constant (K_a) was found to be :

$$K_a = 0.00071 \ (V.kg^{-1}.s) \qquad \text{Equation 3.1}$$

This is 20% greater than the static calibration value of 0.00059 $V.kg^{-1}.s$. This difference may be due to the difficulty in ensuring true steady state flow during each test or inaccuracies in the model due to the complex nature of flowing materials.

Using K_a, the transducer signal was then converted into flow rate and plotted alongside the EORT signal, showing flow rate against time for transducer and catch bin, an example of which is shown previously, in Figure 3.2. A lag between signals of 3 seconds is clearly visible. As flow commences, both signals ramp up, taking between 0.5 – 1.0 second to reach full signal as flow from the hopper reaches steady state. An initial peak in signals is apparent, caused by an early surge of material from the intermediate (flow control) hopper, until steady state is achieved. At the end of each test, the signal takes approximately 10 to 12 seconds to tail off, before the signal returns to zero.

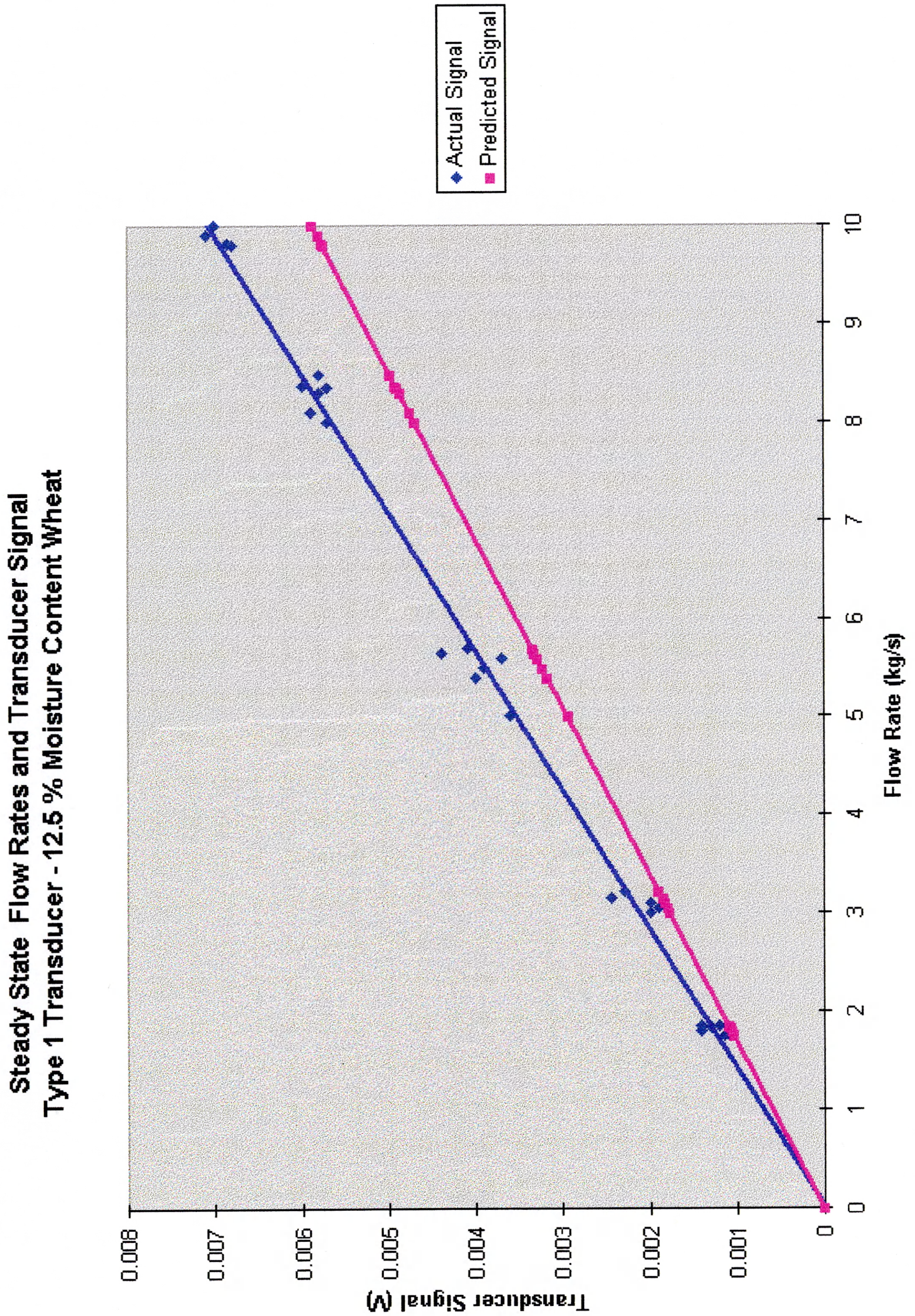


Figure 3.4 - Steady State Flow Rates and Transducer Signal - Type 1 Transducer
12.5 % Moisture Content Wheat

By integrating the transducer signal with respect to time an accumulated signal can be found and a typical example is shown previously, in Figure 3.3. Once again the lag between the signals can be seen and as expected, the signals show good correlation. Any deviation in flow rate can be seen as a change in the slope of the lines.

3.3.3.2 - Type 2 Transducer

Initially, thirty tests were conducted using wheat at 12.5% moisture content. Data was treated in the same manner as the type 1 transducer, K_a being found from the slope of line illustrated in Figure 3.5. This being :

$$K_a = 0.0025 \ (V.kg^{-1}.s) \qquad \text{Equation 3.2}$$

When compared to the static calibration value (0.0022 $V.kg^{-1}.s$) developed from the model, the actual figure is 14 % higher. Once again, this can be attributed to difficulties in ensuring steady state flow.

Figure 3.2, Appendix 3, shows flow rate against time for the transducer and catch bin signals. A lag is again apparent between the two signals and both signals take between 0.5 - 1 second to reach full signal as flow from the hopper reaches steady state. The initial peak in both signals is again apparent and the signals takes approximately 10 to 12 seconds to tail off at the end of each test. All characteristics of the signals appear the same, the only change being an increased level of signal output from the transducer.

The accumulated signals plotted against time in Figure 3.3, Appendix 3, show exactly the same characteristics as with the type 1 transducer. Once again the lag between the signals can be seen and the signals show good correlation.

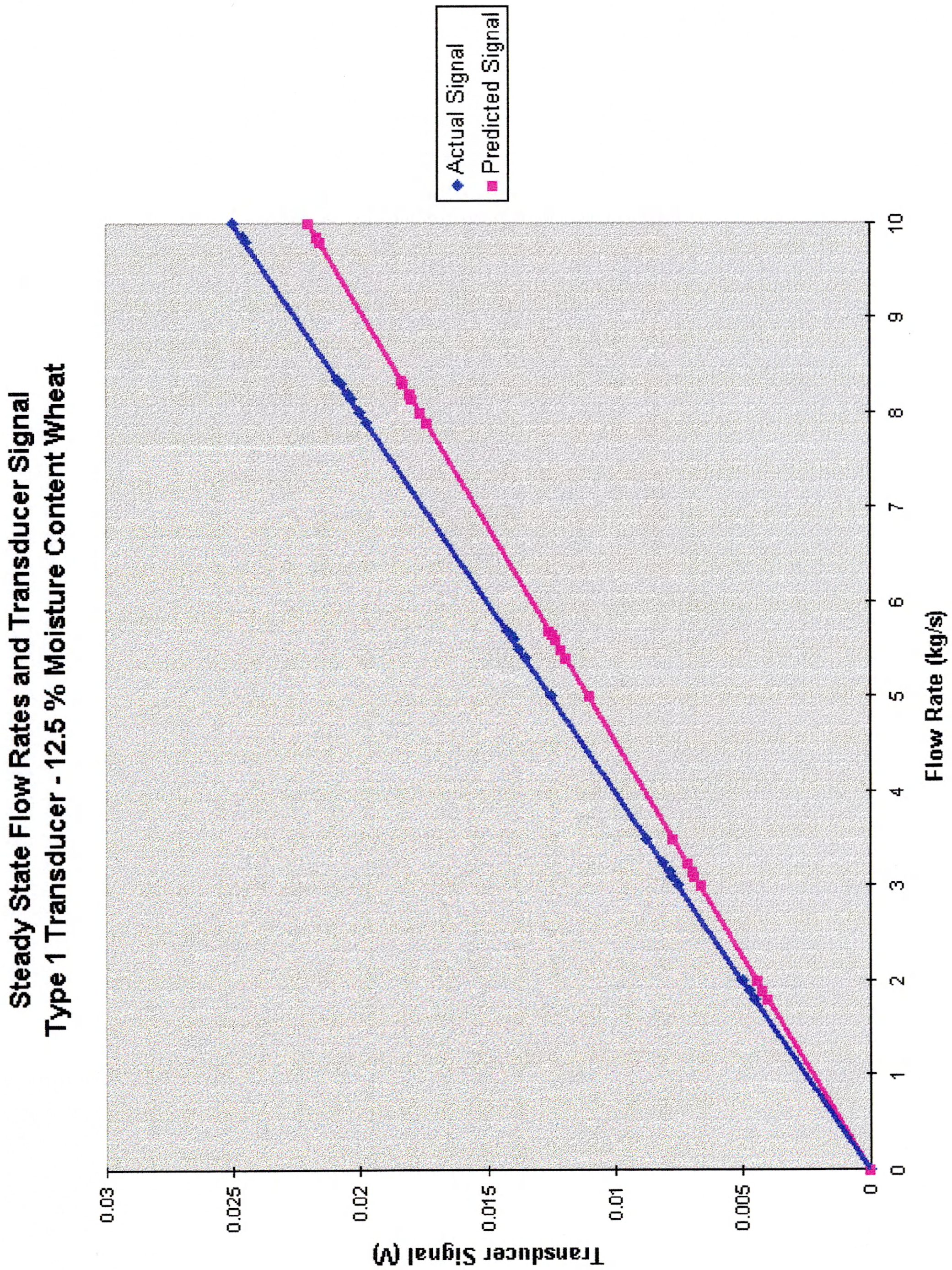


Figure 3.5 - Steady State Flow Rates and Transducer Signal - Type 2 Transducer
12.5 % Moisture Content Wheat

Having established K_a for wheat, the full range of materials were tested in exactly the same manner. For each set of tests, the K value and corresponding R^2 value can be compared, as in Table 3.2

Table 3.2 - Experimental K and R^2 Values for a Range of Test Materials

Crop	K ($V.kg^{-1}.s$)	R^2
12.5 % Wheat	0.0025	0.989
24.0 % Wheat	0.0024	0.997
31.5 % Wheat	0.0024	0.984
Oilseed Rape	0.0024	0.989
Oats	0.0024	0.995
Barley	0.0025	0.995
Sand	0.0024	0.976
Gravel	0.0023	0.964

From the values of R^2, it can be seen that each data set was close to linear. This relationship between the constant K and moisture content, for wheat, is shown in Figure 3.6 which shows that as the moisture content increases, the K value becomes smaller in a linear manner over the range. This can be attributed to an increase in the coefficient of friction as the wheat becomes wetter, combined with a small decrease in impact force, i.e. more material upon the reaction plate, whilst the impact force is only slightly reduced, hence a lower K value is required to convert transducer signal to flow rate.

Figure 3.7 shows a typical signal from the sand, with small initial and final peaks and a very short tail off period. This is because sand, being relatively symmetrical, flowed very smoothly and evenly. Figures 3.4 to 3.9, Appendix 3 show the transducer signal over time from a typical test run with each of the other test materials.

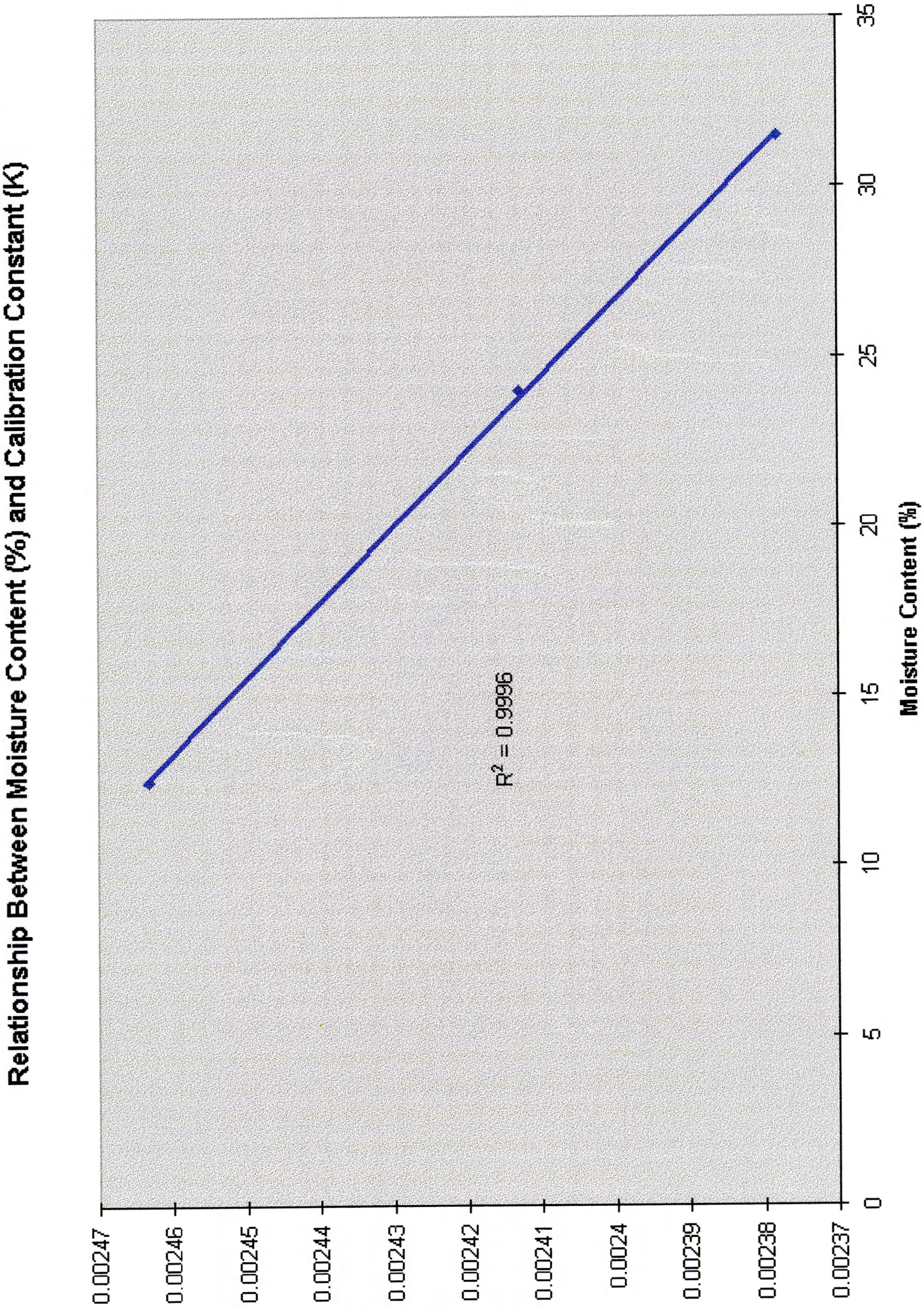


Figure 3.6 - Relationship Between Moisture Content and K Value - Wheat

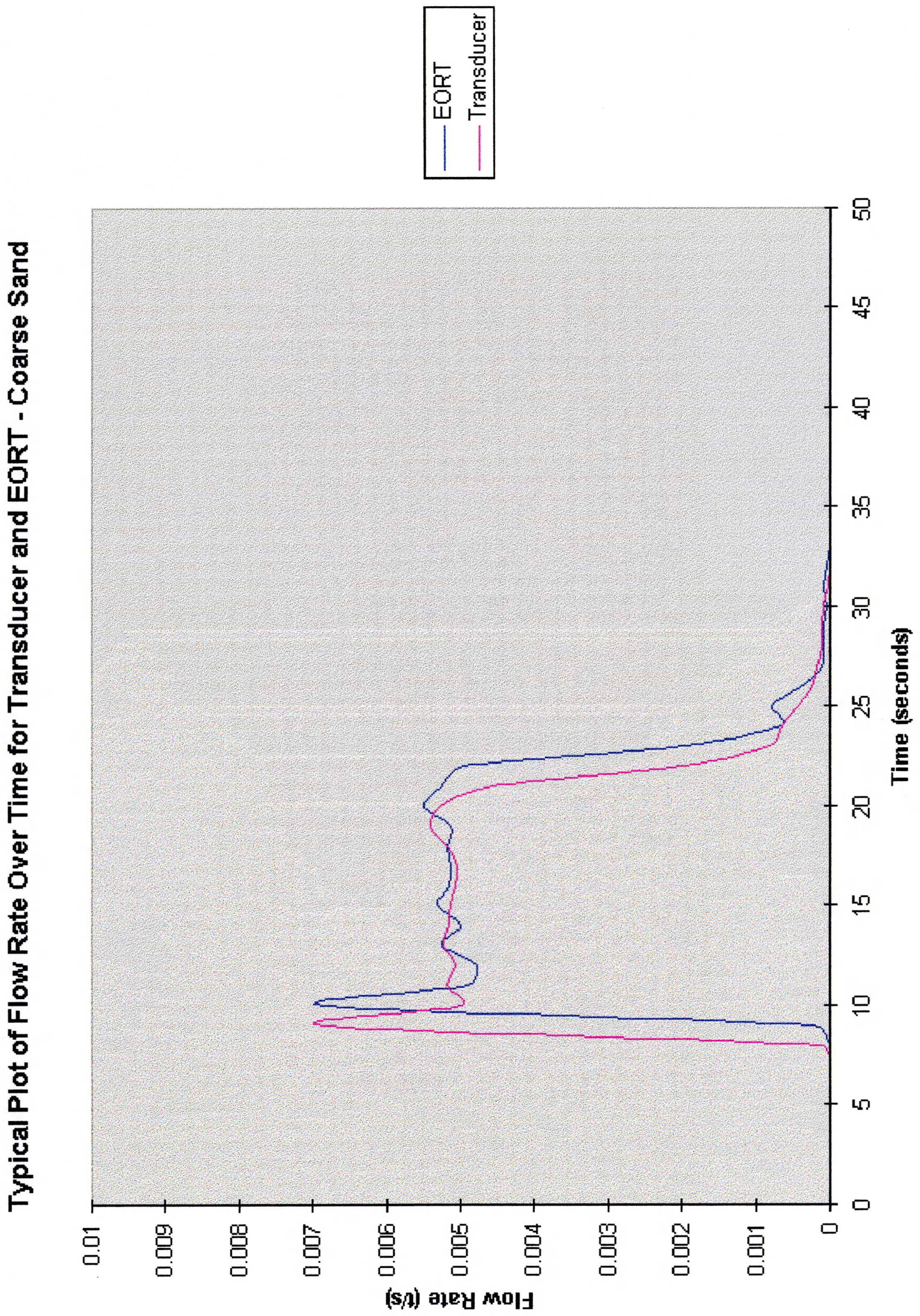


Figure 3.7 - Typical Plot of Flow Rate Over Time for Transducer and EORT - Coarse Sand

Gravel gave the largest difference between wheat at 12.5% moisture content and the actual calibration constant due to the noisy signal from impact upon the reaction plate. Considering agricultural grains, 31.5% moisture content wheat gave the largest difference, the K value being 3.19% smaller than the 12.5% moisture content base line. When data sets for all materials are plotted, as Figure 3.8, an overall K value can be found, this being

$$K_a = 0.00244 \text{ V.kg}^{-1}\text{.s with an } R^2 \text{ value of } 0.989$$

If this is compared to the static calibration value derived in Chapter 2 it can be seen that the K_a figure is 9% greater. When deriving the theoretical value, it was assumed that each particle of the complete crop mass would exhibit the same characteristics. However, the biological materials considered do not flow uniformly and have caused a small change in this calibration constant.

Comparing this overall average K value to the individual K values for biological materials, as in Table 3.2, wheat exhibits variations of ± 1.5 % across the entire moisture content range (12.5 % to 31.5 %). The K value for oats and barley are 0.8 % below and 4.5 % above the grand average, respectively.

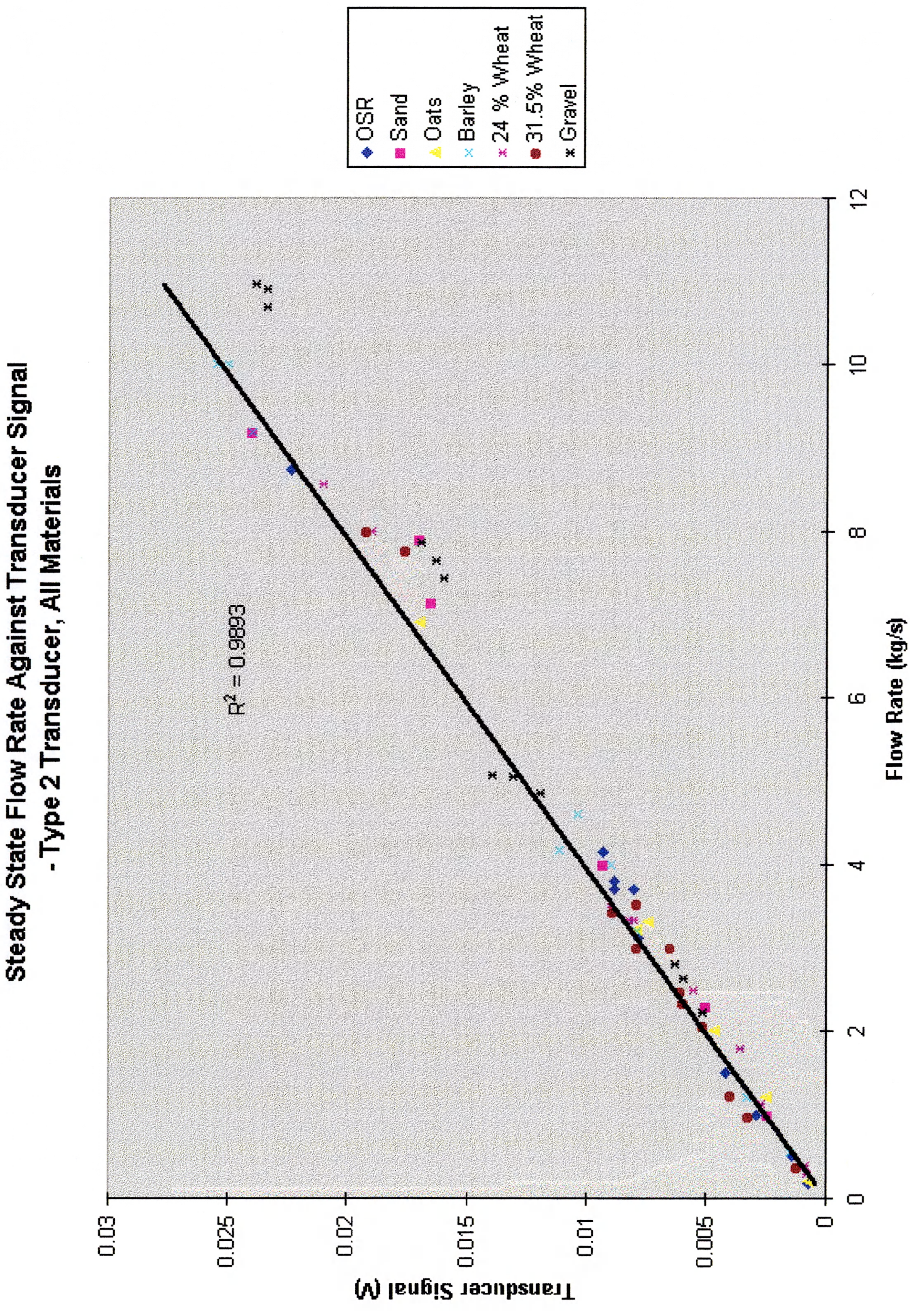


Figure 3.8 - Steady State Flow Rate Against Transducer Signal - Type 2 Transducer - All Materials

3.4 - ANGULAR EFFECTS

When a combine is working on sloping ground, any transducer fitted will also be subject to this slope and its performance may be adversely affected. Following personal communications with Hunter (Hunter 1996, personal communication) the following limits were defined for a combine on a slope:

- Harvesting up / down slope — Maximum 15 ^{O} — (Combine slips at 20^{O})
- Harvesting across slope — Maximum 10 ^{O} — (Combine rolls at 15^{O})

The object of this study was to optimise the angle at which the transducer beam was mounted, achieving maximum signal with minimum sensitivity to angular variation. Using this optimum beam angle, the effects of plate angle upon signal were then studied, finding an angle which would, once again, give minimum angular sensitivity. At present, the sponsor's mount both the transducer beam and plate at 45^{O} to the horizontal, as detailed in Chapter 2.

3.4.1 - Effects of Altering Strain Gauge Beam Roll Angle

A type 2 strain-gauged beam using a stabilised twelve volt excitation was mounted on a variable angle test rig and loaded with a 0.45 kilogram mass in place of the reaction plate. The beam was mounted horizontally and inclined from -15^{O} to +60^{O}, (positive inclination being with the mass pointing downwards). A digital voltmeter was used to record the steady state transducer output.

3.4.1.1 - Results & Discussion

The transducer beam is designed to measure forces acting perpendicular to its gauges. Therefore the maximum force should occur when the beam is horizontal (0 degrees) and the mass acts directly down through the beam. As the beam becomes inclined the mass will only act as a cosine of the beam angle and hence a reduced force will result.

Figure 3.9, verifies this and it can be seen that the points, when joined, create approximately a cosine curve. This means the full signal is output at 0 degrees (cos 0 = 1) and no signal is output at 90 degrees (cos 90 = 0). Also noteworthy, as the beam angle increases the beam becomes more sensitive to slight angular changes. That is to say, a one degree change from horizontal (zero degrees) will cause a 0.015 % decrease in signal whereas at fifty degrees beam angle, a one degree change will cause a 1.35% reduction in signal.

From this it becomes apparent that the beam should be mounted horizontally, ensuring maximum signal with least sensitivity to any angular variations. This recommendation also applies to the sponsor's current model.

3.4.2 - Effects of Altering Plate Roll Angle with Horizontal Beam

Using the test rig as in section 4.2, coarse sand was again tested over a range of angles from 40 to 65 degrees. The beam was kept horizontal (0 degrees) throughout all tests. At each plate angle, several tests at different flow rates were conducted. From each test the steady state transducer signal was noted and the flow rate recorded, again allowing the construction of a series of calibration curves.

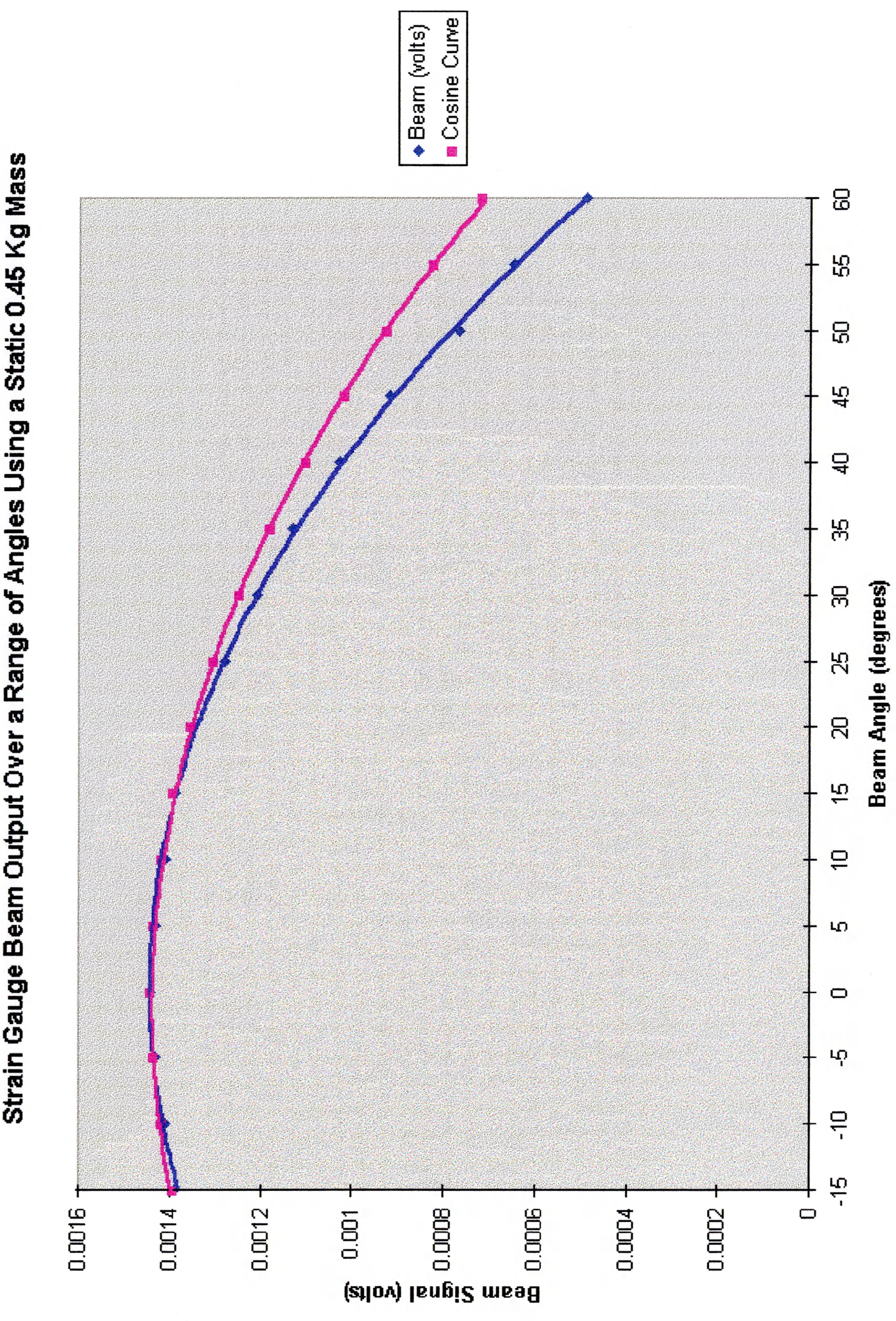


Figure 3.9 - Strain Gauged Beam Output Over a Range of Angles
Using a Static 0.45 kilogram Mass

3.4.2.1 - Results and Discussion

Figure 3.10, shows the calibration of a series of reaction plate angles using a horizontal beam. It can be seen, as previously, that a 40 degree plate angle gives a considerably higher output than the 45 - 65 degree range. Whilst a greater signal is desirable, this signal will decrease by 28 % (Figure 2.3) when subjected to a 5 degree side slope, (creating a 45 degree reaction plate angle), an unacceptable variation. The plate angle range from 45 to 65 degrees give a much smaller variation which is linear, indicating that any variation due to slope would have much less effect on signal size.

An angle of 55 degrees is central to the closer grouped outputs and will allow an increase or decrease of 10 degrees with minimum variation in signal. Also with a crop exhibiting a high coefficient of friction, there may be problems ensuring even flow at low reaction plate angles. A 55 degree reaction plate angle allows for 10 degrees of roll before even a crop with an unfeasibly high coefficient of 1 would encounter flow problems. Therefore, it is recommended that any further work with a plate type force reaction transducer uses a plate angled at 55 degrees to minimise angular effects. This recommendations also applies to the sponsor's current model.

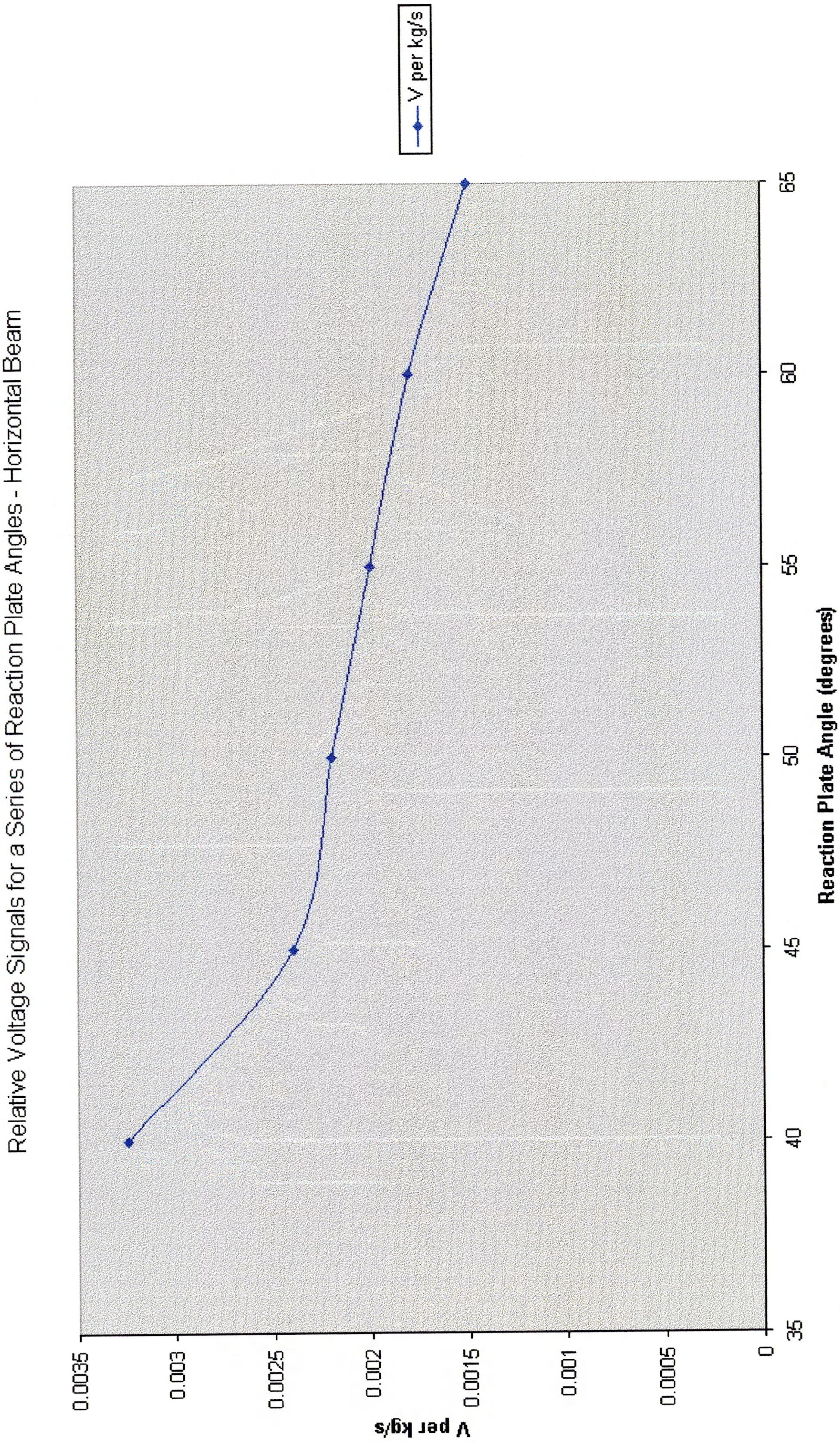


Figure 3.10 – Relative Voltage Signals for a Series of Reaction Plate Angles – Horizontal Beam

3.5 - CONCLUSION

Type 1 and 2 transducers were tested using 12.5 % moisture content wheat, and by comparing the actual flow rate to the transducer signal a calibration constant 'K_a' was established. This gave the following values, which are compared to static calibration values developed in Chapter 2.

Transducer	Type 1	Type 2
K - Theoretical	0.00059 $V.kg^{-1}.s$	0.0022 $V.kg^{-1}.s$
K - Actual	0.00071 $V.kg^{-1}.s$	0.0025 $V.kg^{-1}.s$

Eight materials were tested, six biological and two mineral. It was found that crop type (and hence friction) had little effect upon the K value, as predicted by the model and an overall K value across all these materials was established as 0.0024 $V.kg^{-1}.s$. When compared to the practically derived K value for wheat across the moisture content range, this was within 1 %. The K value for oats and barley were 1 % and 4 %, respectively, above the wheat value.

The following limits were defined for a combine working on a slope.

- Harvesting up / down slope : Maximum 15 ^{O}. (Combine slips at 20^{O})
- Harvesting across slope : Maximum 10 ^{O}. (Combine rolls at 15^{O})

Transducer beam angle, in isolation, was shown to have a significant effect upon signal. At zero degrees (horizontal) the beam gave the largest signal per force input and had minimal angular sensitivity, a one degree change from horizontal caused a 0.015 % decrease in signal. As this angle was increased, the signal became lower per force input and angular sensitivity increased, at fifty degrees beam angle, a one degree change caused a 1.35% reduction in signal, the relationship between force input and signal output being a cosine one. Hence, the beam should be mounted horizontally, ensuring maximum signal with least sensitivity to any angular variations. This recommendation also applies to the sponsor's current model.

Reaction plate angles between 40^{O} and 65^{O} were analysed using a horizontal beam and it was found the 40^{O} plate angle gave a considerably higher output than the 45 - 65^{O} range, which were uniformly spaced over a small range. An angle of 55^{O} is central to this range and allows an increase or decrease of 10 degrees with minimum variation in signal.

Therefore, it is recommended that any further work with a plate type force reaction transducer uses a plate angled at 55 degrees to reduce angular effects. This recommendations also applies to the sponsor's current model.

TO WHOM IT MAY CONCERN

PLEASE NOTE

"Although this thesis was submitted for the degree of EngD, it was considered to be appropriate for the award of the degree of **MPhil**.

This award will be conferred at the **Graduation Ceremony** on **14 July 1999**"

Caroline Johnson
Senior Assistant Registrar

CHAPTER 4

DESIGN CONCEPT AND CALIBRATION OF DOUBLE INCLINED PLANE TRANSDUCER

4.1 - INTRODUCTION

This study aimed to develop a novel transducer from design concept to a calibrated prototype suitable for harvest field trials, whilst proving whether the transducer was a viable device which could be self compensating for crop type and roll angles. When viewed in context of the overall new product development process, this stage can be considered as "concept testing". A possible design solution has been devised and is calibrated in the laboratory to assess practical performance.

By extending the mathematical model developed in Chapter 2, the transducer design was examined with respect to slope effects and transducer behaviour. This was then proved practically with a laboratory calibration and an assessment of total mass recorded was made using different crops at different flow rates with the transducer at differing roll and pitch angles. Transducer material was also considered and longer term tests were undertaken to assess repeatability of transducer mass accumulation.

4.2 - DESIGN CONCEPT

Having shown both theoretically and practically that an inclined plate force reaction transducer is sensitive to angular change, a mechanism was needed to compensate for this, maintaining a reliable signal up to the angular limits defined.

Two options were considered:
(i) The transducer signal could be combined with an inclinometer signal through a comparator to remove angular effects. A suitable inclinometer could be purchased direct from the manufacturer in low volumes for £900 each.

(ii) Using the fact that as reaction plate angle increased, signal reduced and vice versa, the concept of having two plates inclined in opposite directions to self-compensate was devised.

The plates could be mounted laterally, with small sides fitted, creating a roof shape, as illustrated in Figure 4.1. When angled, this roof would self compensate by generating a larger vertical force from its shallower face but a lower one from its steeper face, as illustrated in Figure 4.2. From previous work on reaction plate angles (Chapter 3), there is evidence to suggest this would be equivalent to the force generated when both plates are at the same angle. The beam for this transducer is mounted horizontally in the same orientation as the roof apex. This concept was termed the Double Inclined Plane (DIP) transducer.

Of the considered options, the DIP transducer was chosen, the inclinometer method being rejected for considerably increasing overall system cost and adding another level of complexity to the system. Before developing a complete mathematical model for the DIP transducer, a simple analysis was undertaken to determine whether the DIP would have the desired slope compensation.

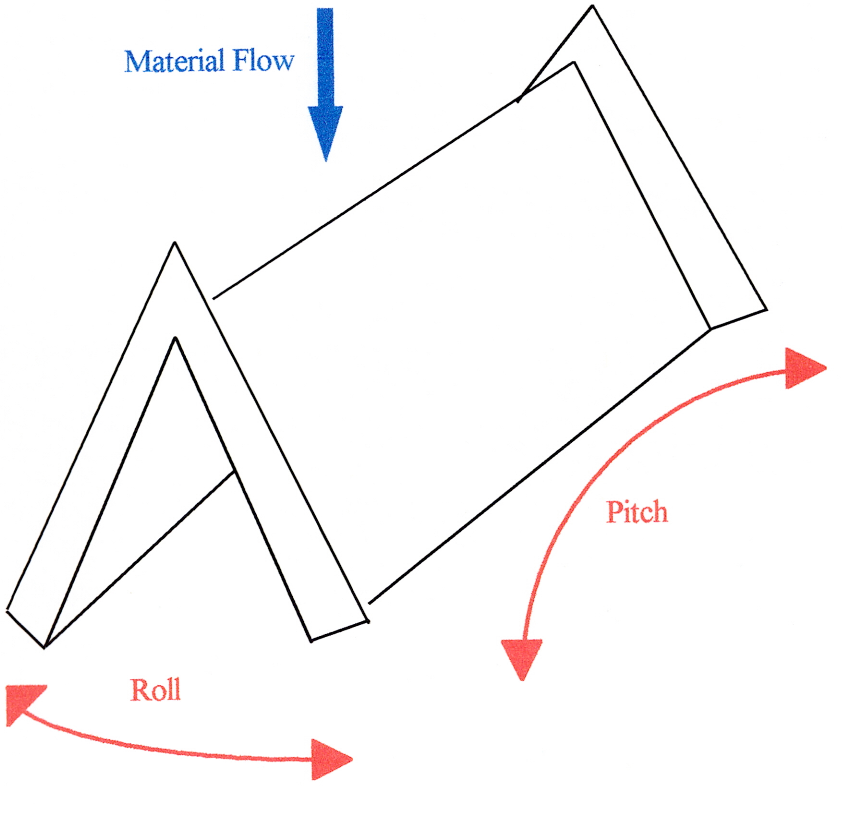


Figure 4.1 - Basic Design of DIP Transducer, Detailing Pitch and Roll

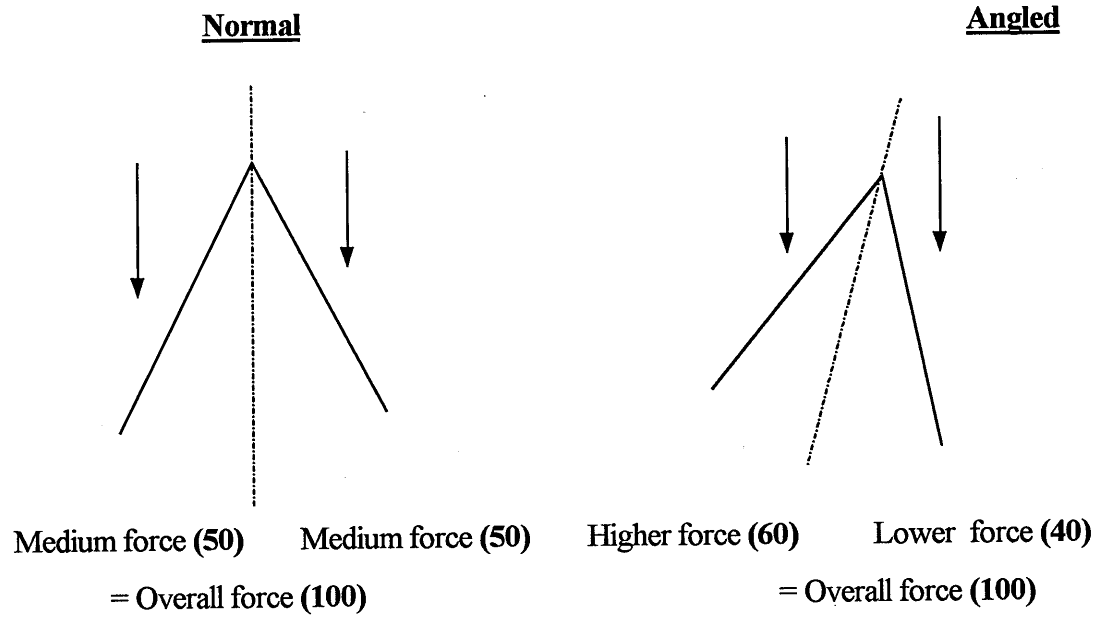


Figure 4.2 - Hypothetical Roll Angle Effects On DIP Type Reaction Plate

The above schematic only allows for even flow splits, i.e. 50 % of the material flows over each face regardless of angle. However, this split will change to some extent with transducer roll angle. From Figure 3.10, estimates can be made on the effect of uneven flow division (over a 55 degree DIP transducer) using the following method.

At 10 degrees roll, with a 75 / 25 split and 10 kg/s flow rate, the two faces are,

- 45 degree face receiving 75 % of flow (7.5 kg/s) = 17.8 mV
- 65 degree face receiving 25 % of flow (2.5 kg/s) = 3.8 mV

Total signal = 21.7 mV

Expected signal from 55 degree reaction plate at 10 kg/s = 21.3 mV

Predicted error in signal = 1.75 %

Using the above method, the percentage error in total signal caused by varying roll angles and flow splits is given in Table 4.1. The first part of the table is based upon the assumption that the crop will fall predominantly upon the shallower face, the second part being based upon flow predominantly over the steeper face. This prediction process has been undertaken as an initial indicator of the effectiveness of angular compensation for the DIP transducer.

Table 4.1 - Percentage Error Caused by Uneven Flow Division Over a 55^{O} DIP Transducer

Higher Flow on	Transducer Roll	Split 50/50	Split 60/40	Split 75/25	Split 100/0
Shallower Face	5 Degrees	- 0.5 %	- 0.5 %	- 1.9 %	+ 9.0 %
Shallower Face	10 Degrees	+ 1.0 %	+ 0.89 %	+ 1.75 %	+ 15.2 %
Shallower Face	15 Degrees	+ 4.0 %	+ 12.8 %	+ 30.2 %	+ 38.7 %
Steeper Face	5 Degrees	- 0.5 %	- 3.7 %	- 0.1 %	- 14.0 %
Steeper Face	10 Degrees	+ 1.0 %	- 7.6 %	- 7.7 %	- 32 %
Steeper Face	15 Degrees	+ 4.0 %	+ 3.3 %	- 3.6 %	- 49.8 %

A 55 degree DIP type reaction plate, theoretically offers angular compensation within the limits previously set up to 10^{O} for even flows. Also it offers reasonable tolerance of uneven flow splits as illustrated above. To offer a more complete proof, a mathematical model was developed, allowing full theoretical assessment of the concept.

4.3 - MATHEMATICAL MODEL OF DIP TRANSDUCER

To develop a force reaction model, the behaviour of the flowing material and reaction plate to material interactions had to be established. Based upon a double sided version of the single reaction plate model in Chapter 2, a free body diagram, Figure 4.3, was constructed, showing that total force 'F' could comprise of two components, the impulse force and the sliding mass of material travelling down the plate. For the DIP configuration, these forces happened on both faces and therefore each face was considered as a separate single plate and the model developed as an extension of the single plate model (Chapter 2).

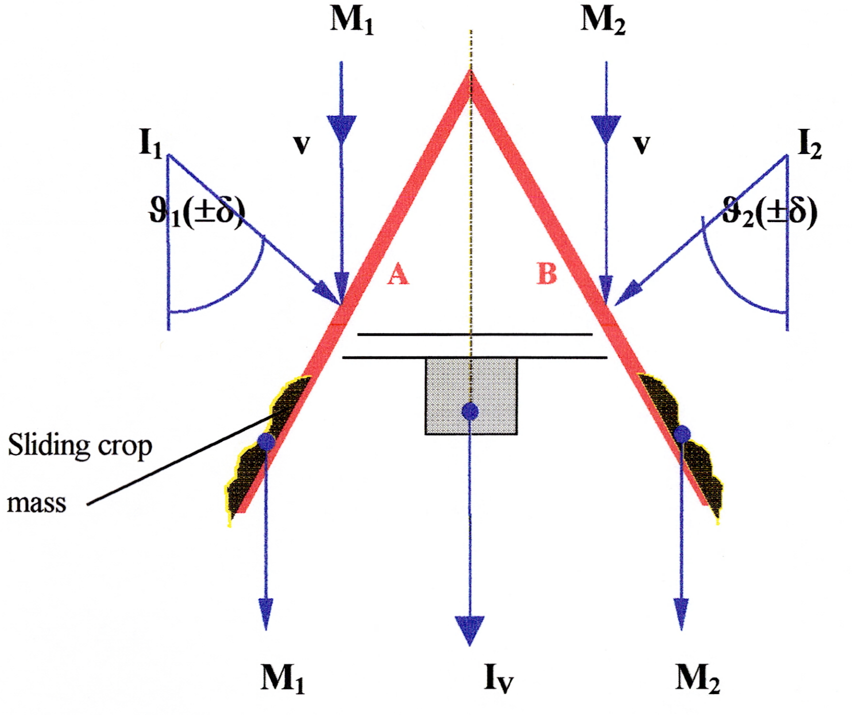


Figure 4.3 - Schematic Layout of DIP Transducer Detailing Forces

Using Equation 2.2, there are now two vertical components of sliding mass, these being:

$$m_1 = \tfrac{1}{2} \cdot m \cdot g \cdot t_A$$

$$m_2 = \tfrac{1}{2} \cdot m \cdot g \cdot t_B \qquad \text{Equation 4.1}$$

where: t_A = Residence time of crop on plate A of DIP transducer

t_B = Residence time of crop on plate B of DIP transducer

It is assumed that $M = M_1 + M_2$ = total flow (where $M_1 \neq M_2$)

Using Equation 2.1, the impulse force normal to each plate is:

$$I = {}^1/_2 \, . \, m \, . \, v \, . \, \cos(\vartheta+\delta) + {}^1/_2 \, . \, m \, . \, v \, . \, \cos(\vartheta-\delta) \qquad \text{Equation 4.2}$$

The total impulse force in the vertical direction is therefore:

$$I_t = {}^1/_2 \, . \, m \, . \, v \, . \, \{\cos^2(\vartheta+\delta) + \cos^2(\vartheta-\delta)\} \qquad \text{Equation 4.3}$$

In the previous single plate model (Chapter 2), friction acted parallel to the reaction plate (and therefore beam), resulting in a force which acted in the beams non-sensitive plane. This was therefore not included in the model. However, this force has a vertical component which must be incorporated into this horizontal beam model.

Force = coefficient of friction $\times$ normal force

$$\text{Force} = \mu \, . \, N \qquad \text{Equation 4.4}$$

$$N = {}^1/_2 \, . \, m \, . \, g \, . \, \{t_A.\cos(\vartheta+\delta) + t_B.\cos(\vartheta-\delta)\} \qquad \text{Equation 4.5}$$

Making friction parallel to the plate:

$$\text{Friction} = {}^1/_2 \, .\mu \, . \, m \, . \, g \, \{t_A.\cos(\vartheta+\delta) + t_B.\cos(\vartheta-\delta)\} \qquad \text{Equation 4.6}$$

Of which the combined vertical component is:

$$\text{Friction}_v = -{}^1/_2 \, .\mu \, . \, m \, . \, g \, . \, \{t_A \, . \, \cos(\vartheta+\delta) \, . \, \sin(\vartheta+\delta) + t_B \, . \, \cos(\vartheta-\delta) \, . \, \sin(\vartheta-\delta)\}$$

Equation 4.7

Therefore the total vertical force (F) is given by:

$$F = {}^1/_2.m.v.\{\cos^2(\vartheta+\delta)+\cos^2(\vartheta-\delta)\} + {}^1/_2.m.g.(t_A+t_B) - {}^1/_2.\mu.m.g.\{t_A.\cos(\vartheta+\delta).\sin(\vartheta+\delta) + t_B.\cos(\vartheta-\delta).\sin(\vartheta-\delta)\} \qquad \text{Equation 4.8}$$

Simplifying:

$$F = \tfrac{1}{2}.m.v.(1+\cos 2\vartheta.\cos 2\delta) + \tfrac{1}{2}.m.g.(t_A+t_B) - \tfrac{1}{2}.\mu.m.g.\{t_A.\sin 2(\vartheta+\delta)+t_B.\sin 2(\vartheta-\delta)\}$$

Equation 4.9

All factors are known except the mass of sliding material upon each face. Assuming a length of 0.2 metres for the DIP reaction plate sides, the sliding mass on each plate can be found from Equation 2.11 and 2.12, developed in Chapter 2.

$$t_A \text{ or } t_B = \frac{v\left[\sqrt{\dfrac{1+2.A.s}{v^2.\sin(\vartheta\pm\delta)}}-1\right]}{A}$$

Equation 2.11

where : $A = g\,(1 - \mu\,.\,\cot\,(\vartheta\pm\delta))$ Equation 2.12

Using this simple force model, the total vertical force exerted on the strain gauge beam can be calculated for a series of DIP face angles. Assuming these as "zero" figures, a range of roll angles (δ) can be included and the error resulting from these calculated. This is illustrated in Figure 4.4, using the following assumed values:

- Mass flow rate = 10 kg/s
- Coefficient of friction = 0.45
- Drop height = 0.45 m

From Figure 4.4, the DIP face angles most effective at reducing error due to roll angle appear to be in the range 40 to 55 degrees. This offers some agreement with previous empirical studies (Chapter 3) which identified 55 degrees as the most effective DIP face angle. Figure 4.4 shows that for a 55 degree DIP, the predicted error due to roll effects will be less than 2% for angles up to 7.5 degrees.

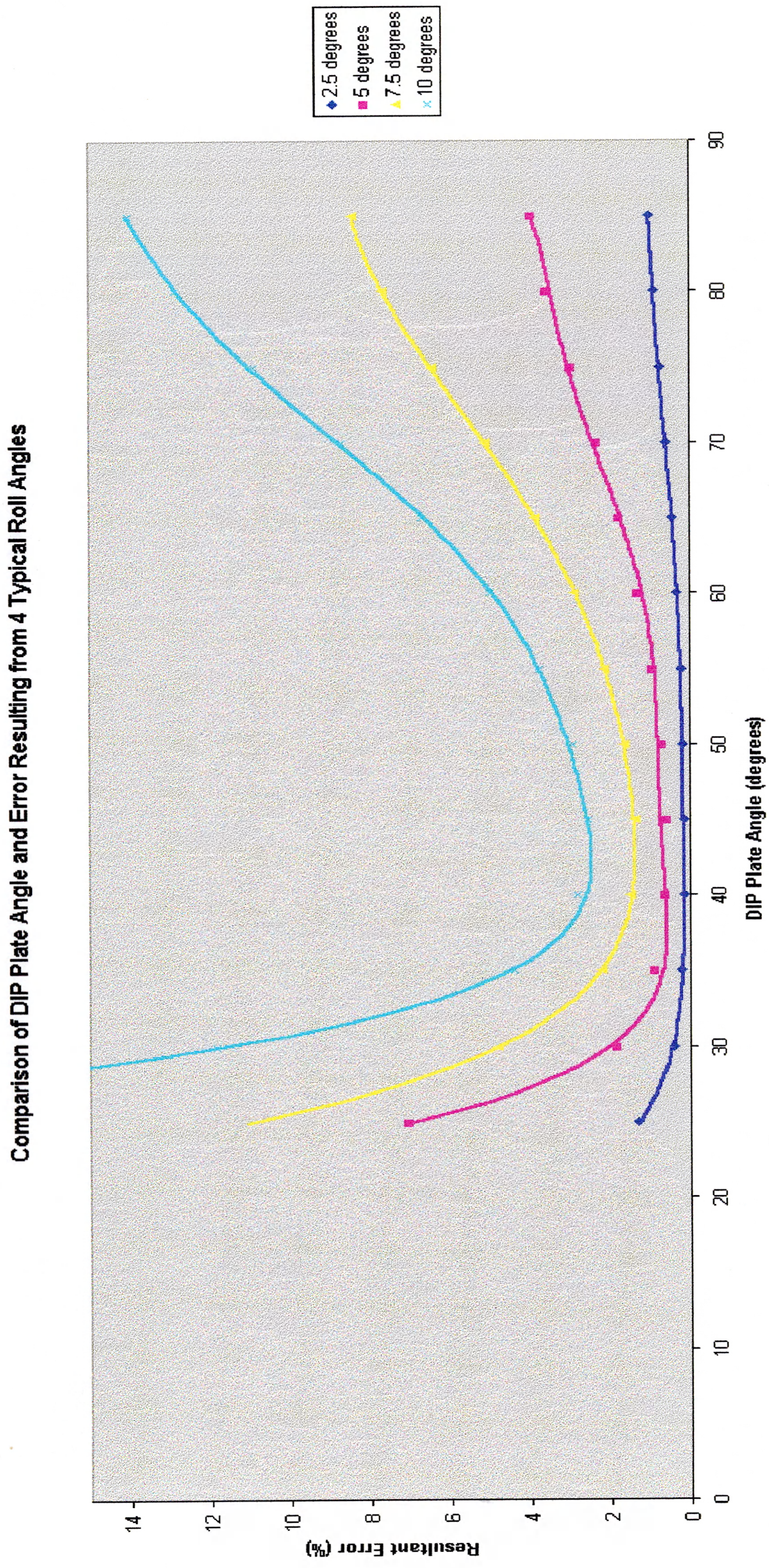


Figure 4.4 – Comparison of DIP Plate Angle and Error Resulting from Four Typical Roll Angles

The improvement in roll compensation can be clearly seen when comparing a 55 degree DIP transducer, with a single 55 degree reaction plate transducer. Figure 4.5 over shows the percentage error over a series of roll angles for both transducer types and at the previously defined maximum roll angle of 15 degrees the single plate introduces six times more error than the DIP.

The model can also be used to quantify errors introduced through varying the coefficient of friction of the flowing material. Figure 4.6 illustrates the predicted error for a 55 degree DIP transducer at 5 degrees roll angle subject to a 10 kilograms per second flow of material with a range of coefficient of friction values. These values are in the range of normal agricultural crops (0.35 to 0.6). It can be seen that by using a 55 degree DIP the range of errors is greatly reduced in comparison with lower face angles. At angles of less than 40 degrees the magnitude of these errors also increases. A 55 degree DIP face angle will allow for 15 degrees of roll before going below this "friction sensitive" angle.

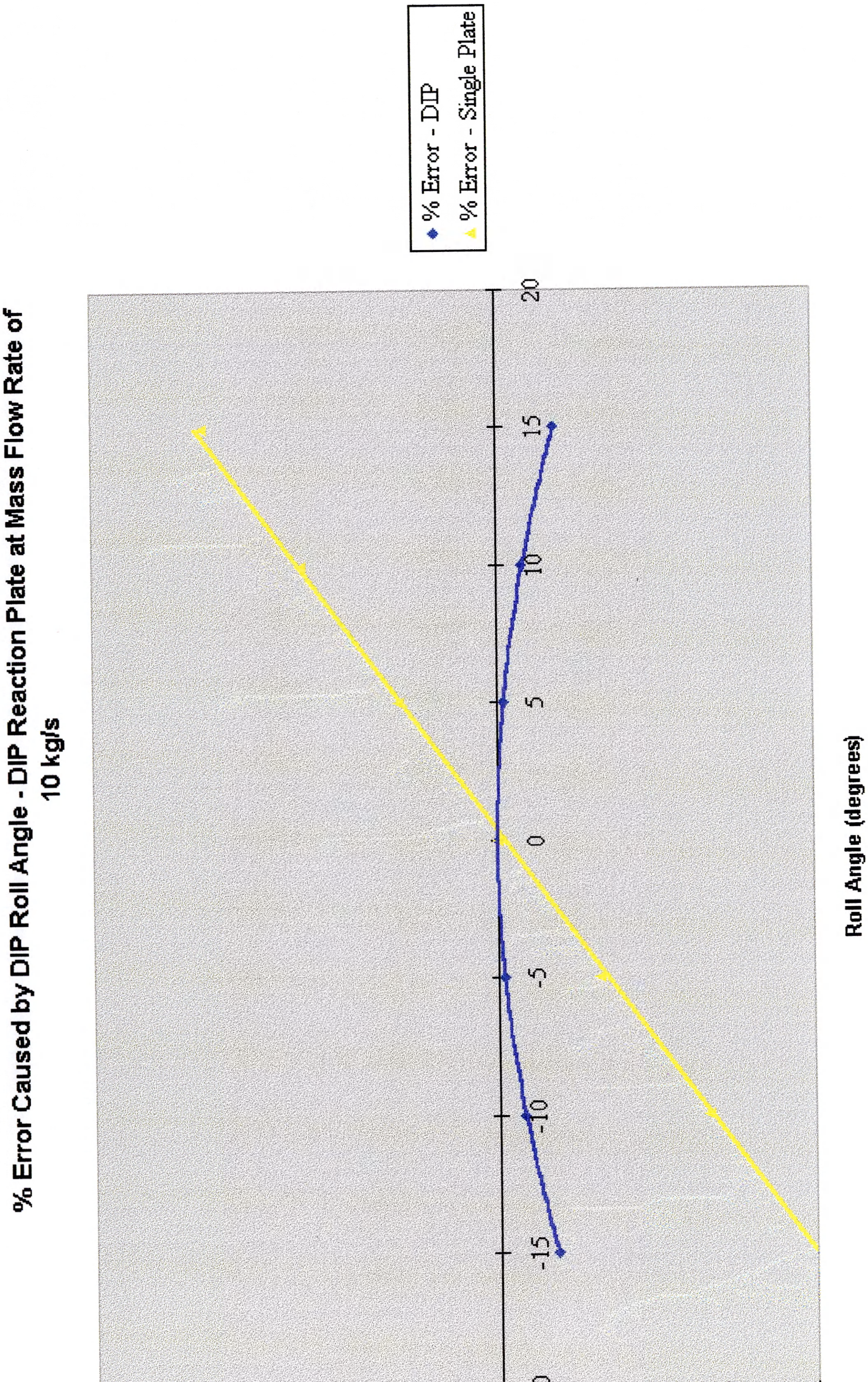


Figure 4.5 – Effect of Roll Angle on 55 Degree Single Plate and DIP Reaction Plate

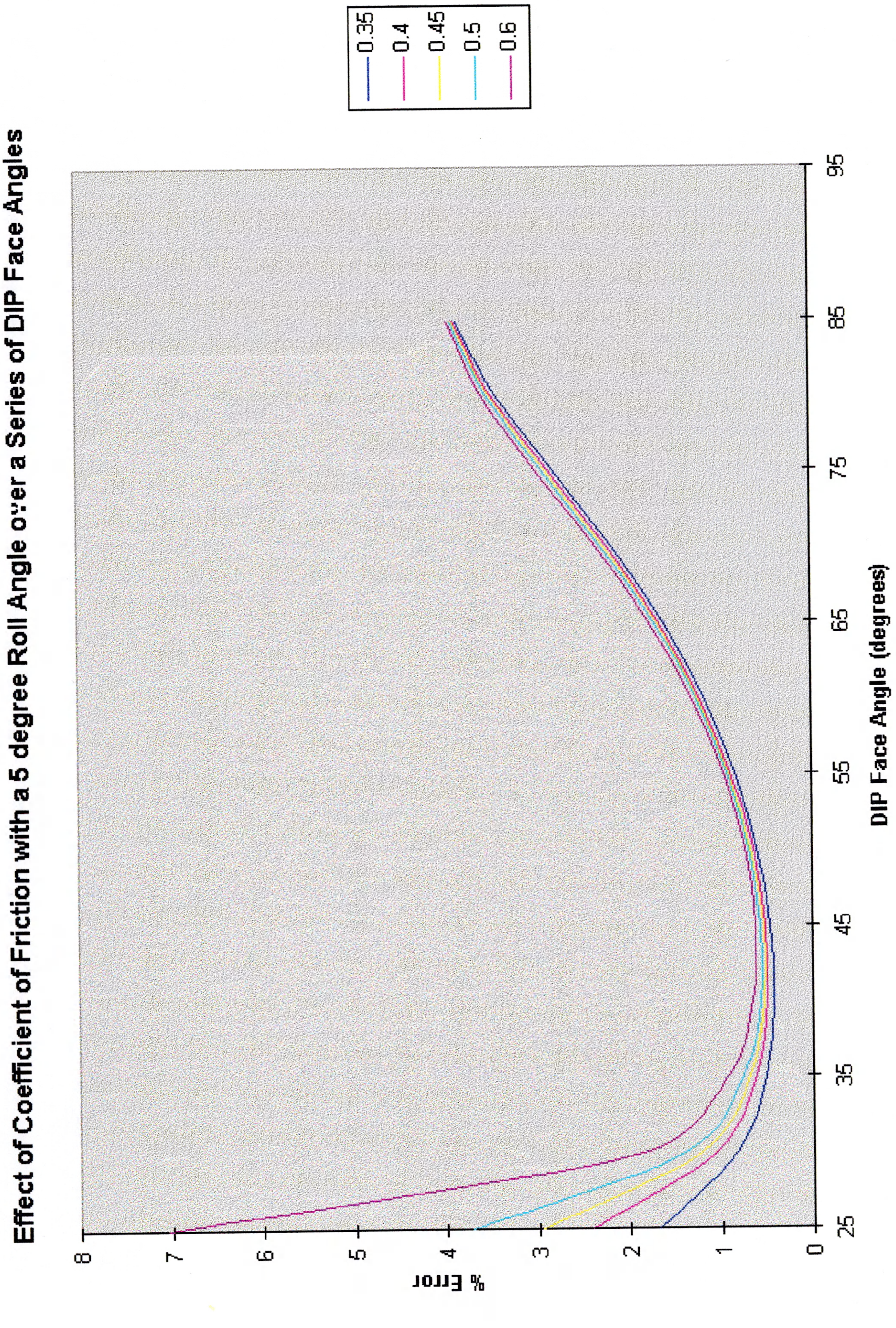


Figure 4.6 – Effect of Coefficient of Friction Over a Range of DIP Face Angles.

4.4 - INITIAL PRACTICAL INVESTIGATION OF DIP TRANSDUCER

Having shown mathematically the DIP transducer should reduce the error in total force and hence signal when rolled, three prototypes were constructed, Plate 4.1. All were made to the same dimensions but used different reaction plate angles (ϑ), these being 45, 50 and 55 degrees to the horizontal, from which the effect of 5, 10 and 15 degrees roll angles could be examined. The purpose of this is to prove the hypothesis that a 55 degree reaction plate angle would offer the most efficient angular compensation. All were fabricated from one millimetre thick mild steel and mounted upon a horizontal type 2 strain gauge beam.

4.4.1 - Methodology

Each prototype DIP reaction plate was mounted in the test apparatus described in Chapter 3. Several tests at 0, 5, 10 and 15 degree roll angles were conducted with coarse sand at 10 kg/s, whilst keeping the beam horizontal throughout. It was ensured that an even division of flowing sand was maintained at each roll angle tested. During each test the transducer and EORT signal were recorded and it was possible to plot the steady state signal against actual flow rate for each type and its relevant roll angles.

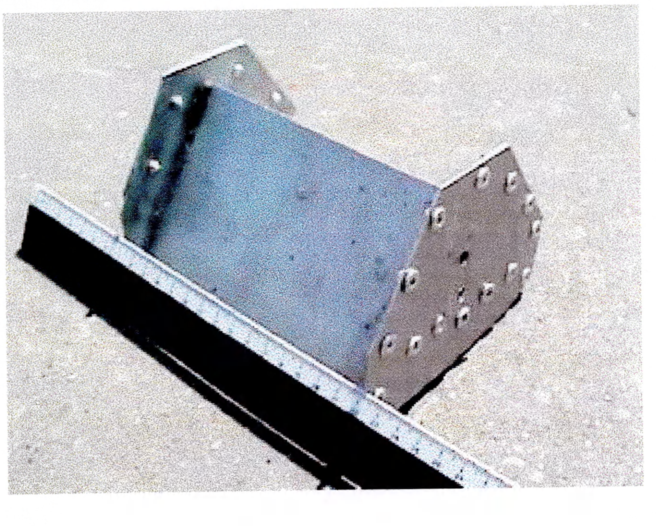


Plate 4.1 - Prototype 55 Degree DIP Reaction Plate

4.4.2 - Results & Discussion

Figure 4.7 over details the relative voltage signals against roll angle for the 45, 50 and 55 degree DIP reaction plates. The 45 degree DIP reaction plate gives signals which vary by 50%, the 15 degree roll angle giving a particularly significant decrease in signal. The 50 degree DIP reaction plate angle offers signals which increase in a relatively linear manner by 30% over the 15 degrees of roll. The 55 degree DIP reaction plate angle offers an almost constant signal across the complete range of roll angles, the 5 and 10 degree roll angles giving a slight reduction in signal and the 15 degree roll angle giving a slight increase in signal. Table 4.2 shows a summary of these results. From these results it becomes apparent that a 55 degree plate angle is the most effective at minimising roll effects on the DIP transducer.

Also shown in Table 4.2 is a summary of pitch testing results, showing that pitch angles up to 15^{O} do not affect the transducer signal significantly.

Table 4.2 - Percentage Error Resulting From Various Reaction Plate and Roll Angles

Roll Angle (degrees)	% ERROR 45^{O} DIP	 50^{O} DIP	 55^{O} DIP
5 Degrees Roll	+ 11.0 %	+ 2.5 %	- 2.7 %
10 Degrees Roll	+ 17.0 %	+ 22 .0 %	- 4.5 %
15 Degrees Roll	- 48.0 %	+ 31.6 %	+ 2.6 %
Pitch Angle (degrees)	**% ERROR 45^{O} DIP**	** 50^{O} DIP**	** 55^{O} DIP**
5 Degrees Pitch	+ 0.7 %	+ 1.2 %	+ 0.6 %
10 Degrees Pitch	+ 1.4 %	- 1.6 %	+ 1.1 %
15 Degrees Pitch	- 1.8 %	+ 1.3 %	- 0.9 %

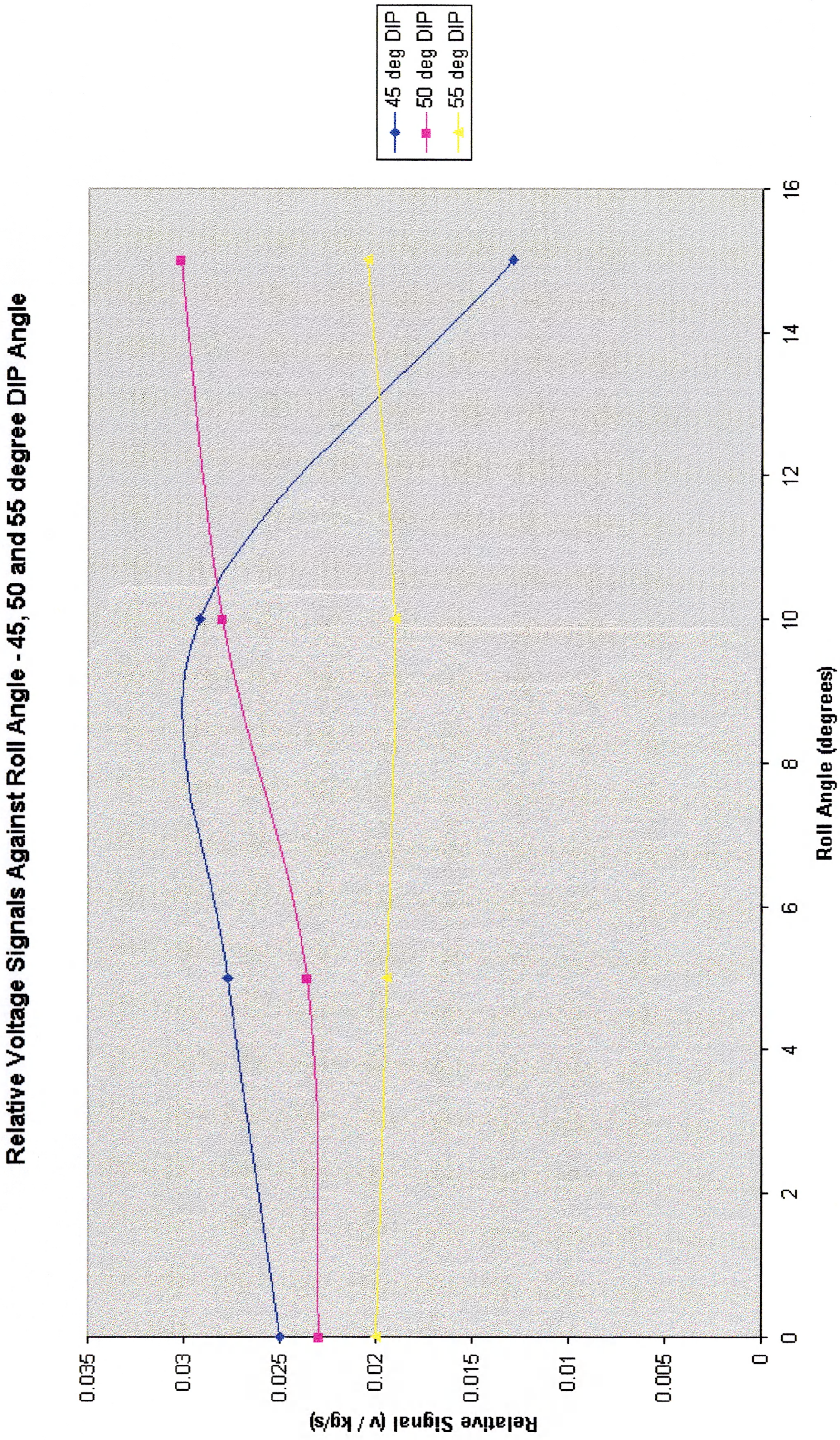


Figure 4.7 – Relative Voltage Signals Against Roll Angle – 45^{O}, 50^{O} and 55^{O} DIP Angles

4.5 - LABORATORY CALIBRATION OF 55 DEGREE DIP TRANSDUCER

This work aimed to objectively define transducer accuracies with respect to flow rates, roll angles, pitch angles and crop types. Having decided that the 55 degree plate angle was the most effective at angular compensation, a DIP reaction plate having its faces angled at 55 degree was used for all tests. Three crops were tested, these being :

- Wheat at 12.5 % moisture content
- Oats at 12 % moisture content
- Oilseed Rape

The majority of cereal crops are grown on slopes between 0 and 10 degrees, therefore roll and pitch angles of 3, 6 and 9 degrees were used with flow rates between 1 and 10 kilograms per second.

4.5.1 - Methodology

The 55 degree DIP reaction plate was mounted in the test apparatus described in Chapter 3 and each of the crop materials was subject to the following tests :

- 3 replications at 3 flow rates (3, 5 and 10 kg/s)
- 3 replications at 3 roll angles 3, 6 and 9 degrees (using a set flow rate of 5 kg/s)
- 3 replications at 3 pitch angles 3, 6 and 9 degrees (using a set flow rate of 5 kg/s)

During each test approximately 50 kg of each test material was used and the reaction plate signal recorded and integrated, allowing a total mass figure to be obtained (using the previously developed calibration constant). This was then compared to the mass accumulated in the catch bin measured with an accuracy of 1 kilogram allowing calculation of the percentage error.

4.5.2 - Results & Discussion

To simplify the large amount of data taken, Table 4.3 details the mean and standard deviation of each data set for each specific condition. All figures shown are the percentage error with respect to total mass flow.

Table 4.3 - Summary of 55 Degree DIP Percentage Errors at 3 Flow Rates, 3 Roll Angles and 3 Pitch Angles (standard deviation shown in brackets)

Flow Rate (kg/s)		ERRORS (%)	
at 0^0 Roll	Wheat	Oats	Oilseed Rape
3 kg/s	-0.13 (0.38)	-0.09 (0.28)	0.71 (1.06)
5 kg/s	-1.15 (0.74)	-1.21 (1.43)	1.12 (1.04)
10 kg/s	-0.14 (0.27)	-0.87 (1.01)	1.39 (0.84)
Roll Angle (degrees)		ERRORS (%)	
at 5 kg/s	Wheat	Oats	Oilseed Rape
3^O	-0.59 (0.96)	0.46 (0.15)	0.01 (0.14)
6^O	-1.86 (1.87)	0.72 (0.54)	-1.08 (1.42)
9^O	-1.5 (1.12)	-7.32 (4.35)	-0.52 (0.87)
Pitch Angle (degrees)		ERRORS (%)	
at 5 kg/s	Wheat	Oats	Oilseed Rape
3^O	-0.08 (0.10)	1.29 (0.86)	-0.76 (0.37)
6^O	-1.58 (1.66)	1.57 (1.77)	-0.61 (0.75)
9^O	1.34 (2.19)	1.51 (1.39)	1.20 (0.92)

Changes in flow rate appear to make little difference to error in accumulated mass, wheat and oats causing a slightly lower signal, whilst oilseed rape resulted in a slightly larger signal, with the percentage errors falling within the initial reaction plate specification.

Roll angles also appear to cause minimal errors in mass accumulation except for the 9 degree angle with oats which resulted in a -7.3 % error. Pitch angle also appears to have negligible effect upon mass accumulation, causing a small increased reading in all crops at high angles.

4.6 - FURTHER DEVELOPMENT OF THE DIP TRANSDUCER

Having established the potential of the DIP transducer for angular compensation, the aim of this work was to produce a transducer specification suitable for harvest field trials. Using apparatus which allowed a much larger mass of grain to be flowed, as would be the case on a combine, the effects of DIP reaction plate size and material were studied, as were the effects of variable flow and a more 'sensitive' strain gauge beam.

All previous laboratory testing has used between 50 and 100 kg of material, giving up to 100 seconds of data. To increase the mass flowed a grain store was adapted for testing purposes, as shown in Figure 4.8 and Plate 4.2. The main elevator was diverted to a 1/2 tonne fertiliser bag suspended on a calibrated five tonne tension link over a grain pit. The tension link was calibrated upon an *Avery* instrumented press as shown in Figure 4.1, Appendix 4 and had an accuracy of 0.04% at full scale equating to 2 kilograms. Underneath the bag a hopper was mounted to allow repeatable flow control and a constant head of grain above the transducer, which was mounted 0.45 metres below the hopper. Flowing grain was then collected in the bottom of the pit, ready for the next test.

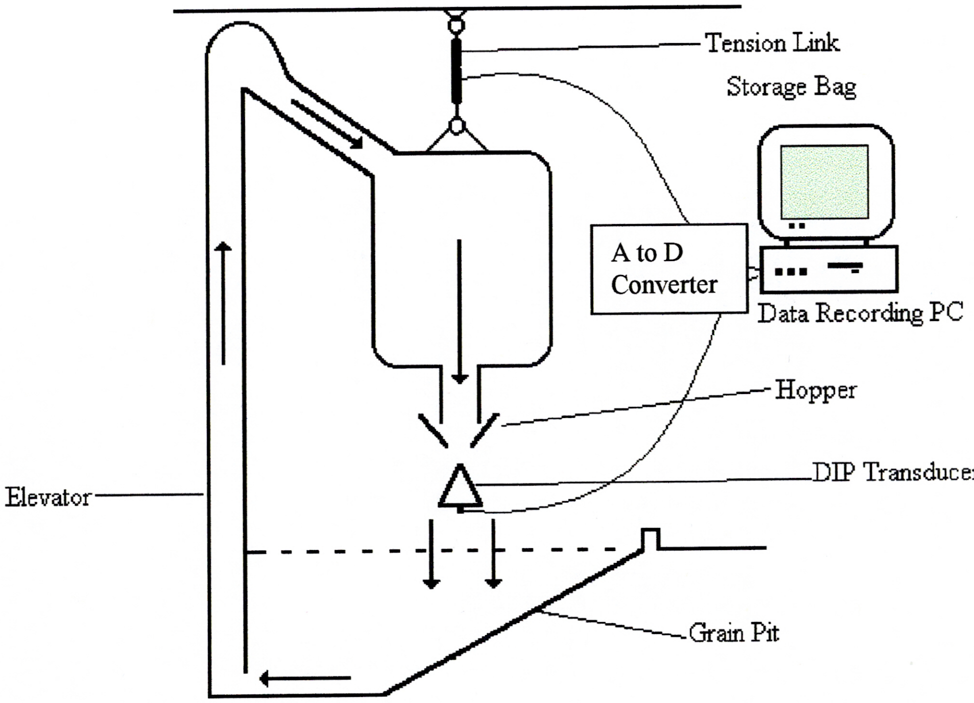


Figure 4.8 - Equipment Layout for Long Term Tests

Plate 4.2 - Layout of Equipment for Long Term Testing

4.6.1 - Plate Material and Size

Griffith Elder currently use the half hard aluminium alloy (NS4) for their reaction plate. This aluminium offers a degree of ductility with a hard wearing surface, is light weight and can be TIG welded. This material was expensive at the time of construction hence a similar aluminium (NS5) was used, which was slightly less ductile and harder. When tested, it exhibited the following properties.

		NS5	NS4
Brinnel hardness	:	80 Brinnel	76 Brinnel
Tensile strength	:	32.5 kg/mm^2	33.5 kg/mm^2

Two DIP reaction plates were constructed, one using the same dimensions as the previous steel one and one with all dimensions reduced to 60 % of the original. The purpose of this was to, (i) produce and test a more compact transducer, fitting space being limited within the combine, (ii) reduce the weight of the reaction plate, which could be of benefit during field work. By having less self weight, inertia would be lessened over bumps and tramlines, although this was not anticipated to be a major problem.

Using the larger of the two DIP reaction plates and a type 2 strain gauge beam, wheat (at 11% moisture content) was tested for 3 replications at 4 constant flow rates. The results, which are shown in Table 4.4, demonstrate the larger reaction plate offers good repeatable results which lie within the project specifications.

Table 4.4 - Test Results Using a Large Aluminium DIP Reaction Plate and Type 2 Strain Gauge Beam

Approximate Flow Rate (kg/s)	Reference Mass (kg)	Measured Mass (kg)	% Error
2.5	541.4	535.2	1.14
2.5	490.2	495.7	-1.12
2.5	438.5	438.1	-0.09
5.0	510.0	503.1	-1.35
5.0	457.1	462.5	-1.18
5.0	469.5	463.2	1.34
7.5	511.1	515.9	-0.90
7.5	517.2	514.6	0.50
7.5	491.3	488.4	0.59
10	491.1	484.8	1.28
10	463.1	455.2	1.71
10	402.8	399.6	0.79

Using the smaller DIP reaction plate and a type 2 strain gauge beam, 4 tests were undertaken at constant flow rates. The results, which are shown in Table 4.5, once again demonstrate good repeatable results but with a small loss of accuracy.

Table 4.5 - Test Results Using a Small Aluminium DIP Reaction Plate and Type 2 Strain Gauge Beam

Approximate Flow Rate (kg/s)	Reference Mass (kg)	Measured Mass (kg)	% Error
2.5	362.7	359.8	0.79
5.0	357.3	347.5	2.74
7.5	347.1	340.6	1.87
10.0	315.1	310.4	1.49

4.6.2 - Variable Flow Rates

The aim of this test was to examine the transducer response to flow variations. Mounting a type 2 strain gauge beam and small aluminium DIP reaction plate upon the long term test equipment as detailed previously, the slider on the underside of the hopper was modified, allowing the aperture to be varied whilst keeping the flow centred on the same point of the DIP reaction plate. Approximately 0.4 tonnes of wheat were flowed over the large aluminium DIP reaction plate as shown in a typical test plot in Figure 4.9. The results of 4 independent tests are summarised in Table 4.6 and show that the total mass recorded by the transducer is not affected by flow variations.

Table 4.6 - Results From Variable Flow Rate Testing, Using a Small Aluminium DIP Reaction Plate and Type 2 Strain Gauge Beam

.Reference Mass (kg)	Measured mass (kg)	% Error
369.5	373.8	-1.16
340.0	336.5	1.03
403.7	403.5	0.05
397.1	403.2	-1.54

4.6.3 - Modified Strain Gauge Beam

A new strain gauge beam offering increased sensitivity was evaluated, this was termed a type 3 beam and is a standard commercially available item (RS Components). It was of a similar construction to the Type 2 beam but had a maximum design loading of 20 kg compared to the previous 50 kg maximum, due to its thinner loading surfaces.

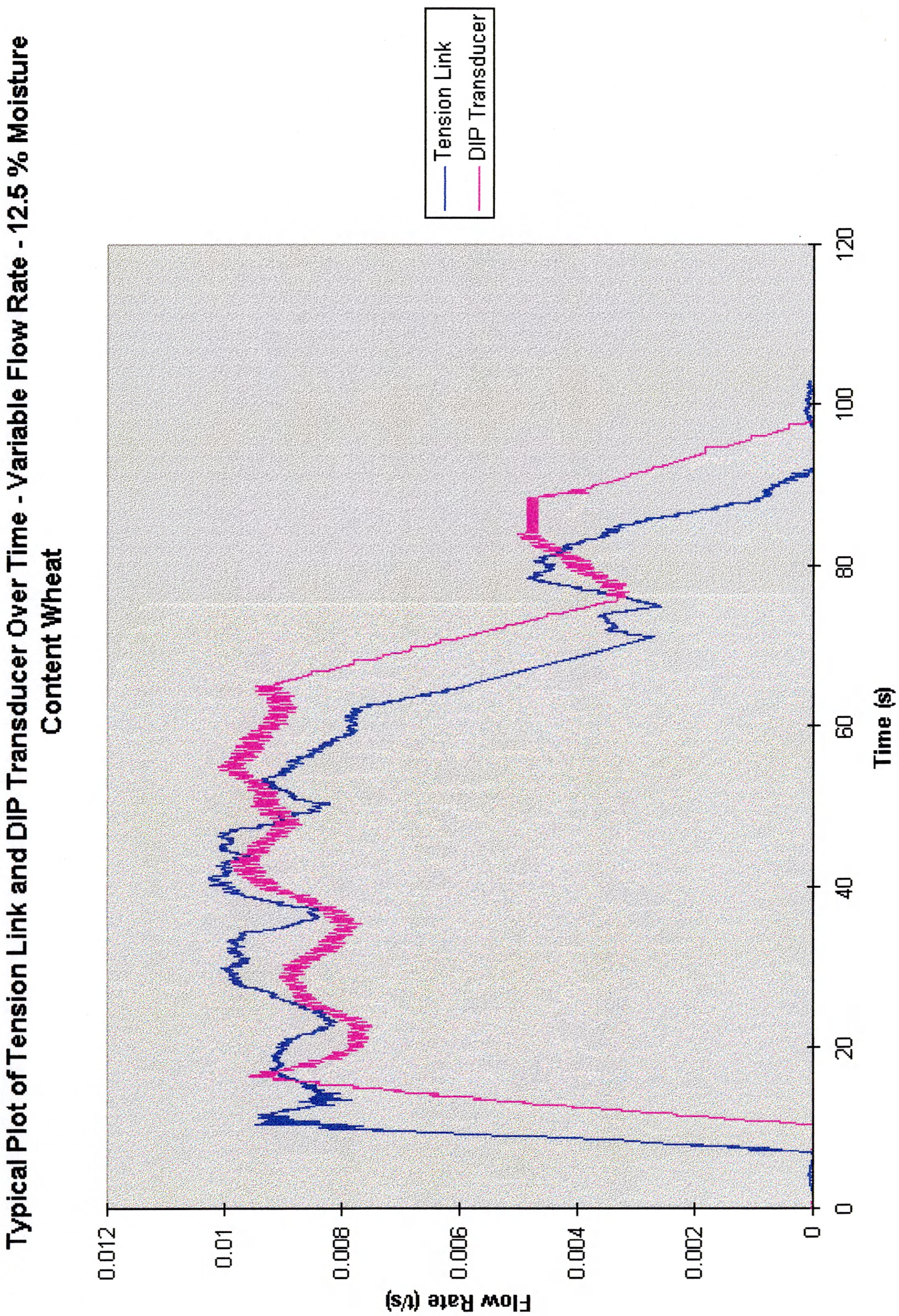


Figure 4.9 - Typical Plot of Tension Link and DIP Transducer Flow Rates Over Time - Variable Flow Rate - 12.5 % Moisture Content Wheat

It was placed on an *Instron Universal Tester 1122* and loaded to full scale, then unloaded. These results of this calibration can be seen in Figure 4.2, Appendix 4 and when related to previous calibrations give a new K value of,

K - Type 3 strain gauge beam = 0.0055 $V.kg^{-1}.s$

Using the Type 3 strain gauged beam, 4 long term flow tests were undertaken, to confirm the new calibration constant (K). All were undertaken with a large aluminium DIP reaction plate and constant flow rates. Table 4.7 details the results.

Table 4.7 - Test Results Using a Large Aluminium DIP Reaction Plate and Type 3 Strain Gauge Beam

Approximate Flow Rate (kg/s)	Reference Mass (kg)	Measured mass (kg)	% Error
2.5	373.3	374.9	-0.50
5.0	376.0	380.1	1.09
7.5	352.9	347.4	1.56
10.0	383.6	387.8	-1.09

From these results it can be seen that the modified calibration constant gives good results. The raw signal, shown in Figure 4.3, Appendix 4, appeared more sensitive than with the type 2 beam, and did not become overloaded at the maximum flow rate of 10 kg/s. For this reason, all further work was undertaken using a Type 3 beam.

4.7 - CONCLUSION

Previous studies have shown that angular effects upon transducer signal are significant and that the reaction plate angle least sensitive to these changes is 55 degrees. To minimise angular effects, the concept of having two reaction plates, inclining in opposite directions, joined together to form a roof shape was devised. Using the fact that as reaction plate angle increased, signal reduced and vice versa, when angled, this device would self compensate by generating a larger vertical force from its shallower face but a lower one from its steeper face. The strain gauge beam was mounted horizontally in the same orientation as the roof apex. This concept was termed a double incline plane (DIP) transducer.

By extending the mathematical model developed in Chapter 2, the DIP transducer's response to angular effects was examined and the results are shown below alongside the results from an initial practical investigation, which was undertaken to confirm that having both reaction plates angled at 55 degrees to the horizontal gave the most compensation. Although some errors are still present, they are reduced by a factor of six when compared to a single reaction plate. However, due to the method of beam mounting, coefficient of friction has a more marked effect, causing a maximum error of 1% over the normal range of agricultural crop friction values at a 5 degree roll angle.

Roll Angle (degrees)	Calculated Error	Actual Error
0	0.0 %	0.0 %
5	-0.7 %	-2.7 %
10	-3.8 %	-4.5 %
15	-6.4 %	2.6 %

A study was then undertaken to objectively define DIP transducer accuracies. Three crops, 12.5 % moisture content wheat, oats and oilseed rape were tested at three roll and pitch angles of 3, 6 and 9 degrees, offering an even distribution across the range 0 to 10 degrees, the angles that the majority of cereal crops are grown on. All results were within ± 1.6 % on total mass flowed.

Two DIP reaction plates were constructed from NS4 aluminium, one using the same dimensions as the previous steel one and one with all dimensions reduced to 60 % of the original. Over a range of flow rates, the larger DIP showed errors between -1.31 % and 1.71 % on total mass flowed and the smaller one between 0.79 % and 2.74 % on total mass flowed. Tests with a constantly varying flow rate showed errors of -1.54 % to 1.03 %, illustrating that variations in flow rate during a test do not affect the accuracy of that test

A new strain gauge beam offering increased sensitivity was evaluated, this was termed a type 3 beam and gave a new K value of 0.0055 $V.kg^{-1}.s$. All further work uses this new beam

The DIP transducer has been taken from design concept to a calibrated prototype suitable for harvest field trials. It has been proven that the transducer is a viable device which offers suitable compensation for crop type and roll angles.

CHAPTER 5

COMBINE / FIELD EVALUATION OF DOUBLE INCLINED PLANE TRANSDUCER

5.1 - INTRODUCTION

This chapter reports the field testing of the double inclined plane (DIP) transducer mounted in a combine harvester under harvesting and simulated harvesting conditions. In terms of the new product development process, this is a continuation of the concept testing phase, gaining further performance data.

Using original combine components, a complete clean grain system was built into a framework allowing controlled grain flow conditions for initial transducer assessment. This was followed by pilot studies during the harvest of 1995 and a complete harvest undertaken during the summer of 1996, using a New Holland TF42 combine,. Although many variables were evaluated in the field, time and commercial pressure resulted in the need to continue testing when all crops had been harvested. This was resolved after completion of the harvesting season by simulating harvesting conditions whilst passing crop through the combine. Consideration was also given to vibrations and shock inputs (such as tramlines), these variables being perceived as a problem upon a working machine.

This chapter considers the systems, preparation, results and conclusions drawn from each study.

5.2 - DESCRIPTION OF COMBINE CLEAN GRAIN SYSTEM

Once separated from the straw and chaff, clean grain is collected in the lower cross auger. This screw auger forms the lowest part of the combine and carries crop across to the clean grain elevator, which is normally a chain elevator, fitted with rubber paddles. This raises the crop approximately 2 metres and as the elevator reaches its peak the crop is ejected into the drop box, a 0.3 m square section box with a depth of approximately 0.5 m, Figure 5.1. In the bottom of this is a screw auger which elevates the grain at 45^{O} to the horizontal into the centre of the grain tank and even when submerged, continues to force grain into the tank. This mechanism is referred to as the bubble up auger and can be seen in Figure 5.2, a section through a combine.

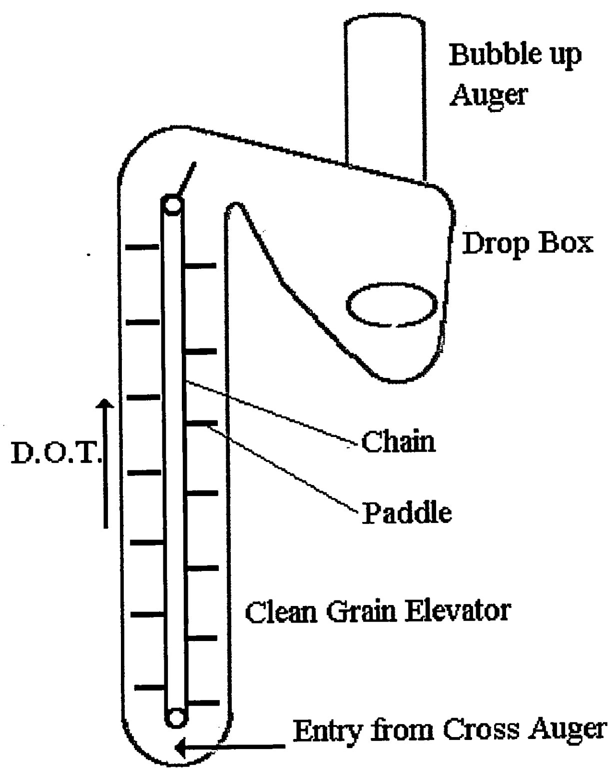


Figure 5.1 - End View of Clean Grain Elevator and Drop Box

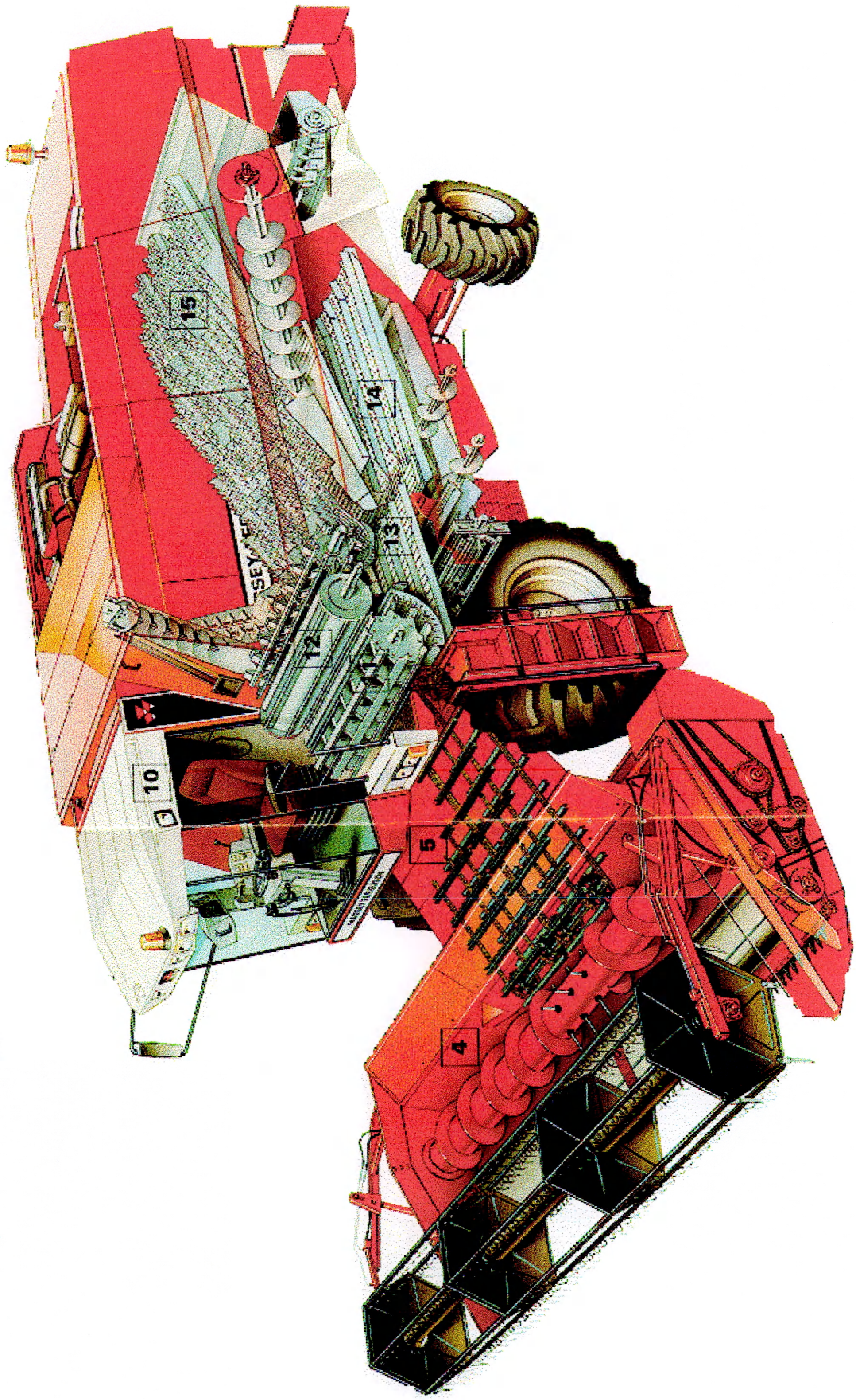


Figure 5.2 - Section Through a Combine Harvester

5.3 - CLEAN GRAIN SYSTEM SIMULATION APPARATUS

These studies were undertaken in co-operation with Mark Moore of Massey Ferguson, the results forming an important component of his Ph.D thesis on yield mapping (Moore, 1997). The aim was to gain data on transducer performance, under controlled operating conditions, similar to actual harvesting. The studies were not intended as a direct comparison with the Massey Ferguson gamma absorption system, as it was agreed that all results would remain confidential and the sole property of the respective sponsors.

5.3.1 - Apparatus

The lower section of a combine was acquired from Dronninborg in kit form. This consisted of the lower cross auger and enclosing grain pan, clean grain elevator and housing and the first section of the drop box.

A framework, Plate 5.1, was constructed to house these components and the rig was mounted on wheels. The top of the grain pan was covered in weld mesh, allowing grain to be dropped through to the lower cross auger. Power to drive the system was via a 3.5 horsepower, 3 phase electric motor, driven through a soft start device, ensuring a smooth uptake of power on start up.

A chute was fitted to the bottom of the drop box, allowing grain to be funnelled to a collection hopper. This hopper was stood in the Massey Ferguson weighing trailer (Godwin and Wheeler, 1997), which permitted recording of the absolute mass flow rate, via a separate computer, with a resolution of ±1kg. The trailer software was modified to allow the standard 18.2 Hz signal to be sampled at 1 Hz and smooth this over a 6 second period using a rolling average algorithm. Grain feed to the system was via a hopper with adjustable aperture.

The Massey Ferguson mass flow rate transducer was fitted in the top of the elevator (the normal position for this device). Data was recorded at 1 Hz via the standard Datavision and flash card system, the smoothing interval and algorithm were confidential. The DIP transducer was fitted in the top of the drop box and grain was directed down to the transducer by a curved plate, Figure 5.3. The transducer was powered from a 12 volt source and data was recorded at 33 Hz using *HMData Snapmaster* software on the desktop computer. The crop selected for this test was winter wheat at 11.5 % moisture content, being the only easily available material.

Plate 5.1 - Clean Grain System Test Apparatus

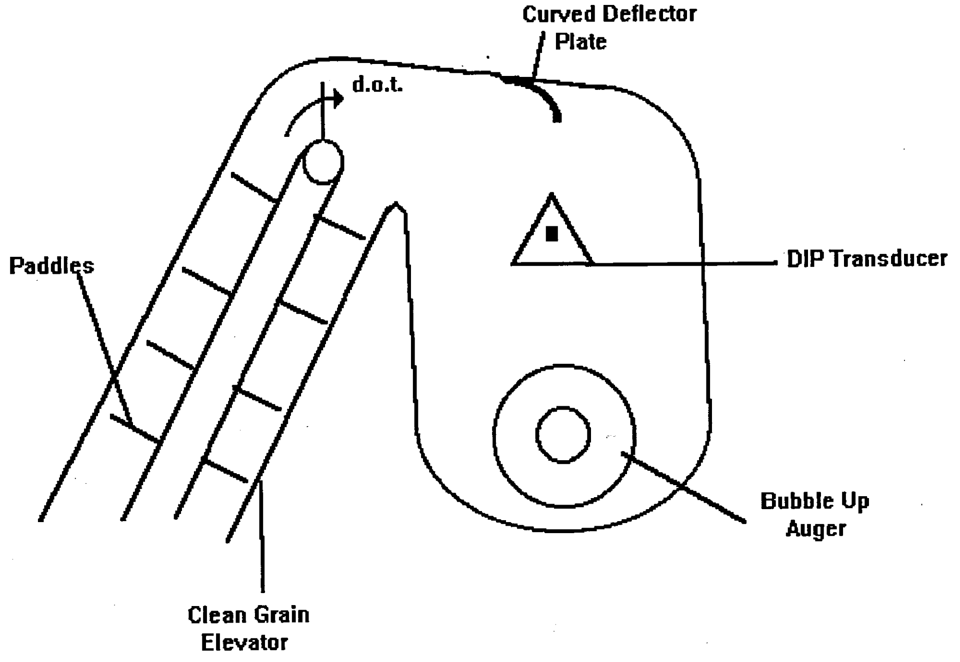


Figure 5.3 - Layout of Transducer System Within Drop Box

5.3.2 - Methodology

Before commencing the main study, 20 kg of wheat was introduced to the rig to fill any spaces that required filling before steady state testing commenced, i.e. the bottom of the cross auger. Each test involved positioning the crop reservoir hopper above the grain pan and lower cross auger. All recording systems and the drive motor were then started. The aperture on the hopper was opened a known amount allowing a steady flow of crop through the rig. The time of crop flow was noted and used to check the trailer figures. At the end of each test the drive motor and recording systems were stopped and the time and final trailer mass noted. Steps in flow were also studied, changing the aperture on the hopper a known amount at a set time during each test. These steps consisted of large and small increases and decreases in flow rate.

5.3.3 - Results and Discussion

Figures 5.4 and 5.5 shows the flow rate over time for the DIP transducer and weighing trailer during typical steady state and variable flow tests, respectively. The DIP transducer signal is also shown subject to a 6 second forward facing rolling average to allow a fair comparison with the trailer signal. All response signals exhibit very similar characteristics, the DIP transducer being slightly more noisy before the smoothing average algorithm was used, but appearing more sensitive to small changes in flow rate. From figure 5.5, it can be seen that both signals show excellent correlation, matching each other closely in terms of magnitude and response.

Table 5.1 details results for all tests. Figures are given for both the trailer and DIP transducer for total mass flowed and steady state flow rates. From these figures, the percentage errors were calculated and show that the transducer offered errors less than ± 2.1 % for the accumulated mass in 35 of the 37 tests and better than ± 2.0 % on spot flow rate in 28 of the 31 relevant tests. It can be seen that the accuracies for accumulated mass and flow rate are within 0.4 % of each other for 28 of the 30 applicable tests.

The rolling average is a simple averaging process, considering the average of a number of previous and future data points around each data point. As the time base (of the average) extends, the time base of the transducer signal is also extended, causing a ramp up and down. The area under the transducer signal remains constant, irrespective of the smoothing time base.

Table 5.1 - Results of Clean Grain Simulation Study

TEST TYPE	Total Mass (kg)		Flow Rate		% Error	
	Reference	Measured	Reference	Measured	Total Mass	Flow Rate
Steady Flow	767	772	4.54	4.57	0.6	0.6
Steady Flow	775	788	3.30	3.35	1.6	1.6
Steady Flow	763	772	5.87	5.94	1.2	1.2
Steady Flow	773	757	5.64	5.53	-2.1	-2.1
Steady Flow	763	779	4.89	4.99	2.1	2.1
Steady Flow	762	751	4.92	4.85	-1.5	-1.5
Steady Flow	759	746	4.20	4.12	-1.7	-1.9
Steady Flow	759	744	5.46	5.35	-2.0	-2.0
Steady Flow	758	751	4.48	4.44	0.9	-0.8
Steady Flow	757	773	3.21	3.28	2.1	2.0
Steady Flow	758	771	6.42	6.53	1.7	1.7
Steady Flow	759	763	2.76	2.77	0.5	0.5
Steady Flow	745	732	2.38	2.34	-1.8	-1.8
Steady Flow	751	757	9.75	9.83	0.7	0.8
Steady Flow	748	756	5.60	5.64	1.1	0.8
Steady Flow	743	730	3.77	3.71	-1.8	-1.7
Steady Flow	747	717	3.01	2.89	-4.0	-4.1
Steady Flow	745	740	4.07	4.04	-0.7	-0.6
Steady Flow	744	732	3.14	3.09	-1.6	-1.6
Steady Flow	742	735	3.80	3.77	-1.0	-0.9
Steady Flow	739	742	2.40	2.40	0.3	0.0
Steady Flow	742	747	5.30	5.33	0.6	0.6
Steady Flow	741	734	2.97	2.95	-1.0	-0.8
Steady Flow	744	752	5.40	5.45	1.1	0.9
Steady Flow	743	750	2.10	2.10	0.9	0.0
Steady Flow	744	747	6.50	6.50	0.4	0.0
Steady Flow	740	727	6.30	6.22	-1.7	-1.3
Steady Flow	702	708	6.00	6.11	0.9	1.8
Steady Flow	742	730	7.42	7.30	0.7	-1.6
Steady Flow	739	732	7.54	7.47	-0.9	-0.9
Steady Flow	738	746	7.61	7.69	1.0	1.0
Small Steps	743	762			2.5	
Small Steps	740	752			1.6	
Small Steps	741	731			-1.3	
Large Steps	740	750			1.6	
Large Steps	737	743			0.9	
Large Steps	736	721			-2.1	

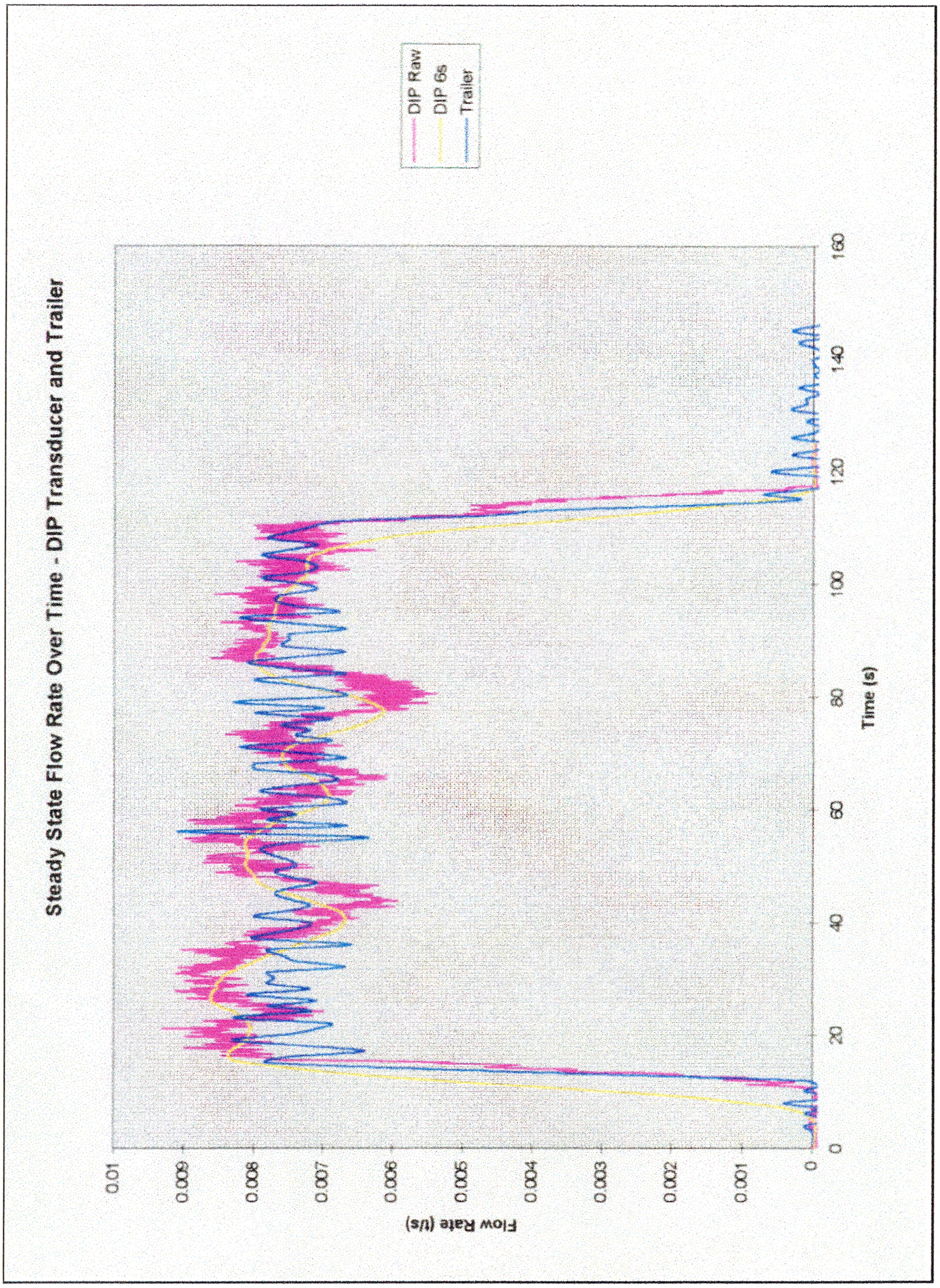


Figure 5.4 - Steady Flow Rate Over Time - DIP Transducer and Trailer

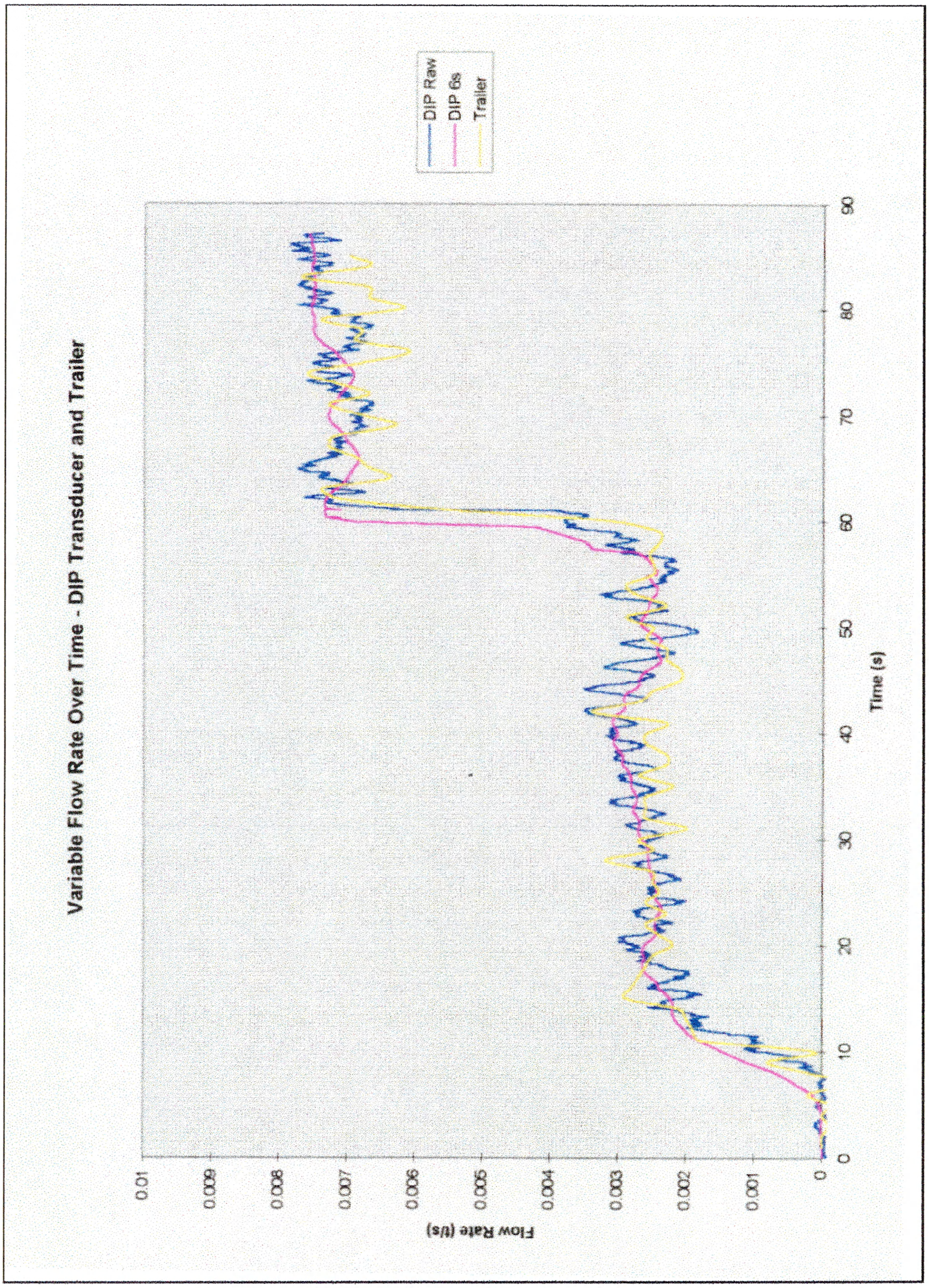


Figure 5.5 - Variable Flow Rate Over Time - DIP Transducer and Trailer

5.4 - PILOT STUDIES OF THE DIP TRANSDUCER PERFORMANCE MOUNTED IN THE COMBINE

The aim of these pilot studies was to initially provide a calibration for the DIP transducer when fitted on a combine and once established, to assess accuracy on mass accumulation. The combine used for these studies was a New Holland TF42, an ex-development machine from the New Holland Zedelgen facility in Belgium. The header had an effective cutting width of 5.2 metres and the maximum harvesting rate was quoted as 36 tonnes per hour. The DIP transducer was fitted on the end of an extended bubble up auger, allowing ease of access for adjustments and observation.

Grain was artificially introduced into the combine and accuracy found by comparing the actual mass of grain in each combine tank load against the integration of DIP signal (accumulated mass). This gave no direct assessment of 'spot' flow rates, only total mass, however there was no apparent method to check actual flow rates on a working combine. As discussed in section 5.3, the accuracy on spot flow rate readings are within ± 0.5 % of accumulated mass accuracies. Therefore, it might be reasonable to assume that if total mass was accurate any spot reading could also be considered reliable.

5.4.1 -Combine Harvester Preparation

When the machine was delivered, the bubble up auger and drop box assembly were removed and replaced by a similar item with the bubble up auger extended by 1 metre, as shown in Figure 5.6. This allowed the crop a drop of at least 30 mm to the DIP, whilst still permitting the full capacity of the grain tank to be utilised. The end of the bubble up auger had a hood fitted which directed the grain downwards in a controlled pattern, the transducer being mounted directly below this.

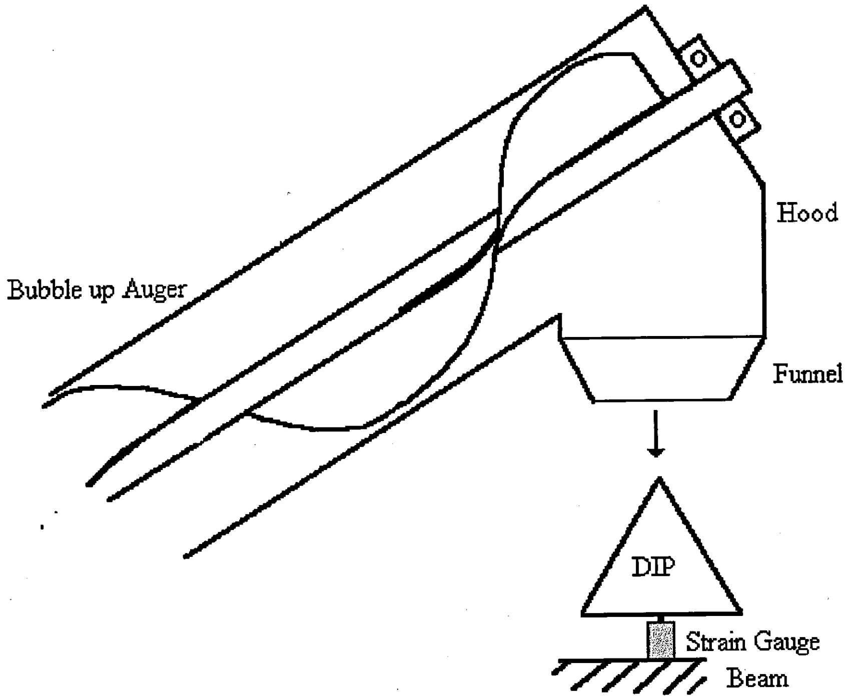


Figure 5.6 - Diagram of Extended Bubble Up Auger

To record the DIP transducer signal whilst in the field, the desktop computer, was used, as previously, which had an internal analogue to digital card (*CIO-DAS-16 Jr*) – 16 bit allowing up to 8 differential analogue inputs, via an external junction box.

To power the computer and monitor, a 12 volt DC to 240 volt AC inverter was used, driven from two 180 amp-hour batteries. The computer was housed in a box mounted on the combine cab roof, having a 12 volt fan, drawing air in through a dust filter to provide cooling.

Finally, a stopwatch and log book were used when harvesting, to record any changes in conditions, such as turning at headlands.

The complete system is illustrated in Figure 5.7.

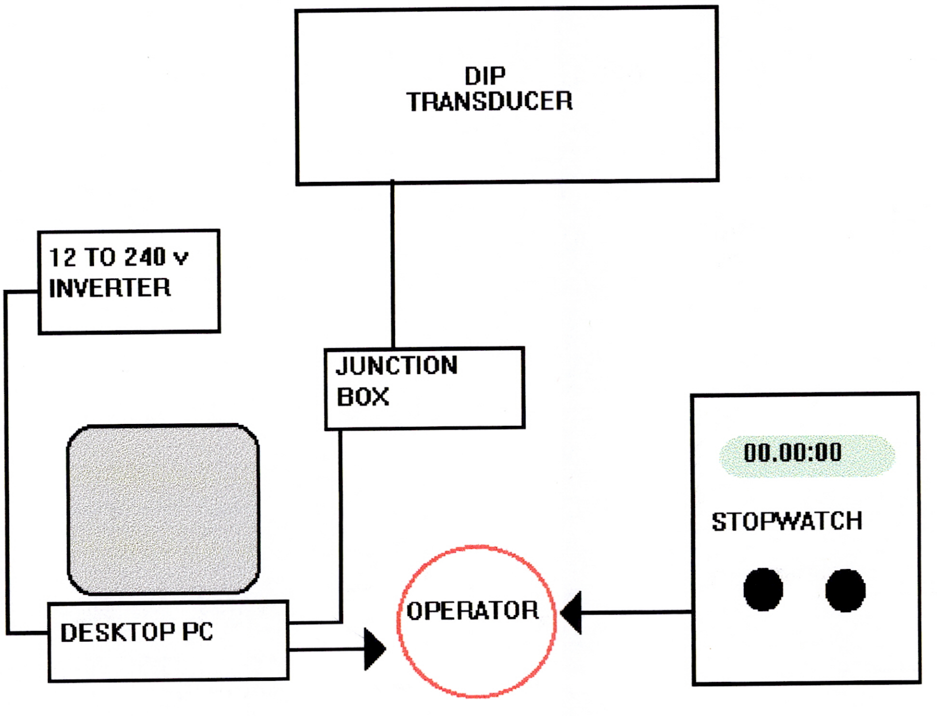


Figure 5.7 - Pilot Studies Data Acquisition System

5.4.2 - STATIC EVALUATION

These studies had five main objectives.

1. To assess the effects of height of drop on calibration constant.
2. To provide a reliable in-situ calibration constant for the transducer.
3. To test the in-situ accuracy of transducer mass accumulation .
4. To investigate the nature and effect of the harsh vibrational effects of the combine upon transducer performance.
5. To determine the most effective method of signal conditioning.

To introduce grain into the combine without actually harvesting, a hopper was made which fitted on the bottom of the clean grain elevator, thus allowing grain to be fed directly to the elevator and consequently the bubble up auger and transducer.

A loading ramp was built allowing a trailer to be positioned above this hopper. The trailer used was modified to allow controlled grain flow. To measure the total mass of grain flowed, an instrumented trailer with a resolution of 1 kilogram and n accuracy of 10 kg (Godwin and Wheeler, 1997) and a weighbridge (10 kg resolution and 50 kg accuracy) were positioned under the unloading auger. The layout is illustrated in Figure 5.8.

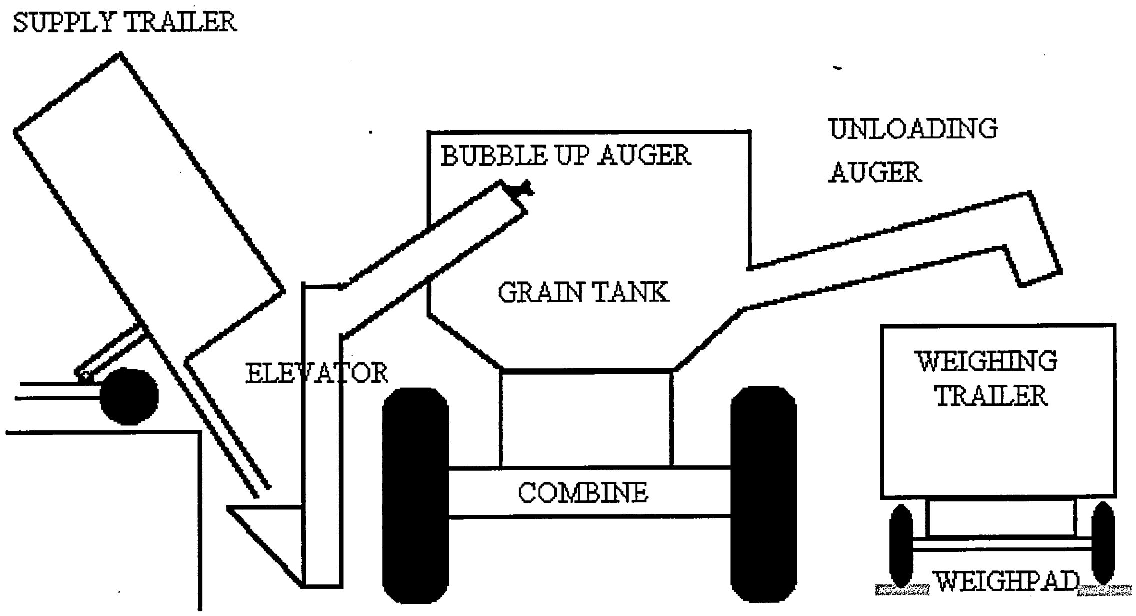


Figure 5.8 - Layout of Static Testing

The combine was then run with the threshing mechanism engaged and the grain flow measured by the transducer. The total recorded mass of grain flowed was compared with the grain mass in the trailer to determine the error in mass accumulation.

To investigate the relationship between drop height and signal, a range of drop heights were tested on the combine. These heights were also substituted into Equation 2.4, to predict the constant and the results are shown in Table 5.2.

Table 5.2 - Effect Of Drop Height (h) On Calibration Constant (K)

Drop Height - h (m)	Calibration Constant - K (V / kg.s^{-1})	
	Experimental	Calculated
0.03	0.0018	0.0020
0.08	0.0020	0.0021
0.12	0.0021	0.0022
0.46	0.0025	0.0024

These results demonstrate that the drop height and hnce impact velocity dominated the calibration constant (k). The relationship between h and K is shown in Figure 5.9, with R squared values of 0.975 and 0.964 for experimental and calculated K, respectively. Also shown are the upper and lower 95 % confidence intervals, both data sets fitting within these, it can be concluded therefore that there is no significant difference.

Using the experimentally derived calibration constants, a series of tests were undertaken on the combine to assess accuracy of mass accumulation. The results can be seen in Table 5.3.

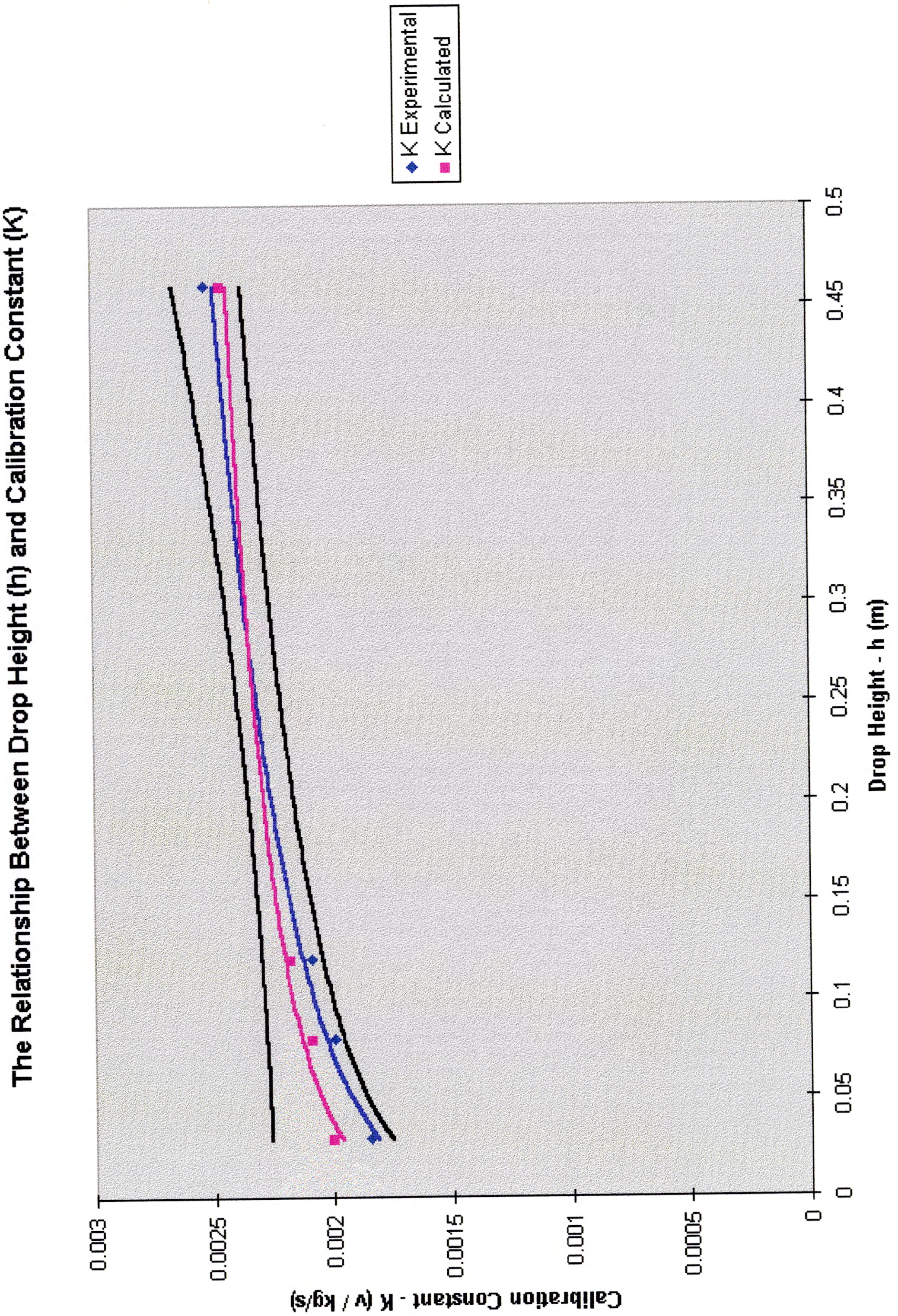


Figure 5.9 - The Relationship Between Drop Height (h) and Calibration Constant (K)

Table 5.3 - Results From Static Testing

Drop Height (h) (mm)	Reference mass (m_a) (kg)	Measured mass (m_r) (kg)	% Error
30	489.0	477.1	2.4
30	500.0	498.1	0.5
30	506.0	514.4	-1.6
30	609.0	596.7	2.0
30	743.0	766.1	-3.1
80	1098.0	1088.0	0.9
80	1098.0	1114.4	-1.5
80	1098.0	1092.1	0.5
80	1098.0	1101.4	-0.3
80	1098.0	1119.0	-1.9
80	1098.0	1091.0	0.6
120	1098.0	1137.7	-3.6
120	1098.0	1076.0	2.0
120	1098.0	1119.7	-2.0
120	1098.0	1097.7	0.0
120	1098.0	1133.0	-3.2
120	1098.0	1116.0	-1.6

The average error of this data is -0.57 %, suggesting the calibration constants fit well. The worst error occurred at the 120 millimetre drop height and was -3.6 %, the results with least error were obtained with an 80 millimetre drop.

This work showed that repeatable results close to the design specification could be achieved from a running combine in a static situation.

5.4.3 - The Effect of Combine Vibrations Upon Transducer Behaviour

To complement the static pilot studies, a series of dynamic studies were undertaken to examine the effects of combine vibrations and shock inputs upon the transducer. This involved recording the transducer output whilst driving the combine over rough and smooth surfaces using each gear with and without the threshing mechanism running and grain flowing.

5.4.3.1 - Vibrational Effects Without Grain Flow

The combine was fitted with a 4 speed manual gearbox and hydrostatic intermediate box. The transducer signal was recorded as the combine was driven over a rough surface in each gear, with and without the threshing mechanism engaged during which hydrostatic box was varied through all of its speed range. Figure 5.1, Appendix 5, shows a typical plot of gear 4 with the threshing mechanism engaged, it can be seen that the signal varies about the x-axis with several small spikes present. Table 5.4 details the mass recorded and the duration of each test and from these an equivalent flow rate was calculated. For error estimation purposes, this equivalent flow rate was compared to the signal at 10 kg/s

Table 5.4 - Mass Recorded During Dynamic Testing with no Grain Flowing

Gear	Threshing	Duration (s)	Measured Mass (kg)	Equivalent Flow Rate (kg/s)	% Error when added to 10 kg/s flow rate
1	Yes	42.0	0.81	0.02	0.2
2	Yes	44.5	2.15	0.05	0.5
3	Yes	47.9	3.92	0.08	0.8
4	Yes	41.0	3.80	0.09	0.9
1	No	35.9	3.18	0.09	0.9
2	No	32.5	2.44	0.07	0.7
3	No	46.4	-2.80	-0.06	-0.6
4	No	26.6	2.21	0.08	0.8

It should be noted that this is a worst case scenario as (i) straw was not present in the combine concave which has a damping effect upon machine vibrations, and (ii) grain was not flowing over the transducer which has a damping effect on transducer vibrations.

These tests show that the effects of vibrations, are less than 1 % and are within the design specification.

5.4.3.2 - Vibrational and Shock Effects with Grain Flowing

A crop storage hopper was positioned in the grain tank above the transducer. This was fitted with a calibrated slider to allow a controlled flow of crop over the transducer. It was filled with a measured mass of grain and the time of flow was noted to calculate steady state flow rate for a range of dynamic conditions given in Table 5.5. During each test the transducer signal was recorded and the results are shown in Table 5.5.
Variables incorporated into each test were

- Two surfaces, one of smooth concrete and one with a simulated tramline.(0.15 m deep)
- Engine running and stopped.
- Crop flowing and no crop flow.
- Threshing mechanism engaged and disengaged.
- Two different flowrates, approximately 2 kg/s and 5 kg/s.

Table 5.5 - Results From Dynamic Testing

Test Type	Reference Mass (kg)	Measured Mass (kg)	Relative Error (kg)
Static	0.00	-1.83	-1.83
Static & 5 kg/s	80.02	80.35	0.33
Engine Running	0.00	2.01	2.01
Threshing	0.00	3.30	3.30
Engine & 2 kg/s	80.02	79.44	-0.58
Engine & 5 kg/s	80.02	79.71	-0.31
Threshing & 2 kg/s	80.02	79.38	-0.64
Threshing & 5 kg/s	80.02	79.07	-0.95
Smooth 2 kg/s	80.02	80.52	0.50
Smooth 5 kg/s	80.02	81.53	1.51
Tramline 2 kg/s	80.02	80.82	0.80
Tramline 5 kg/s	80.02	80.78	0.76
Smooth No Grain	0.00	0.71	0.71

The largest errors encountered were 1.51 kg for cases where grain was flowing, equivalent to 1.25 % error and 2.01 kg for cases where grain was not flowing, equivalent to 2.6 % if the 80.02 kg mass is used as an indicator.

A major concern was the effect of the combine crossing tramlines in the field which may cause a significantly larger error than the other dynamics introduced during harvesting conditions. As shown in Figure 5.10 however, the dynamics are such that the shock causes firstly a negative then positive spike. If the mean area under each spike is considered, the resultant approaches zero, negating tramline effects, depending upon the time base used for signal conditioning.

5.4.4 - Comparison of Signal Conditioning Methods

Signal conditioning can be used to 'clean' the transducer signal by reducing or removing any spurious components of the signal, such as high frequency 'noise', as often generated by the analogue to digital conversion process. The aim of this conditioning is to leave only the part of the signal which relates to flow rate. Two conditioning processes were assessed, (i) smoothing through the method of rolling averages, averaging each data point over a previous number, damping any sudden signal variations, and (ii) filtering, allowing only certain frequencies to pass, effectively screening the signal. In all cases the data was conditioned at the post process stage on a computer, i.e. the data was logged in raw format at 33 Hz, ensuring important signal characteristics were not 'smoothed' before they were recorded. This also allowed different forms of signal conditioning to be applied to the same data set. Once determined, the most suitable method can be recreated electronically for a production model.

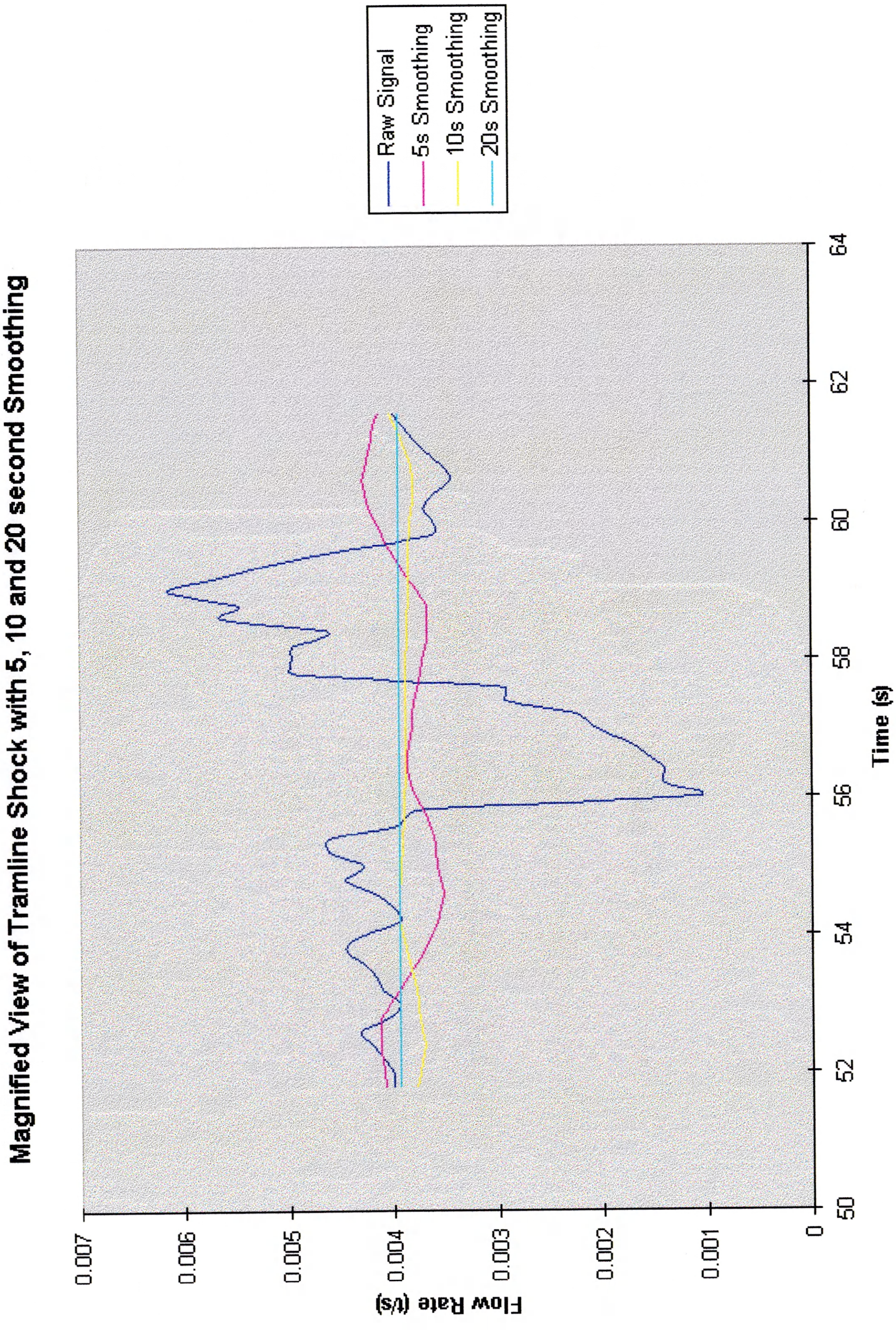


Figure 5.10 - Magnified View Of Tramline Shock with 5, 10 and 20 second Smoothing

5.4.4.1 - Smoothing (method of rolling averages)

Smoothing, via the method of rolling averages, involves considering each individual data point as an average of a number of the previous or following values. An example is shown in Figure 5.11, a rolling average of 5, 10, 20, 30 and 60 seconds having been applied to a step input of 30 seconds duration. As the time base (of the average) extends, the time base of the input is also extended, causing a ramp up and down. The length of each ramp is the same as the time base of the smoothing algorithm, i.e. at 10 seconds smoothing, the ramp up lasts for 10 seconds.

When the time base of the smoothing algorithm is equal to the length of step input, as for the 30 second smoothing in Figure 5.11, the signal consists of only a ramp up and down with no steady state. Once the smoothing time base exceeds that of the input, the magnitude of the signal is reduced, as with the 60 second smoothing algorithm. However the area under the step remains constant, whichever time base is used for smoothing.

A typical shock input was closely examined, and is shown previously, on an much enlarged scale, in Figure 5.10. This shows a rise and fall in signal following an impact lasting approximately 2 seconds. Also shown is the shock input run through a 5, 10 and 20 second rolling average. It can be seen that a 5 second average is sufficient to reduce the shock considerably with rolling averages in excess of this, effectively negating any effect from the shock.

5.4.4.2 - Filtering

When a signal is filtered, certain frequencies are screened out, allowing only the desired part of the transducer signal to pass. High frequencies can be screened, allowing only low frequency signals through (lowpass), or low frequencies can be excluded, permitting only high frequency signals to pass (high pass). Alternatively, signals outside the band between 2 defined frequencies can be excluded (band pass). By measuring typical transducer signal frequencies and their amplitudes, Table 5.6, it could be possible to remove any spurious 'noise', leaving a clean signal, the only variations being those in flow rate.

It is believed that variations in yield will be apparent as low frequency variations (approximately 0 to 1 Hz), therefore it is important not to remove these. The higher frequencies with larger amplitudes are believed to be spurious noise that needs to be removed to further increase transducer accuracy.

Table 5.6 details the 3 most apparent frequencies in each signal (in Hz) and their amplitudes (shown in brackets, in kg/s). In all cases there is one relatively low frequency (0.1 - 0.3 Hz), and two higher frequencies, normally with slightly larger amplitudes. These vary according to the circumstance due to the different vibrations present and their larger amplitude suggests they are the main cause of error in the accumulated mass.

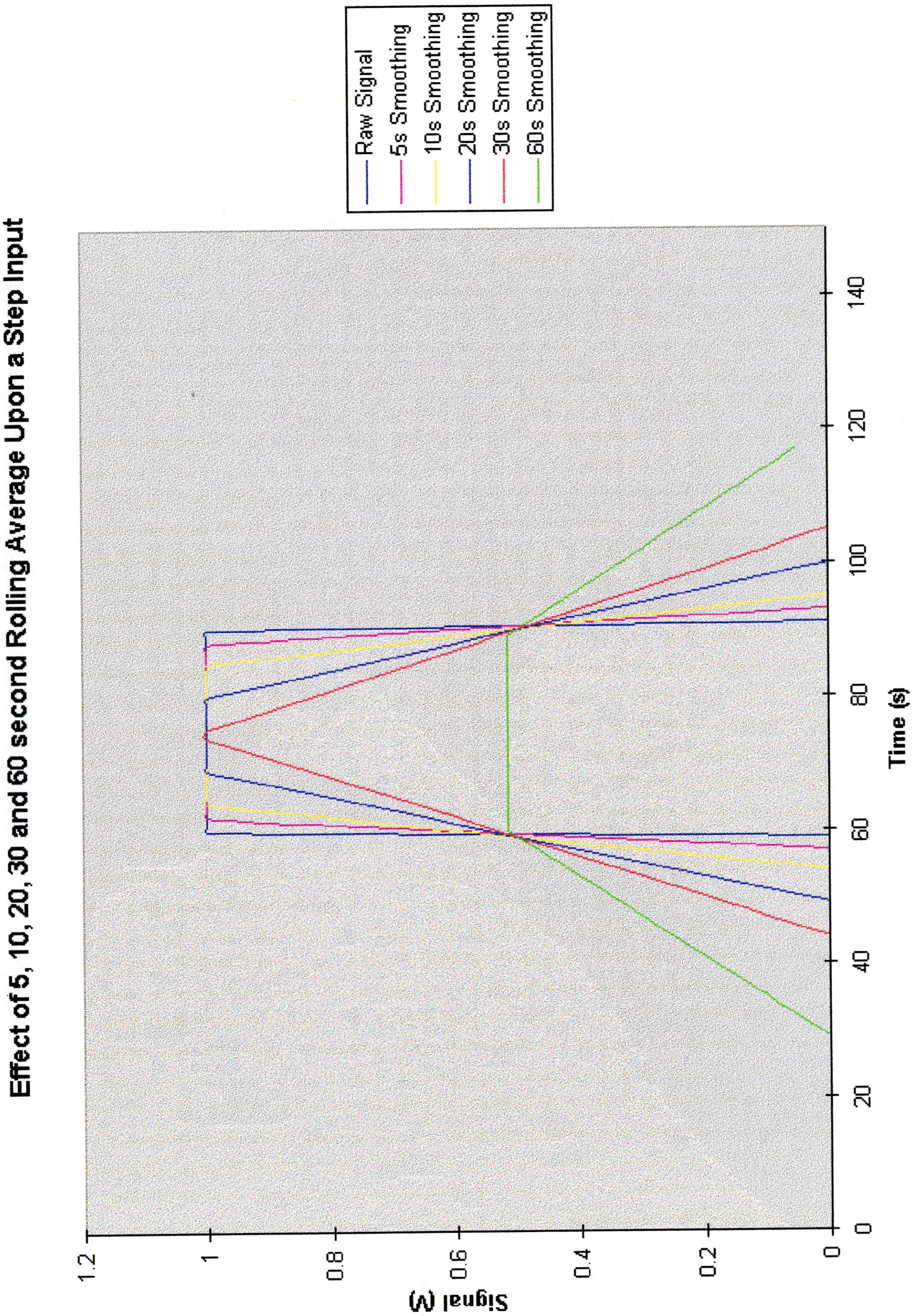


Figure 5.11 - Effect of 5, 10, 20, 30 and 60 Second Rolling Averages Upon a Step Input

Table 5.6 - Apparent Signal Frequencies and Amplitudes From Dynamic Testing (Relative)

Test	Low	Mid	High
Silence	0 Hz (0 kg/s)	0 Hz (0kg/s)	4.00 (0.04kg/s)
Engine Running	0.12 Hz (0.01kg/s)	0.40 Hz (0.06kg/s)	3.60 Hz (0.05kg/s)
Threshing	0.12 Hz (0.01kg/s)	0.40 Hz (0.1kg/s)	10.00 Hz (0.11kg/s)
Engine & 2 kg/s	0.15 Hz (0.02kg/s)	0.45 Hz (0.05kg/s)	16.40 Hz (0.15kg/s)
Engine & 5 kg/s	0.22 Hz (0.01kg/s)	5.00 Hz (0.20kg/s)	12.50 Hz (0.21kg/s)
Threshing & 2 kg/s	0.25 Hz (0.05kg/s)	0.50 Hz (0.07kg/s)	7.00 Hz (0.14kg/s)
Threshing & 5 kg/s	0.25 Hz (0.04kg/s)	1.92 Hz (0.04kg/s)	16.40 Hz (0.34kg/s)
Smooth 2 kg/s	0.13 Hz (0.02kg/s)	4.00 Hz (0.02kg/s)	8.00 Hz (0.10kg/s)
Smooth 5 kg/s	0.35 Hz (0.01kg/s)	6.00 Hz (0.13kg/s)	12.00 Hz (0.28kg/s)
Tramline 2 kg/s	0.25 Hz (0.03kg/s)	4.00 Hz (0.08kg/s)	14.00 Hz (0.17kg/s)
Tramline 5 kg/s	0.30 Hz (0.01kg/s)	6.00 Hz (0.10kg/s)	12.00 Hz (0.06kg/s)

PV-Wave Advantage 4.2 software was used to simulate a band pass filter, using fast fourier transforms. A typical data set was considered and had three different bandwidths applied, Figure 5.12. The pass frequencies used were

- 0 Hz to 1 Hz
- 0 Hz to 0.5 Hz
- 0 Hz to 0.1 Hz

The 0 to 1 Hz filtered signal appears to offer least signal distortion whilst removing the high frequency ‘noise’. A band pass of 0 to 0.1 Hz appears to damp the signal excessively, flattening any of the features.

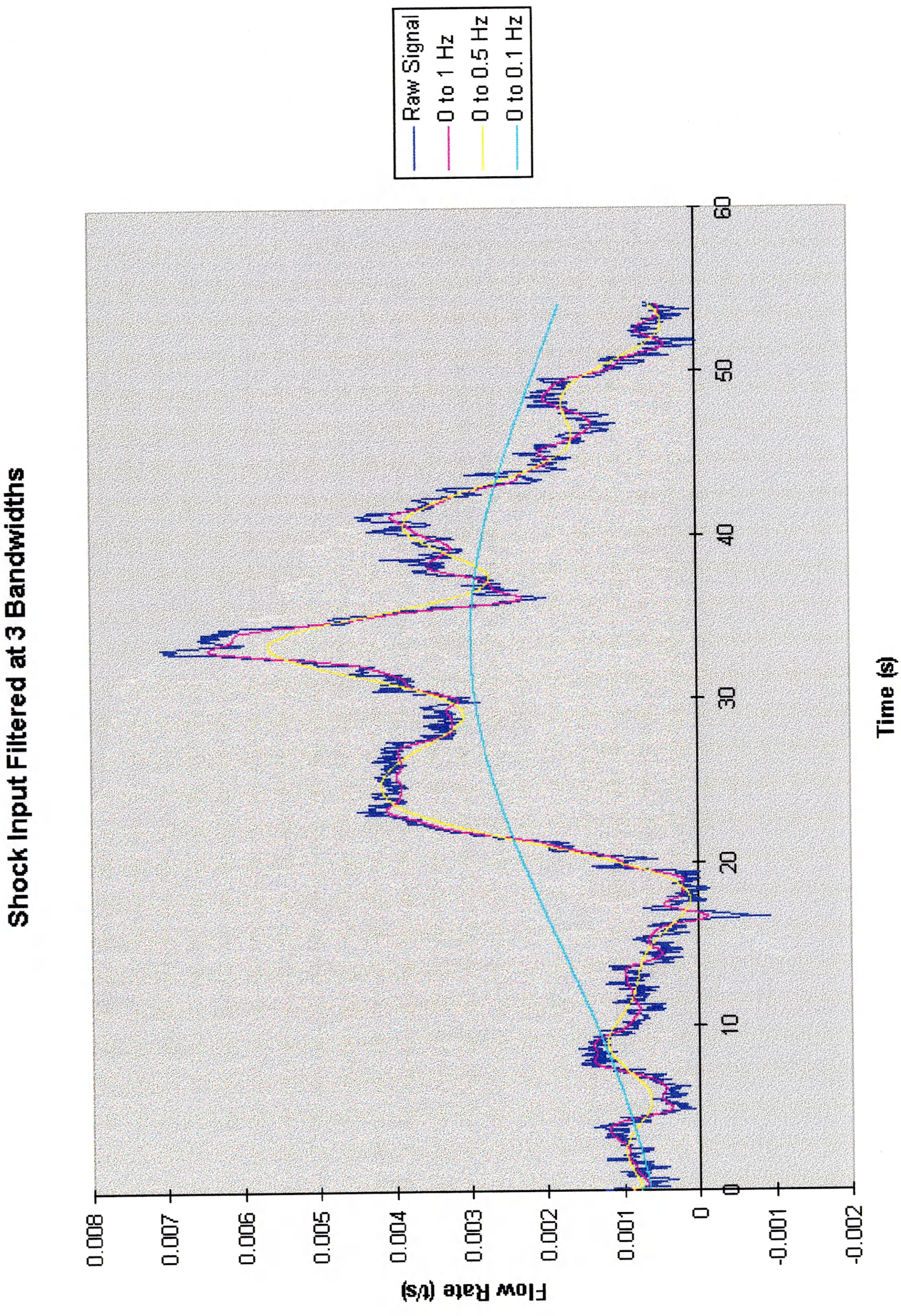


Figure 5.12 – Tramline Shock Input Filtered at 3 Bandwidths

5.4.4.3 - Comparison Of Filtering And Smoothing

From section 5.4.3.2, the data recorded during a test run with the engine running and a flow rate of 5 kg/s was considered. It was smoothed over 3 time bases and filtered over 3 band pass frequencies, the resulting accumulated mass being recorded in Table 5.7.

Table 5.7 - Effect of Signal Conditioning Upon Integrated Mass

Test	Reference Mass (kg)	Integrated Mass (kg) Smoothing			Integrated Mass (kg) Filtering		
		5 s	10 s	20 s	0 - 1 Hz	0 - 0.5 Hz	0 - 0.1 Hz
Smooth 2 kg/s	80.0	80.2	80.2	80.2	79.7	79.7	79.7
Smooth 5 kg/s	80.0	80.2	80.2	80.2	81.4	81.4	81.4
Tramline 2 kg/s	80.0	80.2	80.2	80.2	80.2	80.5	80.5
Tramline 5 kg/s	80.0	80.2	80.2	80.2	80.6	80.6	80.6

Errors in the filtering process are almost identical in all bands, offering acceptable errors between -0.3 % and +1.76 % error. However, the smoothing process, through a rolling average, does not alter the total mass recorded, offering the same figure for accumulated mass over all time bases. For this reason and its ease of post processing application, the rolling average was recognised as the preferred method of signal conditioning during this study.

5.5 - FULL FIELD TRIALS - SUMMER 1996

This study aimed to test the DIP transducer using field trials during actual harvesting. This involved, (i) a pre-harvest calibration, (ii) a full field test with many differing harvesting situations and (iii) a post harvest study to complete this work. Many valuable lessons were learnt from the earlier pilot studies and using this experience, the harvesting methodology, data acquisition system and transducer placement were all reviewed

Once again the New Holland TF42 combine was used but the DIP transducer was mounted in the drop box, the area between the clean grain elevator and the bubble up auger. The in cab electronics, used to display the transducer signal, were based upon a standard Griffith Elder unit, known commonly as a "Brainbox". This unit is normally used in conjunction with a "Grain Brain" mounted on the unloading auger. It records and displays the mass flowed with a resolution of 1 kilogram (and calculates dry mass when suitable moisture contents are input), the forward speed (0.1 miles per hour resolution) and area harvested (0.01 hectare resolution). It also has a facility to vary calibration constant, primarily designed for varying crops and moisture contents. An independent record of the signal was taken with a laptop computer.

Two other transducers were fitted, a magnetic forward speed pick up was mounted on a front wheel drive shaft and a header position switch was mounted on the header lift cylinder to indicate when the machine was harvesting (the header being raised when not in work).

Following problems with the initial data recording system, a fresh approach to on-machine data acquisition was taken for this study. It was decided the system should, wherever possible, use the sponsor's electronics, offering a cab display ('Brainbox') with facilities to re-zero, start a new job and alter calibration constant.

The DIP transducer signal was fed through an external 16 bit analogue to digital (binary coded decimal) converter, mounted as close to the transducer as possible. This ensured minimal signal corruption whilst in its exposed analogue state. This digital signal was supplied to the cab display, which displayed the signal multiplied by the calibration constant, integrated over time (the accumulating mass). Also fitted was a record on/off switch to allow control over whether the cab display recorded data. When switched off it allowed the cab display to measure a zero signal from the transducer. This was used because the amplifier fitted tends suffer from zero drift when left running for long periods.

The forward speed monitor took the form of a magnet attached to a front wheel drive shaft and fixed reed switch. This was calibrated within the cab display and allowed forward speed and area harvested (after inputting header width) to be recorded.

The header switch was used to negate any data taken whilst the machine was not in work. This was only used for area data because lag through the machine means crop is still being processed whilst turning. It took the form of a simple on/off switch.

A spur was taken from the communication bus between the cab display and junction box and fed to the laptop computer, via the communication port, this ASCII signal being transmitted at RS-232 level, 9600 baud, with no parity, 8 data bits and 1 stop bit. When tested using *Terminal* software in *Microsoft Windows*, a data file (*.txt) was recorded which could be imported into *Excel* and detailed accumulated mass. This signal was not a true 'raw' signal, but already converted to mass, via an internal calibration constant. Also the sampling rate was fixed at the bus communication rate of 16 Hz.

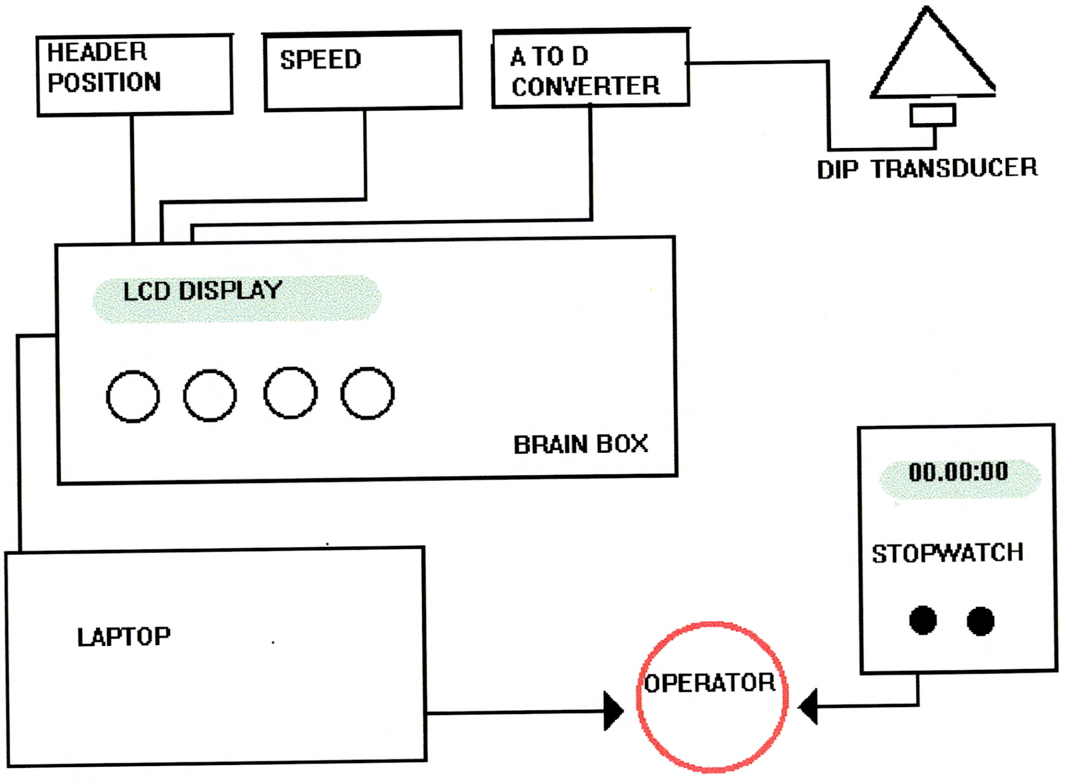


Figure 5.13 - Data Acquisition System for Full Harvest Field Trials

For post harvest calibration and performance studies, in addition to the previously described system, the desktop computer and *Snapmaster* software were once again used, allowing the sampling of a true 'raw' signal alongside the processed display signal.

The New Holland TF range of combines are fitted with the most restrictive of drop boxes of all major combines on the market, thus making it the most difficult to fit the transducer into. It is known that the combine was designed to work across the slope when on hillsides (having self levelling sieves) and thus by fitting the transducer transversely, the transducer is pitched (the least sensitive plane from earlier studies) when harvesting on a hillside.

Two designs were tested, the initial being to enlarge the drop box downwards, allowing space for the complete transducer (DIP reaction plate and beam) to be fitted inside the box. A funnel was made and fitted above the transducer to give an even feed of crop. The lower part of the box (under the transducer) was sloped to encourage the crop to slide down to the bubble up auger. A clear perspex inspection window was fitted in the box, level with the transducer allowing the roof behaviour to be observed.

Upon pre harvest testing, it was found that the system would not flow at more than 3 kg/s, due to the restriction of the funnel. At this flow rate the transducer was seen to give a negative signal (indicating that the transducer was lifting instead of being forced downwards). This was due to the slope below the transducer being less than the angle of repose of the grain. The inspection window became dirty very quickly with the dust from the crop suffering from static charge and sticking to the perspex. It became obvious that this design would not be practical and involved a complicated retrofit because much cutting and fabrication work is involved.

The second design was the same as used previously upon the clean grain system test apparatus, the main benefits being practical retrofit with a functional design. The drop box shape was not altered as it only needed to accommodate the DIP reaction plate, the strain gauge beam being mounted outside. It was connected to the endplate of the DIP reaction plate through a small hole cut in the side of the drop box.

To replace the restrictive funnel, a curved plate was fitted to the roof of the box. As crop left the paddles of the elevator, it was thrown across the roof of the box and the curved plate deflected the crop downwards onto the transducer. Provision to adjust the plate position was incorporated. Pre-harvest testing proved the transducer gave repeatable results with no restriction or blockage problems.

5.5.1 – Pre-Harvest Calibration

Pre-harvest testing had four aims :

- To assure the satisfactory operation of the system.
- To determine the calibration constant for the Brainbox.
- To determine the repeatability of results.
- To assess the effects of rough ground conditions on mass recorded.

An initial trailer load of 12.5 % moisture content wheat was conveyed through the machine to ensure satisfactory operation of the system and to fill any cavities in the system.

Initial tests were undertaken statically as with the pilot study post harvest calibration. A known mass of wheat was placed in a trailer which had an outlet spout and slider to control the flow rate. The trailer was raised on a ramp and the spout positioned above a hopper fitted on the bottom of the clean grain elevator. This allowed the crop to be introduced into the combine. Once a test was completed, the trailer was parked under the unloading auger on weighpads (to check grain mass) and recharged.

The same methodology was used in all tests :

1. The datalogging system was started.
2. The combine was started and the threshing mechanism engaged.
3. The trailer chute was then opened and a constant flow of grain ensured.
4. When the trailer was emptied, the threshing mechanism was disengaged.
5. The combine was stopped.
6. The logging system was stopped.

In order to integrate and calibrate the Griffith Elder "Brain Box", an arbitrary calibration constant of 16000 was chosen and twelve tests undertaken with a known grain mass of 1136 kg. This showed that the recorded mass was 406.5833, therefore the constant needed to be raised to :

$$16000 \cdot \frac{1136}{406.6} = 44710$$

From this, a new calibration constant of 44710 was calculated and entered, which gave the correct mass flowed (in kg) on the display screen and in the data file. Also it could be seen that the system was not restrictive and functioning correctly. These results are detailed Table 5.8, showing errors of less than 2.2%.

Table 5.8 - Results from Static Testing With Winter Wheat

Reference Mass (kg)	Measured Mass (kg)	Calibration Constant Used	Ideal Cal Constant	% Error Using Ideal Cal Const
1136	404	16000	44990	-0.6
1136	412	16000	44117	1.3
1136	398	16000	45668	-2.2
1136	412	16000	44117	1.3
1136	409	16000	44440	0.6
1136	401	16000	45327	-1.4
1136	405	16000	44879	-0.3
1136	409	16000	44440	0.6
1136	414	16000	43903	1.8
1136	408	16000	44549	0.3
1136	402	16000	45214	-1.1
1136	405	16000	44879	-0.3
1136	406.583		44710	0

To assess the effects of rough ground on the transducers output under zero flow conditions, the combine was driven along a rough track with no grain flowing. The track had ruts running along each side of it which were approximately 150 mm deep. There was also a rut of similar depth and 300 mm width across the whole width of the track.

This was repeated in all gears, with and without the threshing mechanism engaged along the same piece of track. It should be noted that this is a worst case situation as there was no straw in the threshing mechanism and no grain flowing on the transducer; both factors which have a damping effect. The results are shown in Table 5.9.

Each run lasted 30 seconds, indicating that in the worst case 0.033 kg/s would be recorded. Fourth gear appears to be the most affected, with the worst situation being not threshing at tick-over travelling in fourth gear, a situation never encountered when harvesting.

From these tests the harvest was approached with a known calibration constant, confidence in the repeatability of results and the knowledge that ground conditions should not affect the results significantly.

Table 5.9 - Results from Pre-Harvest Dynamic Testing

Type	Engine Revs	Threshing	Gear	Measured Mass (kg)	Measured Flow Rate (kg/s)
Static	Tick-over	No	N/A	0	0
Static	Working	No	N/A	0	0
Static	Tick-over	Yes	N/A	0	0
Static	Working	Yes	N/A	2	0.06
Dynamic	Tick-over	No	1	1	0.03
Dynamic	Tick-over	No	2	0	0
Dynamic	Tick-over	No	3	-1	-0.03
Dynamic	Tick-over	No	4	-2	-0.06
Dynamic	Working	No	1	0	0
Dynamic	Working	No	2	0	0
Dynamic	Working	No	3	0	0
Dynamic	Working	No	4	1	0.03
Dynamic	Tick-over	Yes	1	0	0
Dynamic	Tick-over	Yes	2	0	0
Dynamic	Tick-over	Yes	3	0	0
Dynamic	Tick-over	Yes	4	1	0.03
Dynamic	Working	Yes	1	0	0
Dynamic	Working	Yes	2	0	0
Dynamic	Working	Yes	3	0	0
Dynamic	Working	Yes	4	1	0.03

5.5.2 - Harvest Field Studies

The aims of the harvest studies were :

- To measure the accuracy and repeatability of the transducer under field conditions.
- To evaluate dynamic effects of the combine under harvesting conditions.
- To test the transducer under a range of field conditions.

Harvesting commenced at Silsoe College Farm, cutting winter wheat, approximately 0.5 hectare was cut to set the combine and ensure the machine was working well. The studies were then started, cutting a further 4 hectares. Harvesting continued at Wrest Park Farm, Silsoe (8 ha) and finished at Taylors' Farm, Wilstead (4 ha).

Each harvested tank load was recorded and weighed individually. Once satisfied the transducer was functioning correctly, each trailer load (three tank loads) was weighed to reduce the time spent evaluating the system.

Initially the headlands were cut which were straight runs of full combine header width with delays when turning in each corner. Then straight runs were taken along the length of the field. Once confidence had been gained, the following variables were individually introduced.

- Harvesting narrow strips, Plate 5.2.
- Harvesting widening and narrowing strips, Plate 5.3.
- Harvesting up and down slope on hillside, Plate 5.4.
- Harvesting in areas of high blackgrass (weed) infestation, Plate 5.5.
- Harvesting crops between 12 % and 18.5 % moisture content.
- Harvesting a full width strip with a transverse section of the crop missing, Plate 5.6.
- Harvesting across tramlines.

During the studies, 1 metre square quadrat samples were taken to calculate the yield from each strip of the field.

Plate 5.2 - Harvesting a Narrow Strip

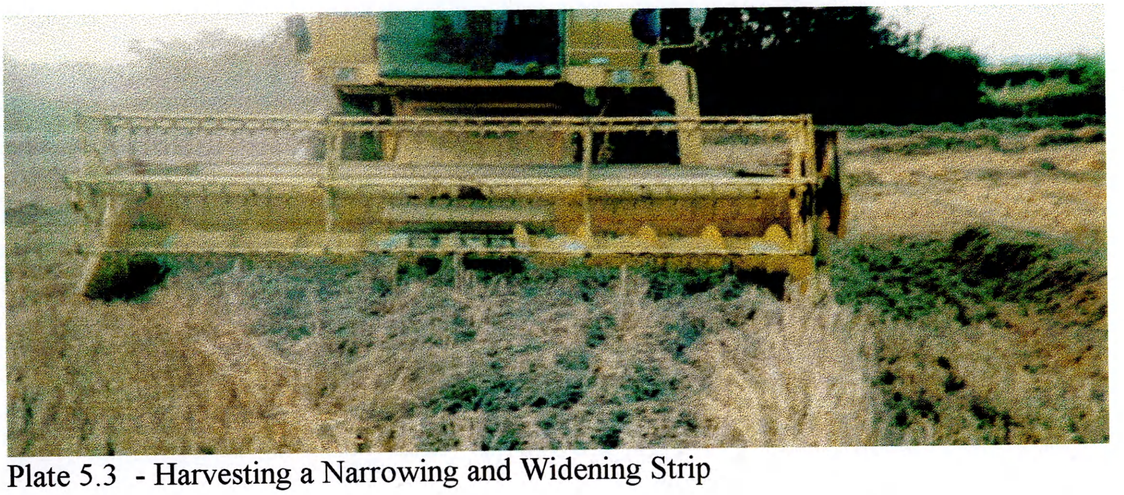


Plate 5.3 - Harvesting a Narrowing and Widening Strip

Plate 5.4 - Harvesting on a Hillside

Plate 5.5 - Harvesting in Areas of High Blackgrass Infestation

Plate 5.6 - Harvesting a Full Width with a Transverse Section of the Crop Missing.

The first experimental field cut was Copse Field, Silsoe College Farm. Whilst cutting the headlands the yield recording system was operative and several problems were noted and resolved :

1. Grain jammed in the gap between the transducer beam and the edges of the access hole cut for it, in the side of the drop box. Initially a small mild steel angled plate was fitted, to deflect crop away from the hole. However this was not completely successful and a sheet of light rubber was cut to extend this plate further downwards. This quick solution was very effective. In future a similar deflector made in stiff plastic could offer a cheap and simple solution.

2. When the combine was stopped with a full tank, grain crept back down the bubble up auger and lifted the transducer, giving a negative signal. The simple solution was to ensure a trailer is always available (as it normally would in a commercial situation), and by ensuring that in all further studies the bubble up auger was not stopped when the grain tank was full.

3. The electronics used in the "Brainbox" were designed for short term (several minutes) use, normally when unloading the grain tank. When not in use it measures a zero signal. When used for continuous field recording, the electronics are operated for a much longer period and consequently the amplifier suffered from a drift in the zero position. This problem was overcome by using the unloading auger switch to re-zero the amplifier, by switching off for approximately two minutes between trailer loads. A practical commercial solution is to fit an upgraded amplifier to cope with long term use, alternatively a photosensitive cell and supply could be fitted, acting as a switch at the outlet of the clean grain elevator. This would allow the amplifier to zero when no crop is flowing in the drop box, but mat suffer from dust contamination.

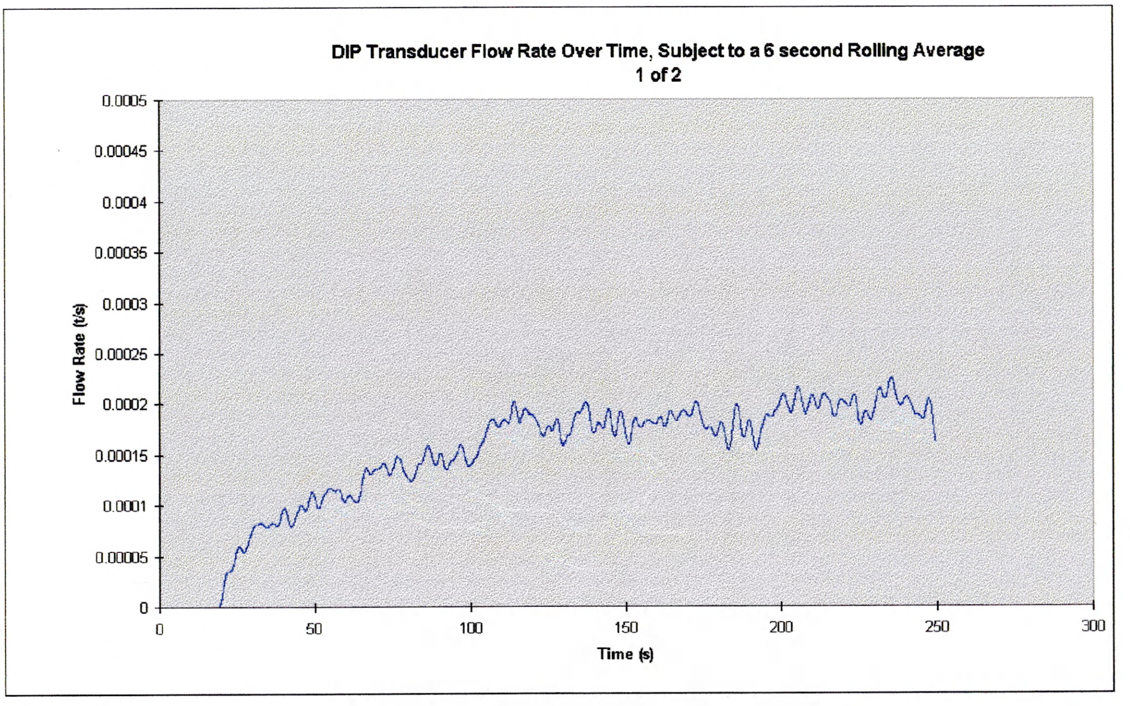
Once the headlands were removed, long straight runs at the full header width were recorded. Several runs cutting a narrow strip were taken as were runs crossing tramlines. For all harvesting in Copse Field, each tank load was weighed individually using an instrumented weighing trailer (Godwin and Wheeler, 1997) and the total mass confirmed using a Weights and Measures calibrated weighbridge (stated accuracy 20 kilograms).

The results for Copse field are shown in Table 5.10.

Table 5.10 - Results from Harvest Field Trials - Copse Field, Silsoe College

Test Type	Measured Mass (kg)	Reference Mass (kg)	% Error	Comments
Headlands	2532	2550	-0.71	
Straight	2804	1769	36.91	Transducer jammed
Straight	2838	1515	46.62	Transducer jammed
Straight	2200	2663	-21.05	Transducer jammed
Straight	1581	1860	-17.65	Transducer jammed
Straight	1852	1760	4.97	
Straight	2044	1924	5.87	
Straight	1975	1970	0.25	
Straight	2085	1938	7.05	
Straight	1791	1806	-0.84	
Narrow	1703	1795	-5.40	
Narrow	1846	1817	1.57	
Tramlines	1787	2028	-13.49	Transducer jammed
Narrow	1491	1761	-18.11	Transducer jammed
Narrow	1781	1739	2.36	
Tramlines	2195	2150	2.05	

This data shows reasonable results for initial field trials, except where grain jammed the transducer. As with previous studies, two methods of data presentation were used, these being (i) mass flow rate (kg/s) against time (s), and (ii) accumulated mass (the integration of the transducer signal in kg/s) over time (s). An example of each of these is shown in Figures 5.14 and 5.15 respectively.



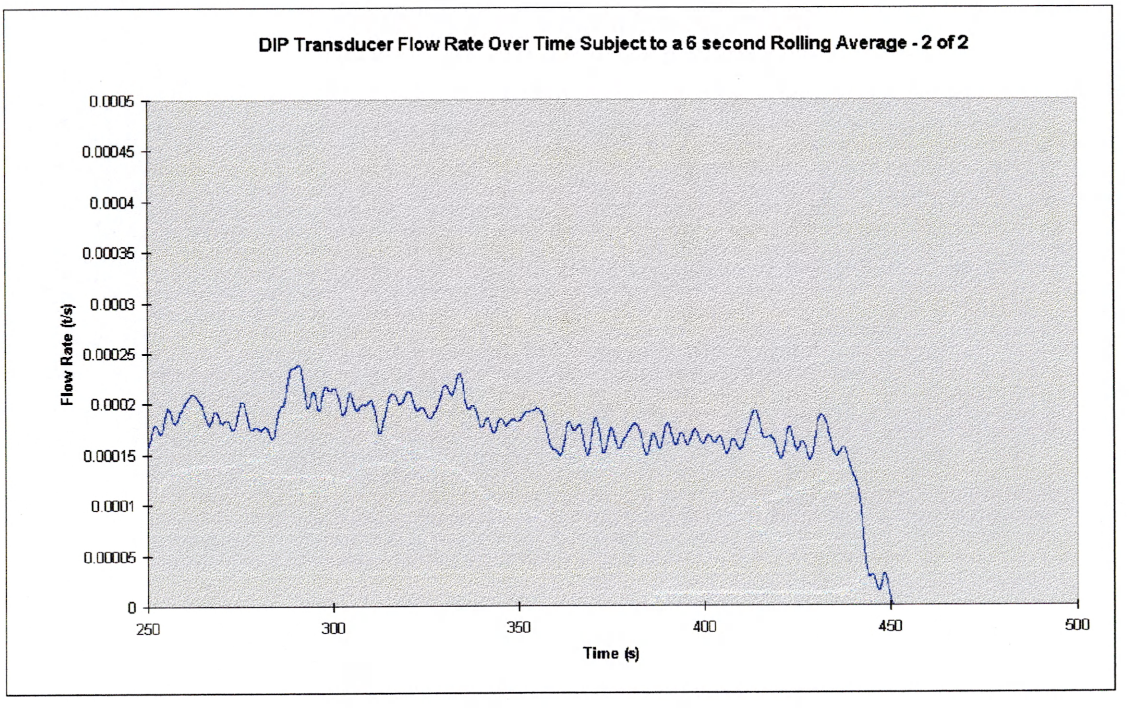
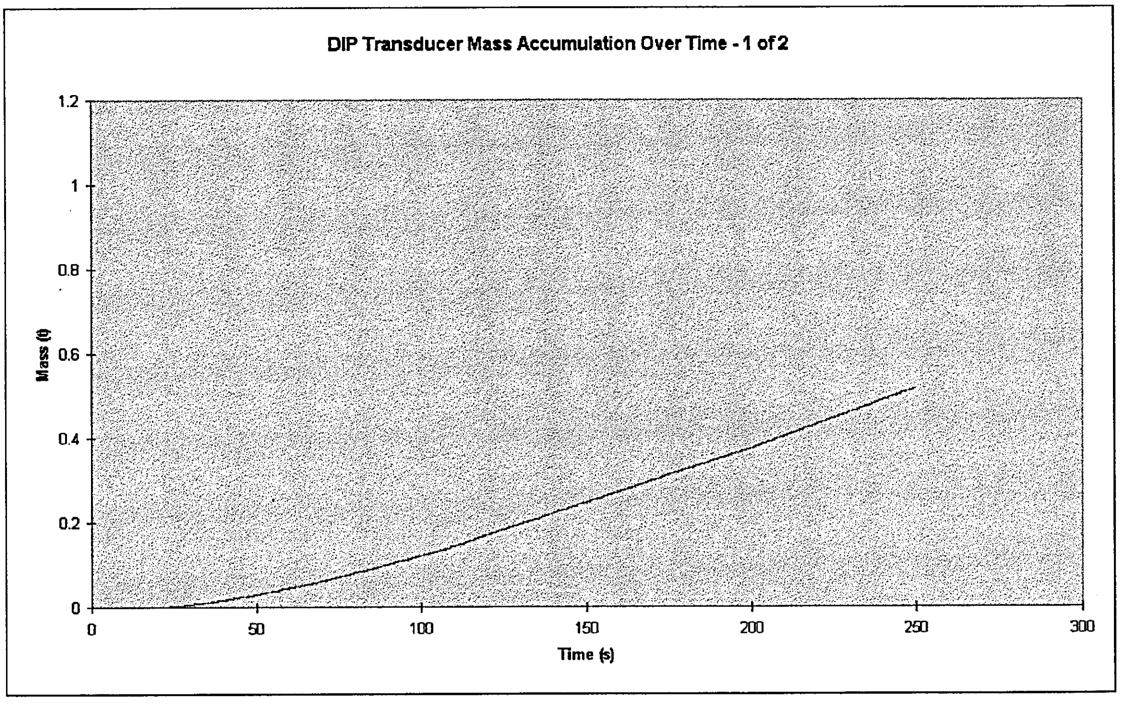


Figure 5.14 - DIP Transducer Mass Flow Rate Over Time - Subject to a 6s Rolling Average



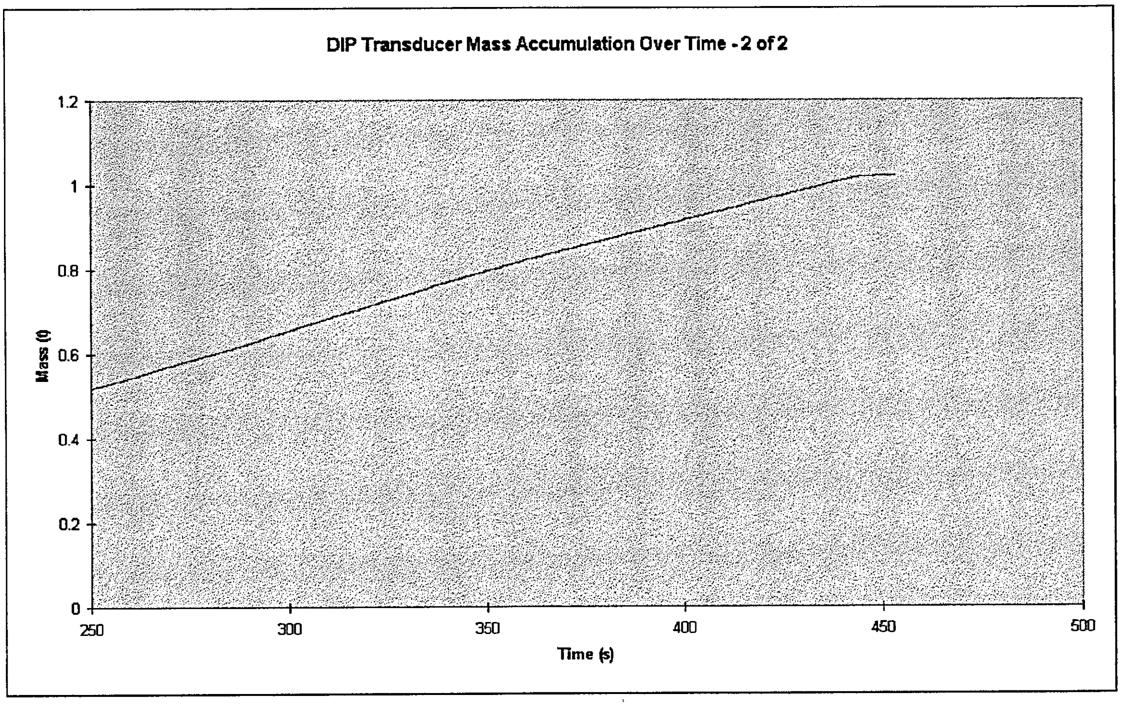


Figure 5.15 - DIP Transducer Mass Accumulation Over Time

Figure 5.14 has had a 6 second rolling average applied to the data set. Each second is equivalent to approximately one metre movement within the field. This 6 second figure was chosen because it gave reasonable data resolution whilst removing any spikes, within a sensible physical distance. Figure 5.16, shows how, when the same data is subject to a one second rolling average, the low resolution of the "Brainbox" causes the signal to 'snap' to the nearest kilogram, resulting in a stepped signal.

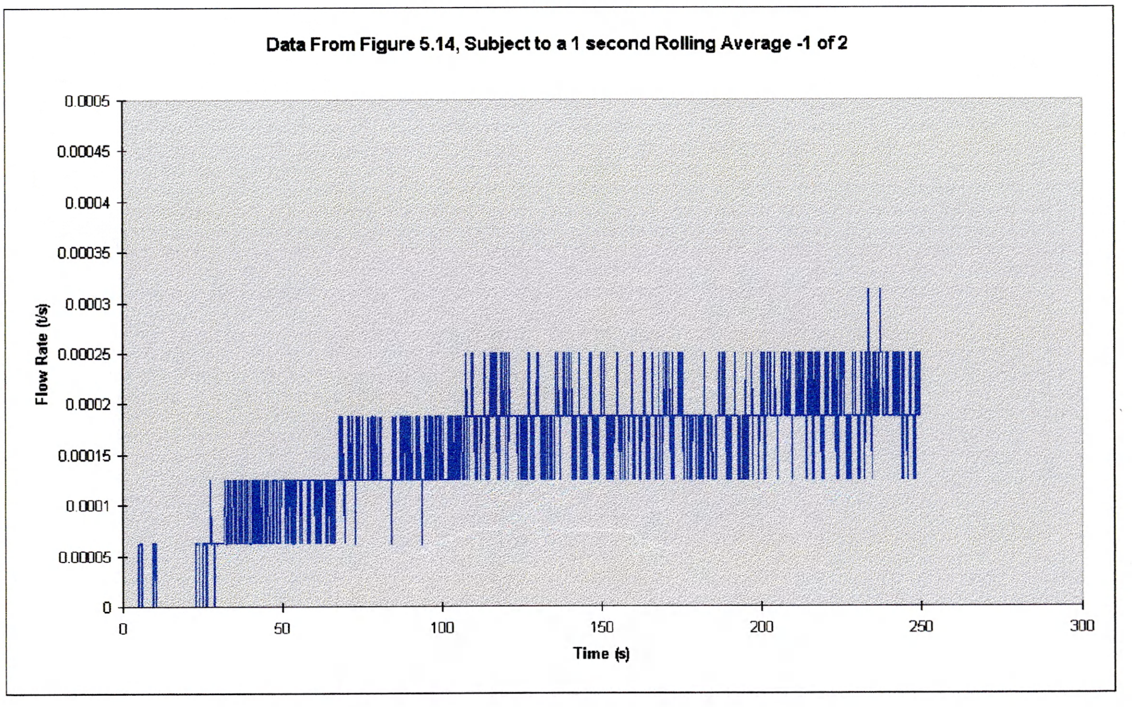
To overcome this problem the resolution of the "Brainbox" was increased by an order of magnitude, when Copse Field was finished, from 1 kg units to 0.1 kg units. This was accomplished by altering the EPROM program in the Brainbox.

Several methods were developed as a fast check of the data integrity. Firstly the area under a segment of the accumulated mass over time graph (Figure 5.15), was measured, in this case from 150 to 200 seconds. The change in mass over that time was 175 kilograms, which equated to 3.5 (175 / 50) kilograms per second. This flow rate was verified on the flow rate over time graph (Figure 5.14). Secondly, the quadrat samples were threshed and the yield from each area calculated. Knowing the average forward speed of the combine and the header width in use, the yield per second could be calculated. In this case, between 150 and 200 seconds :

Cut width	= 3.5 m
Speed	= 1 m/s
Therefore harvesting	= 3.5 m^2/s
Yield	= 0.98 kg/m^2
Therefore flow rate is	**3.43 kg/s**

Area under mass accumulation graph

175 kg in 50 s = **3.5 kg/s**



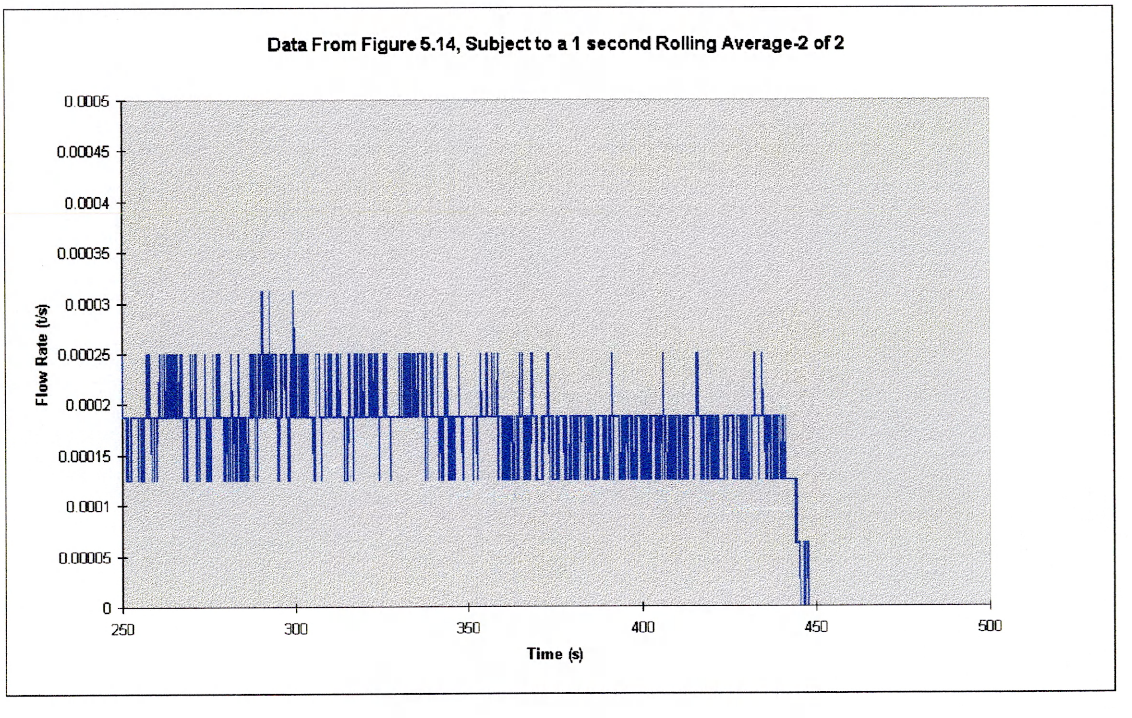


Figure 5.16 - Data From Figure 5.14 Subject to a 1 second Rolling Average

Once the Brain Box resolution was increased, the combine was taken to Wrest Park and harvesting continued on Obelisk Field, Table 5.11, cutting winter wheat. The following variables were introduced:

- Cutting across tramlines
- Harvesting narrow strips
- Harvesting narrowing and widening strips.
- Cutting a full width strip with a 10 metre gap halfway through the run.

Table 5.11 - Results from Harvest Field Trials - Obelisk Field, Wrest Park

Test Type	Measured Mass (kg)	Reference Mass (kg)	% Error
Headlands	7262.9	7341.1	-1.08
Across Tramlines	3925.9	3784.8	3.59
Headlands	6809.6	6731.4	1.15
Normal Combining	7317.2	7112.4	2.80
Normal Combining	6756.7	7010.8	-3.76
Normal Combining	8524.1	8230.1	3.45
Narrow Strip	4689.7	4826.3	-2.91
10m Gap in Crop	7532.8	7417.3	1.53
Narrowing Strip	2821.0	2768.8	1.85

It can be seen that the poorest result came from a straight run and was of -3.76 %.

Figure's 5.17 and 5.18, show the flow rate and accumulated mass plots, respectively, for a run across tramlines. Once again the quadrat samples can be used as a fast check for data integrity, thus

Width of cutter bar = 5.182 m

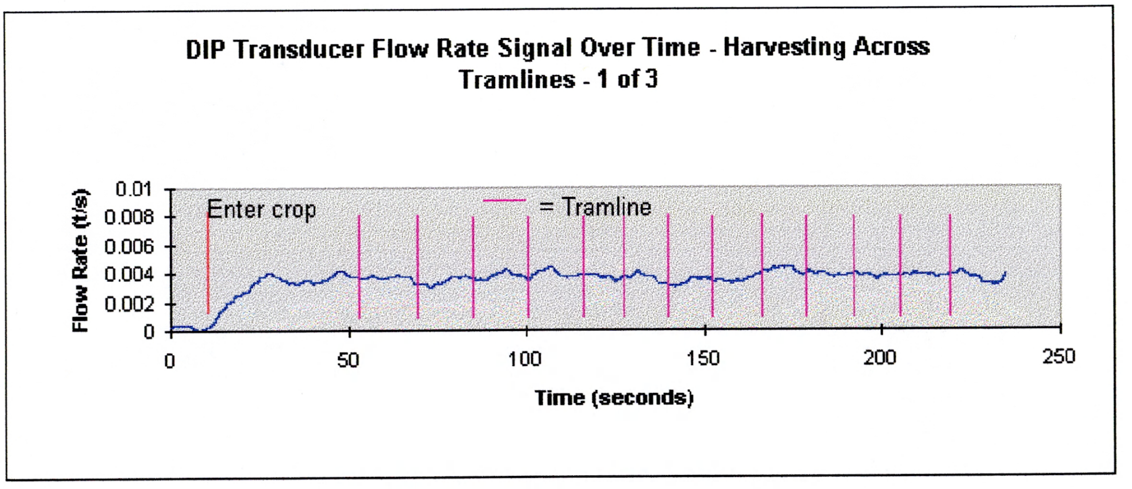
Mean forward speed = 0.833 m/s

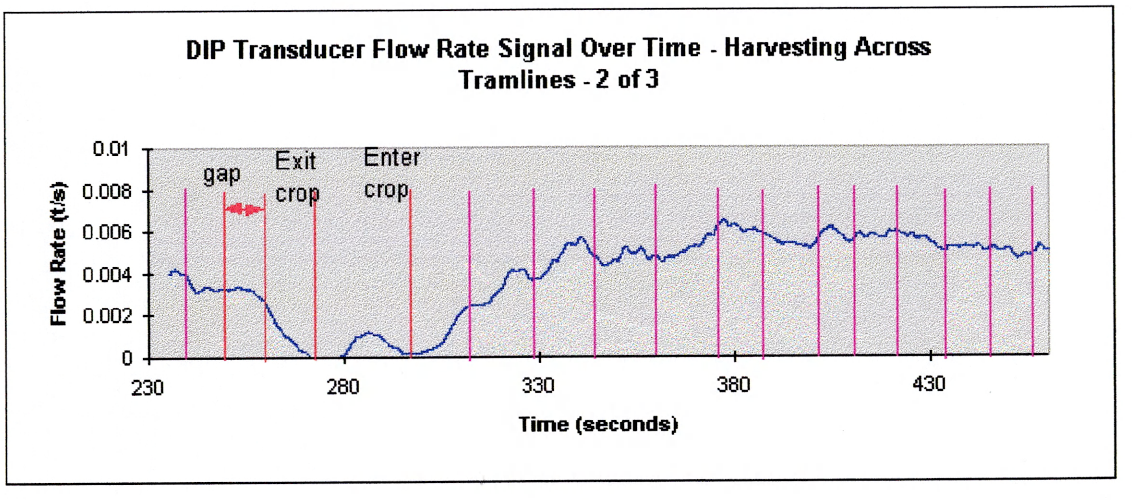
Yield (from quadrat) = 0.9143 kg/m^2

Therefore, Flow Rate = **3.95 kg/s**

Area under mass accumulation graph

540 kg in 150 s = **3.6 kg/s**





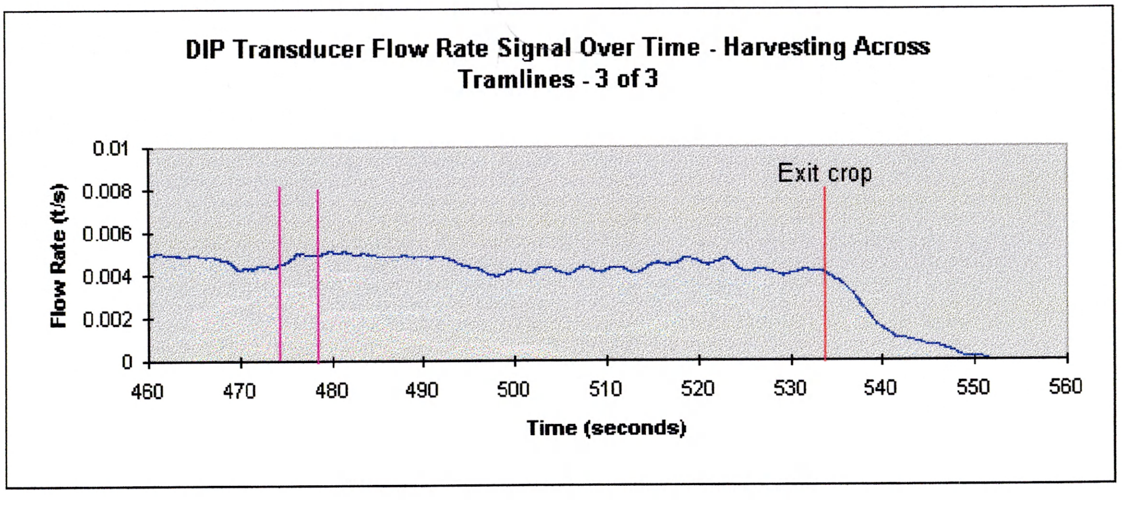
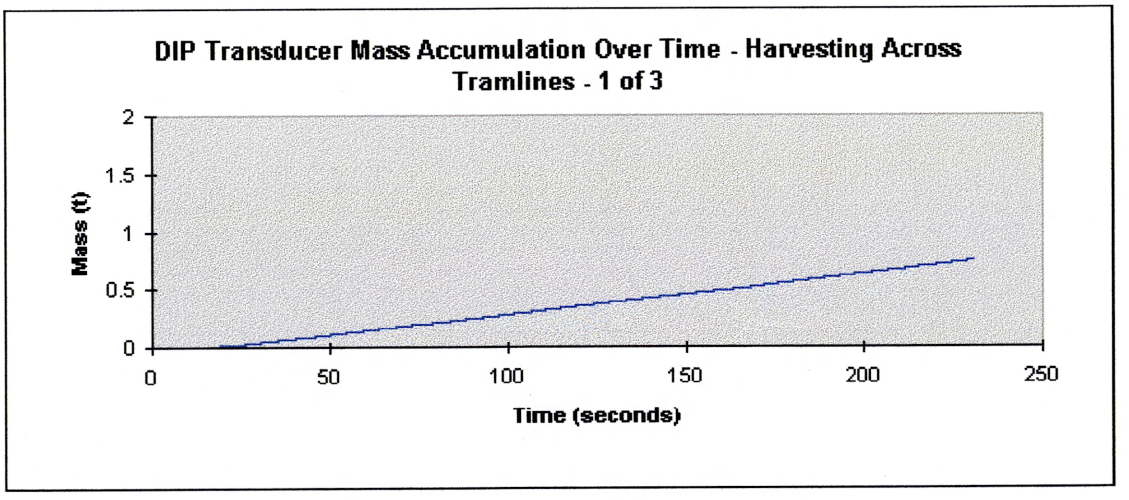
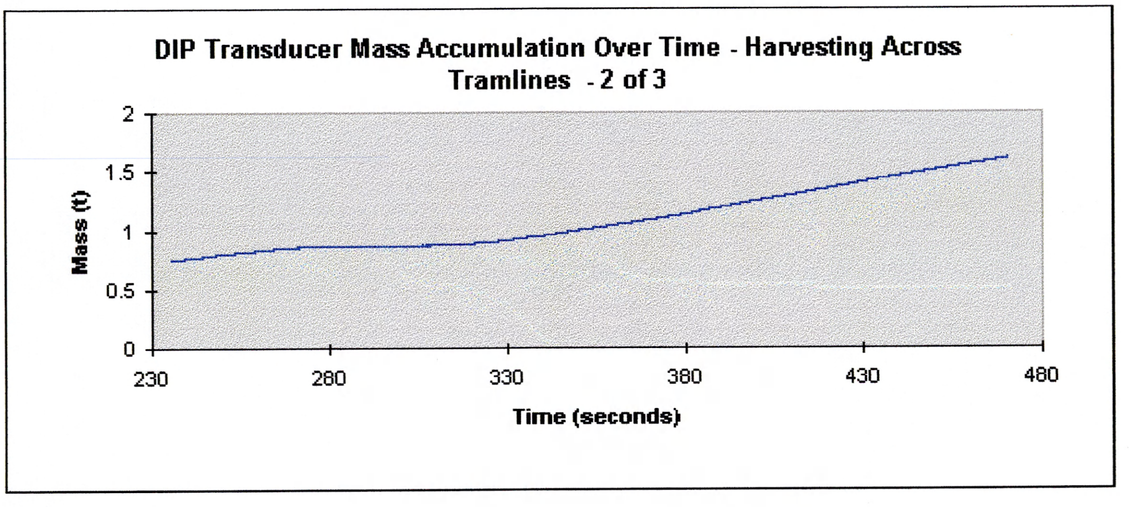


Figure 5.17 - DIP Transducer Flow Rate Signal Over Time - Harvesting Across Tramlines





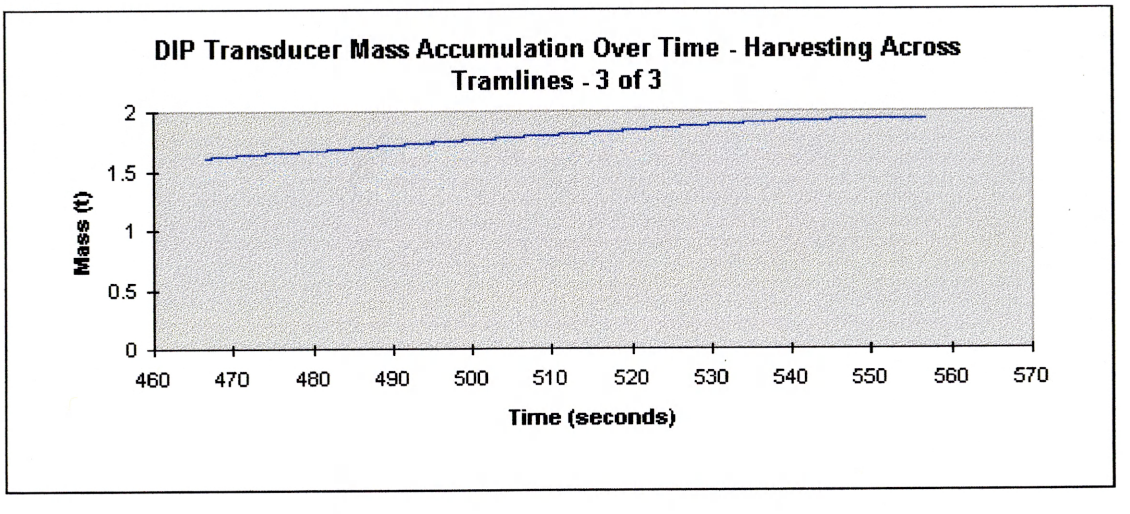


Figure 5.18 - DIP Transducer Mass Accumulation Over Time - Harvesting Across Tramlines

A series of figures in Appendix 5 illustrate typical signals from each of the other harvesting situations. Figures 5.2 and 5.3, Appendix 5, show the flow rate and accumulated mass plots for a run over a narrow strip (approximately 2 metres). Figure 5.4 and 5.5, show the flow rate and accumulated mass plots for a run with a 10 metre strip missing halfway along it. Figures 5.6 and 5.7, show the flow rate and accumulated mass plots for a run where the crop narrows.

When these plots were examined, it was noted that apparent noise within each signal exhibited similar frequencies. To analyse these, a small segment of each plot was printed, to allow closer examination, the predominant frequencies noted for each, Table 5.12. Each frequency was then compared with an operation of the combine.

Table 5.12 - Apparent Signal Frequencies from Harvest Field Trials

Test Type	Frequency (Hz)		
	Primary	Secondary	Third
Across Tramlines	1.1	0.4	0.1
Narrow Strip	0.8	0.4	0.07
10m Gap in Crop	0.95	0.4	0.16
Narrowing Strip	1.2	0.45	0.1

The following frequencies for common combine operations were identified.

- Tyres 5 Hz
- Engine 35 Hz
- Shaker Shoe 4 Hz
- Knife 26 Hz
- Front Cross Auger 8 Hz
- Rotors 10 Hz
- Bubble up auger 4 Hz
- Lower Cross Auger 4 Hz

- Clean Grain Elevator 12 Hz
- Straw Spreader 10 Hz
- Fan (wheat) 18 Hz

The very consistent 0.4 Hz signal was thought to result from the clean grain elevator. One of 26 paddles had been renewed and sat higher than the others. The 4.55 m long chain and paddle assembly travelled at 1.82 m/s and took 2.5 seconds to complete a revolution, which gives a frequency of 0.4 Hz.

The 1 Hz signal is suspected to be a function of the shaker shoe drive. A very low 0.1 Hz signal is clearly visible. It has a greater magnitude than the other signals and is not consistent or repeatable. It is believed this is caused by variations in the crop flowing and therefore the desired flow rate signal.

The next field harvested was Boot Field at Wrest Park. This was a very small field which had been overlooked when spraying in the spring which resulted in a serious blackgrass problem. Although the yield was recorded, this field offered the opportunity to see how the transducer coped with trash in the crop. After each run the top of the drop box was removed to see if any trash was caught around the roof. No problems were encountered with trash and only one trailer load was harvested, giving -0.13% error on accumulated mass.

The next field, Boothill, was once again small and gave the opportunity to test the transducer on hillside work. The field shape necessitated harvesting up and down the slope which was approximately 4 degrees.

From the single trailer load harvested an error of -3.25 % in total mass accumulated was recorded indicating slopes may have a small effect on signal. Previous laboratory testing suggested that slope effects would be less than this. Therefore, further consideration was given to this in subsequent post harvest testing..

Figure's 5.19 and 5.20, show typical plots for hillside work. Figure 5.19 is a plot of mass flow rate against time for an uphill cut with the next cut (downhill), reversed and superimposed upon it. This was done to observe if variations in signal, mirror each other and may then be considered as variations in crop mass passing through the machine. This plot shows that variations in signal are similar, however overall signal size is slightly larger when travelling downhill. This is caused by the difference in engine speed as the machine labours uphill, slowing engine speed and consequently elevator speed and crop velocity onto the transducer.

The final field harvested was winter wheat at Taylors' Farm, Wilstead. The crop had a higher moisture content than any previously harvested (between 16 % and 18.5 %). The results are as shown in Table 5.13.

Table 5.13 - Results from Harvest Field Trials - Taylors' Farm, Wilstead.

Moisture Content (%)	Measured Mass (kg)	Reference Mass (kg)	% Error
18.5% mc	4843	4945	-2.11
18% mc	9540	9680	-1.46
17 % mc	3663	3665	-0.06
16% mc	10045	10335	-2.88

It can be seen that these higher moisture contents cause the transducer to slightly under-read. Further investigation of moisture content effects are needed and this is done in post-harvest testing.

During the 1996 harvest, a total of 126.02 tonnes were harvested whilst the transducer recorded 127.18 tonnes, giving an overall error of 0.91 %.

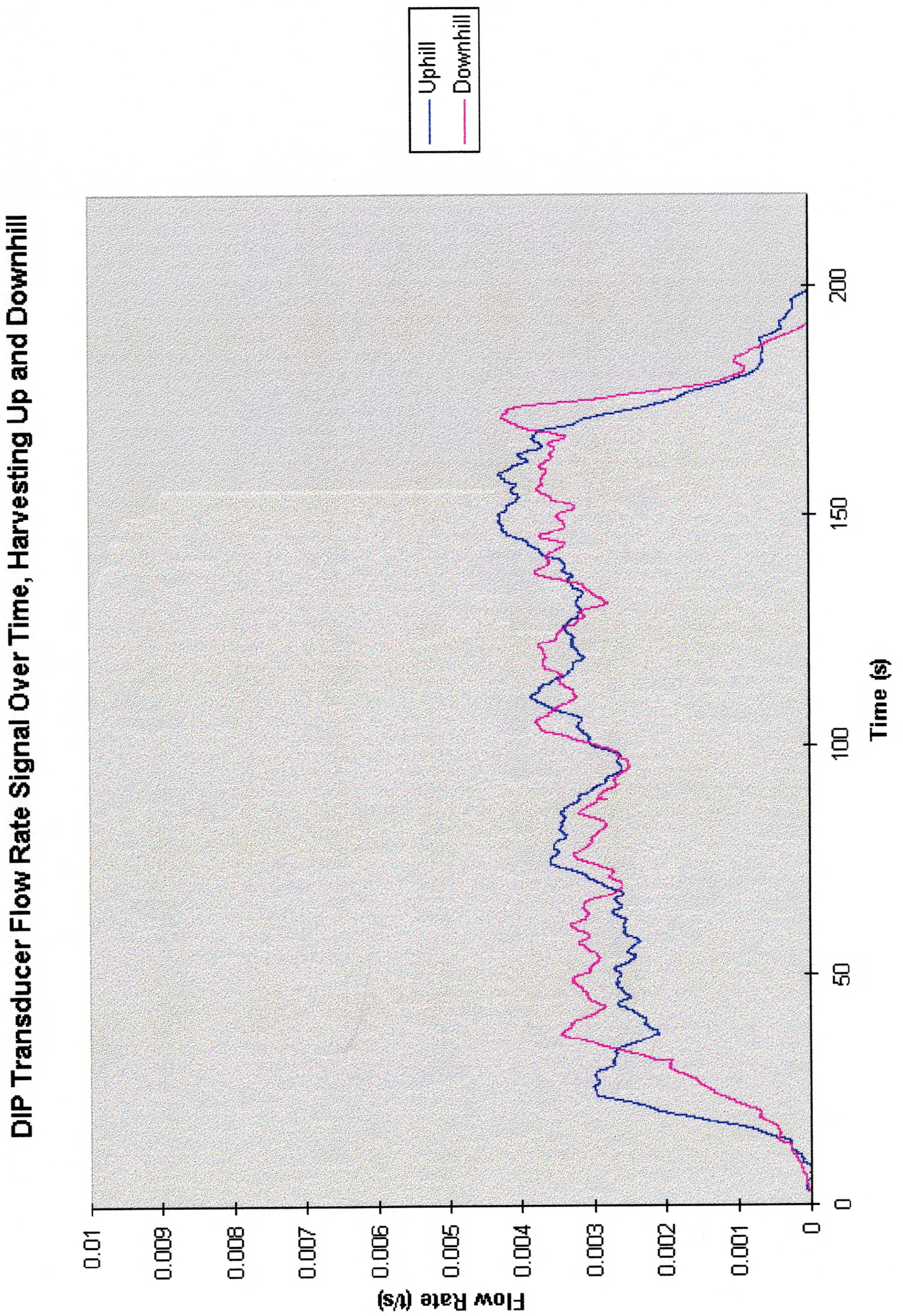


Figure 5.19 - DIP Transducer Flow Rate Signal Over Time, Harvesting Up and Downhill

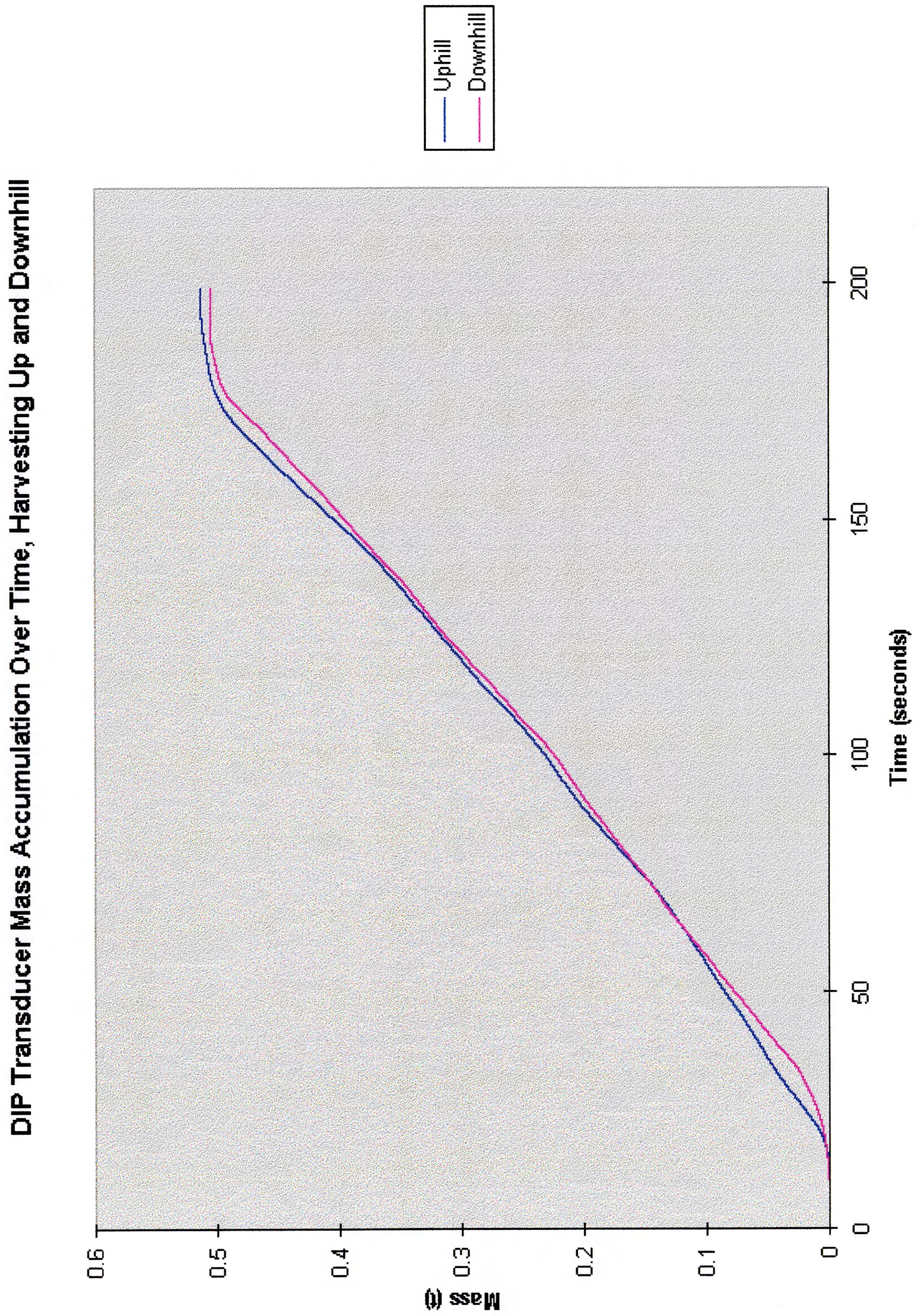


Figure 5.20 - DIP Transducer Mass Accumulation Over Time, Harvesting Up and Downhill

5.5.3 - Post Harvest Studies

The aims of these studies were :

1) To test crops not available during the harvest.
2) To allow, in isolation the effect of a number of variables to be observed, namely
   - Left and right sides raised at 10^{O} (hillside) using wheat.
   - Front and back raised at 7.5^{O} degrees (hillside) using wheat
   - 30 % moisture content wheat.
   - 26% moisture content wheat.
   - Using oilseed rape as the test crop.
   - Using field beans as the test crop.
3) To record the DIP transducer signal in its unprocessed state (in mV).

The test methodology for initial post-harvest testing was the same as for pre-harvest testing with three repetitions of each test performed. For each set of tests one condition was varied, allowing that individual variables effect to be assessed.

The other test included involved a bag of grain suspended on a calibrated tension link above the clean grain elevator hopper and the grain released. This allowed an assessment of instantaneous accuracy, the input flow being compared with the transducer output (with an allowance for lag).

The results from post harvest testing with winter wheat are shown in Table 5.14.

Table 5.14 - Results from Post Harvest Winter Wheat Testing

Test Format	Measured Mass (kg)	Reference Mass (kg)	% Error
Normal	536.2	529.7	1.2
Normal	526.4	529.7	-0.6
Normal	549.6	529.7	3.8
Normal	534.8	529.7	1.0
Normal	548.0	529.7	3.4
Normal	527.0	529.7	-0.5
Normal	540.4	529.7	2.0
Normal	531.2	529.7	0.3
Normal	534.2	529.7	0.9
Front Up (7.5^{O})	537.6	529.7	1.5
Front Up (7.5^{O})	524.7	529.7	-0.9
Front Up (7.5^{O})	529.2	529.7	-0.1
Back Up (7.5^{O})	538.4	529.7	1.6
Back Up (7.5^{O})	538.7	529.7	1.7
Back Up (7.5^{O})	526.4	529.7	-0.6
Left Side Up (10 ^{O})	535.4	529.7	1.1
Left Side Up (10 ^{O})	525.8	529.7	-0.7
Left Side Up (10 ^{O})	532.6	529.7	0.5
Right Side Up (10^{O})	536.5	529.7	1.3
Right Side Up (10^{O})	537.6	529.7	1.5
Right Side Up (10^{O})	515.5	529.7	-2.8
Tension Link	526.4	529.7	-0.6
Tension Link	518.0	529.7	-2.2
Tension Link	518.8	529.7	-2.1
26% Moisture	904.4	909.8	-0.6
26% Moisture	893.2	909.8	-1.8
26% Moisture	900.5	909.8	-1.0
30 % Moisture	875.6	893.1	-2.0
30 % Moisture	866.9	893.1	-2.9
30 % Moisture	880.0	893.1	-1.5

These results prove that in most cases, sufficiently accurate and repeatable results to meet the initial specification can be achieved. One error occurred on the second test, where the rubber sheet shielding the transducer beam lifted allowing crop to jam the transducer.

The hillside work showed that tilting the combine had a small effect, the poorest result being with the right hand side up, causing an error of -2.8 %.

Using wet and very wet wheat resulted in a lower signal from the transducer, reinforcing the harvest trials at Wilstead. The poorest result came, as expected, from the 30 % moisture content wheat giving -2.9 % error.

To measure the instantaneous accuracy, a test using a calibrated tension link to measure the mass of grain being fed into the combine was used. Figure 21, shows both transducer and tension link mass accumulation over time. The two signals follow each other closely, but the transducer signal lags due to the transport delays as the crop passes through the combine and the inefficiency of the combine clean grain elevator, which allows a small amount of crop to fall down its sides, requiring re-conveying.

Two other crop types were tested, these being field beans and oilseed rape. The results for these can be seen in Table 5.15. The recorded and actual accumulated masses are shown with the resulting percentage error between the two. Also shown is the percentage error if the calibration constant is revised to suit the particular crop. In this case the field beans, this constant being reduced by 7% and the oilseed rape being reduced by 3%.

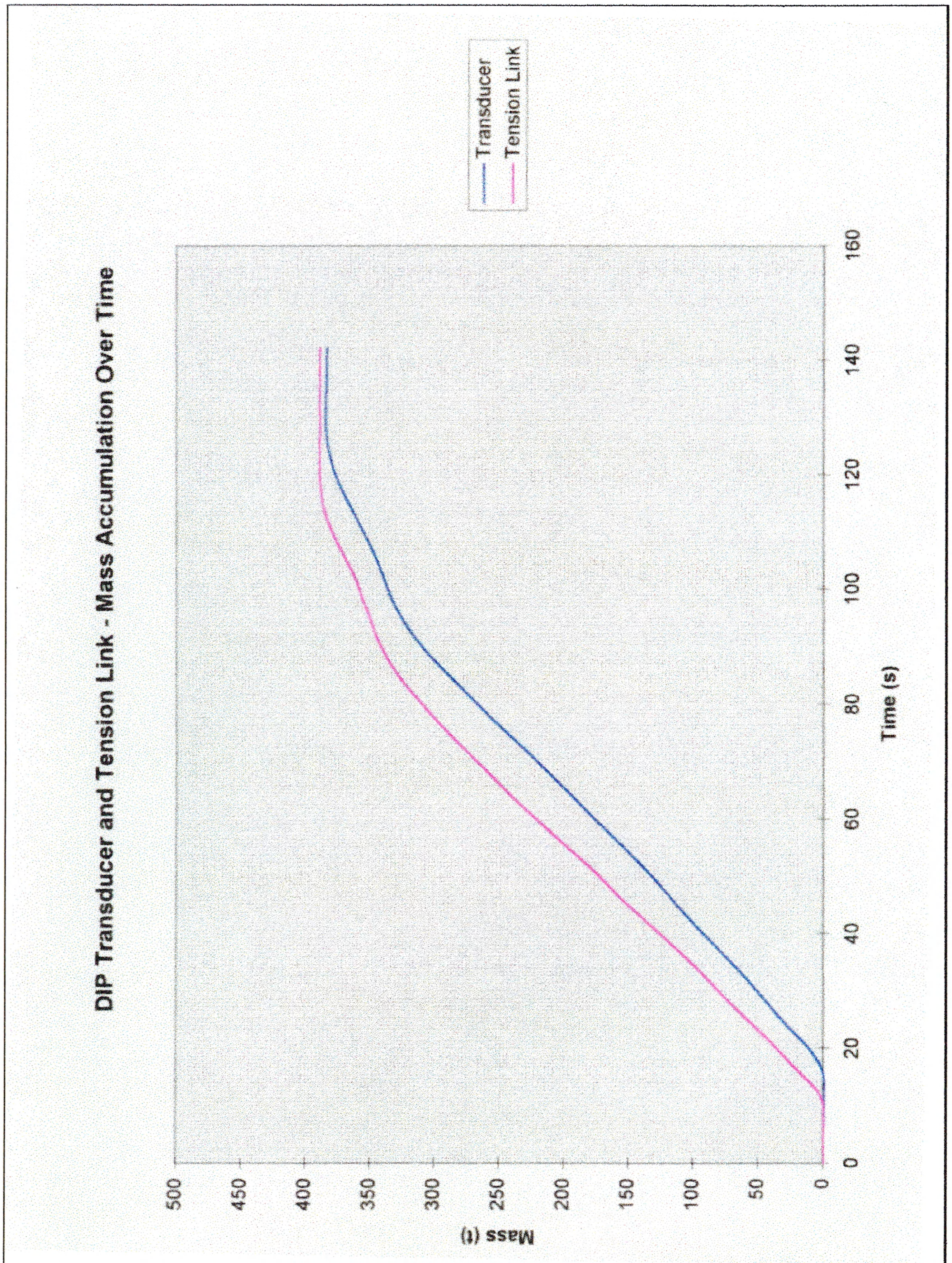


Figure 5.21 - DIP Transducer and Tension Link - Mass Accumulation Over Time

Table 5.15 - Results from Post Harvest Field Beans and Rape Testing

Crop	Measured Mass (kg)	Reference Mass (kg)	% Error	% Error Using Revised Calibration Constant
Field Beans	1385.16	1269.50	8.35	1.62
Field Beans	1366.40	1269.50	7.09	0.27
Field Beans	1355.76	1269.50	6.36	-0.51
Field Beans	1365.56	1269.50	7.03	0.21
Field Beans	1347.64	1269.50	5.80	-1.12
Field Beans	1355.48	1269.50	6.34	-0.53
Oilseed Rape	865.12	830.30	4.02	-0.65
Oilseed Rape	852.60	830.30	2.62	0.46
Oilseed Rape	860.16	830.30	3.47	-0.42
Oilseed Rape	856.52	830.30	3.06	0.01
Oilseed Rape	865.20	830.30	4.03	-1.12
Oilseed Rape	842.80	830.30	1.48	1.61

Both crops gave sufficiently repeatable results to match the initial specifications but were both reading too high when using the same calibration constant as for wheat. If a revised calibration constant is used for these specific crops, equally repeatable results with smaller errors can result. This suggests the possibility of inserting several pre-set constants into the "Brainbox", allowing the selection crop and hence the selection of correct calibration constant before harvesting.

5.6 - ERROR ANALYSIS

Throughout this study, each major causal factor of signal error has been considered separately, in terms of relative error in accumulated mass and, where applicable, 'spot' flow rate. During harvesting, any loss of accuracy will result from a combination of these errors and an error analysis may be used to determine the possible extremes, the absolute error being, at most, the squareroot of the sum of the squares of the individual relative errors (Bajpai et al, 1992). Considering the extremes of error for winter wheat

Error Source	Lower extreme	Upper Extreme
Vibrations	-1.8	3.3
Roll	-0.9	1.7
Pitch	-2.8	1.5
High Moisture Content	-2.9	-1.8
TOTALS	-4.5	4.3

When an error analysis is performed, accounting for all sources of variability tested, in their most extreme cases, the errors are found to be –4.5 % to 4.3 %. However, the summation of these errors was never found to be present. This is confirmed by the fact that (i) over the total field trial, the transducer exhibited a 0.9 % error on a total accumulated mass of 127 tonnes. (ii) On the clean grain simulation apparatus the 'spot' flow rate readings were within 2 % of the absolute (trailer) value in 28 of the 30 tests.

5.7 - CONCLUSION

Using a clean grain system simulation apparatus, the total error on accumulated mass was shown to be better than 2.1 % on accumulated mass in 35 of 37 tests and better than 2 % on spot flow rate in 28 of the 30 tests undertaken.

Vibrational effects upon the transducer from the engine, transmission and threshing mechanism were present, giving between -0.6 % and +0.9 % error when considered with a 10 kg/s signal. From pre-harvest testing the worst case dynamic situation without grain flowing was in fourth gear at tick-over without threshing, giving a false - 0.06 kg/s signal, a situation never encountered when harvesting. During harvest field trials and simulated testing, tramline effects upon transducer output were found to be self cancelling, causing a positive and negative 'spike' in the signal, which when summed over time approximated to zero.

Three predominant frequencies were noted in signals achieved during harvest work. To remove these, both filtering and smoothing were considered, the filtering process offering acceptable errors between -0.3 % and +1.76 %. However, the smoothing process, through a rolling average, did not alter the total mass recorded, and for this reason and its ease of post processing application, the rolling average was recognised as the preferred method of signal conditioning.

Material drop height onto the transducer had a definite effect on signal magnitude, and consequently calibration constant, which was reliably predicted theoretically and established by practical testing. Once calibrated, using the extended bubble up auger, the transducer gave results with errors between 2.4 % and -3.6 % on accumulated mass. When mounted in the drop box, pre-harvest testing showed errors between -2.2 % and +1.8 % on accumulated mass and during post harvest errors between -0.6 and +3.8 % were recorded

During the harvest trials, a 6 degree slope caused the transducer to under-read by 3.25% on mass accumulation. However when tested in a static situation this error reduced to between -0.9 % and 1.7 % at 7.5 degrees. Combining the results for all slope studies gave an average error of 0.35% on mass accumulation. Changes in pitch angle, up to 10 degree caused between 1.5 % and -2.8 % error.

Field beans and oilseed rape required calibration constants 6.8 % and 3.1 % lower than that for 12.5 % moisture content wheat, but with adjusted calibration constants, gave excellent repeatable results. Increasing moisture contents of up to 30 % in wheat resulted in the transducer under reading by, on average, 1.6 %.

During harvest trials, a high moisture content crop caused the transducer to under-read by, on average, 1.6 % on mass accumulation. During post harvest testing, winter wheat gave errors up to -1.8 % and -2.9 % at 26 % and 30 % moisture content, respectively.

No problems were encountered with trash or weeds in the crop lodging across the top of the DIP.

When an error analysis is performed, accounting for all sources of variability tested, in their most extreme cases, the cumulative errors were found to be -8.4 % to 4.7 %. However, the summation of these errors were never found to be present, this is confirmed by the fact that over the total field trial, the transducer exhibited a 0.9 % error on a total accumulated mass of 127 tonnes.

TO WHOM IT MAY CONCERN

PLEASE NOTE

"Although this thesis was submitted for the degree of EngD, it was considered to be appropriate for the award of the degree of **MPhil**.

This award will be conferred at the **Graduation Ceremony** on **14 July 1999**"

Caroline Johnson
Senior Assistant Registrar

CHAPTER 6

COMMERCIAL ANALYSIS

6.1 - INTRODUCTION

Throughout this thesis, several processes have been used to identify each stage reached and ensure the work progressed in a controlled manner. This chapter further considers the business and commercial implications of this research work.

A manufacturing cost of the DIP transducer and associated brackets has been determined and a technical specification drawn up to support sales. Due to the commercial sensitivity of the product, a draft patent has been written and is awaiting submission by the sponsor. In addition to the New Holland TF42, other combine types have been considered in terms of design and size of drop box. Recommendations to the sponsor have been made for further market analysis and technical studies.

6.2 - MANUFACTURING COSTING

Although the sponsor of this study is recognised for their expertise in strain gauge measurement systems and most development work is carried out in-house, the majority of their current products are out-sourced in component form. This approach ensures each component is manufactured by a specialist in that area helping to reduce cost. This study followed the same approach by listing the component parts of a DIP transducer and quotes were obtained from several sources for manufacturing 30, 100 and 300 of each.

Each component is listed below and detailed engineering drawings are presented in Appendix 6.

1 1 off NS5 aluminium DIP crop interface
2 1 off Transducer beam
3 1 off Curved crop deflector
4 1 off Transducer beam mounting bracket
5 4 off M6 transducer beam securing bolts
6 2 off M8 curved crop deflector mounting bolts

A quote was obtained from TJ Welding of Stalbridge for fabrication of DIP crop interface, curved crop deflector and the transducer beam mounting bracket. Tables 6.1 to 6.4 detail each stage of the relevant production process. Cost of materials and labour have been combined to give one cost for each stage. All costs are in pounds sterling and do not include VAT.

Table 6.1 - Production Process and Costing for DIP Crop Interface

Process	30 Units	100 Units	300 Units	3000 Units
Purchase aluminium sheet	400	1200	3400	34000
Fabricate jigs for cutting	150	150	150	150
Cut sheet	60	180	500	4400
Deburr	30	90	250	2200
Degrease	15	50	150	1500
Fabricate welding jigs	140	140	140	140
TIG welding	200	600	1700	15000
Clean finished DIP	15	40	100	600
Inspection	15	40	100	600
TOTAL (£)	1025	2490	6490	58590
COST PER UNIT (£)	34.16	24.90	21.63	19.53

Table 6.2 - Production Process and Costing for Curved Crop Deflector

Process	30 Units	100 Units	300 Units	3000 Units
Purchase steel sheet	90	270	750	6450
Fabricate jig	80	80	80	80
Cut	15	45	120	1100
Drill	6	18	45	400
Degrease	10	25	65	440
Deburr	10	30	80	700
Roll	15	40	100	880
Inspection	10	25	65	440
TOTAL	236	533	1305	10490
COST PER UNIT	7.87	5.33	4.35	3.50

Table 6.3 - Production Process and Costing for Transducer Beam Mounting Bracket

Process	30 Units	100 Units	300 Units	3000 Units
Purchase steel plate	60	170	460	4120
Fabricate jig	100	100	100	100
Cut	30	90	240	2070
Drill	6	18	45	390
Deburr	10	30	80	700
Degrease	10	25	65	440
Electric arc weld	20	60	150	1260
Clean welds	10	30	80	700
Inspection	10	25	65	440
TOTAL	256	548	1285	10220
COST PER UNIT	8.53	5.48	4.28	3.41

The transducer beam was sourced directly from RS Components, the securing bolts from Aerotek. The prices for these are listed in Table 6.4, the overall cost summary.

Table 6.4 - Overall Costing Summary

Component	30 Units	100 Units	300 Units	3000Units
DIP crop interface	34.16	24.90	21.63	19.53
Curved crop deflector	7.87	5.33	4.35	3.50
Mounting bracket	8.53	5.48	4.28	3.41
Transducer Beam	101.32	98.71	94.50	82.75
Securing bolts	0.24	0.18	0.15	0.11
Transport	2.00	1.30	0.60	0.29
TOTAL COST PER UNIT	154.12	135.90	125.51	109.59

These costs represent solely manufacture of the DIP transducer, with no account for storage or spares held. Once finalised consideration will need to be given to the cost of the cab display and data storage, the header switch, distance meter, cabling, plugs and a suitable differential global positioning system (DGPS). However, these items were not within the specification of this study.

6.3 - TECHNICAL SPECIFICATION

A technical specification was written for the DIP transducer, based upon data obtained during this study and was primarily for sales purposes.

"The mass flow rate transducer works upon the force reaction principle. By measuring the flowing crop in 2 ways, the impact upon the transducer and the mass of the crop as it slides down each face, compensation is made for different crop types and moisture contents. The transducer consists of a double inclined plane that compensates for slope effects when working on hillsides. This is mounted in the drop box between the clean grain elevator and the bubble up auger. If the transducer is not used, the combine can keep working"

Transducer type	Double Inclined Plane (DIP)
Measurement method	Force reaction using strain gauges
Transducer material	NS5 half hard aluminium
Minimum flow rate	3.6 tonnes per hour
Maximum flow rate	Over 36 tonnes per hour
Static accuracy on total mass	± 1.5 %
Dynamic accuracy on total mass	± 2.5 %
Resolution	0.1 kg
Dimensions	0.2 m × 0.12 m × 0.12 m
Power requirements	12 volt supply
Combine types	All machines fitted with a bubble up auger, irrespective of drop box design.

6.4 - PATENT APPLICATION

A draft patent was constructed for the DIP transducer. It should be noted that although complete, further modifications may be necessary from a patent agent, due to the complexity of patent protection and law. The complete draft patent is detailed in Appendix 7.

6.5 - RECOMMENDATIONS FOR FURTHER TECHNICAL AND COMMERCIAL STUDIES

Three weeks before final submission of this thesis, negotiations were undertaken with Agco, a major multi-national agricultural machinery company, who are evaluating several prototype systems in America. The following recommendations were written to assist the sponsor's in adopting this technology but are equally applicable for any other manufacturer.

The concept of new product development (NPD) has been followed through this study, allowing each stage of research to be identified. The final stages, brand development and implementation are considered below.

The brand development phase has 2 objectives, to further develop the prototype, so that it can be manufactured and delivered to the customer in an efficient manner and to develop the elements of the marketing mix (namely product, price, place and promotion), which will augment the physical product and communicate its value to the target market.

To further develop the prototype will require studies in 2 areas,
(i) further field trials
(ii) technical studies to develop and integrate system components outside the scope of this study, namely :

1. Display unit - for mounting in the cab to act as an operator interface. This unit could be used to inform the operator of time, date, yield (tonnes per hectare), mass flow rate, forward speed, positioning system status (doe it have enough satellites to give reliable data and whether the system is recording and in what file name. This interface should be back-lit and simple to read and operate, as the combine operator has very little time to use it.

2. The recording system will be used to store the field data until it can be down loaded onto the farmers home computer. If cost to the farmer is to be kept to a minimum, it should be of a type the farmer can use directly on a conventional *IBM* compatible personal computer. This would suggest the use of diskettes but the other important factor is the environment, which, although having a stable temperature (most modern combines have air conditioning) is normally dust laden. This would suggest a system where a conventional computer diskette of a suitable size is used in a drive that can be sealed.

3. Positioning units are normally of the global positioning system type calculating latitude, longitude and altitude from American military satellite signals. These units are highly variable in cost and accuracy with a differential correction being essential to greatly improve accuracy (Saunders, 1996).

4. Mapping software is used to analyse the field records and draw yield maps. Care is needed to ensure compatibility with other software on the market. If a farmer is using a complete agronomic planning system, such as Farmplan (formerly Optimix), there will be a need to import map data straight into this system therefore a suitable communication protocol will be needed.

During this study, it has become apparent that the farmer considers accuracy on total mass flowed as the indicator of system integrity. Therefore, once a complete 'operator ready' system is developed the DIP transducer should be subject to further field trials, measuring mass accumulation on actual farmers machines. The aim of this is to gain experience and further data from a DIP transducer being used by a number of typical operators in a normal commercial situation. The farmer should be shown how to operate a device reducing the need for persons to monitor systems. This will allow valuable feedback upon system operation and highlight any problems.

The second phase of the branding process is to develop the elements of the marketing mix where each of the following is considered separately.

- *Product* - The main thrust of this study has been the technical development of a suitable product within the design constraints. However, for a commercial product, there are additional requirements. The variety of products needs consideration, will the product be fitted to other manufacturers machines, what are the size constraints and will the fitting be carried out by farmer or skilled company employees ? The product requires a brand name which will appeal to the consumer whilst adequately describing it. The range of after sales services also need considering. Will a technical helpline or field backup service be available, are there people skilled enough to undertake troubleshooting and will they need training. What warranties will be provided and how will warranty repairs be accounted for.

- *Price* - Although, in this case, the manufacturer will set the list price, it can be considered as a two way exercise. If the price is excessive, market share, sales and hence income will be reduced.

A pricing objective should be selected which will maximise income. In this circumstance, with precision farming still in its infancy and growing, the objective should be to maximise sales volume. This will assist a drop in production costs through economies of scale and the resulting lower price could be used to further increase demand. Also a lower price will discourage actual and potential competition.

Determining potential demand is a very difficult exercise in such a new market. If the demand is inelastic (i.e. demand is not affected by price), the price can be raised but the pricing objective of maximum sales growth must be retained. Possible sources of demand information could be a survey of present customers or potential customers at the numerous agricultural shows the sponsor's visit. Other manufacturers information on sales numbers may be available through company annual reports, Mintel or the specialist press.

A costing exercise has been undertaken for the DIP transducer and brackets but other system components also need costing. This overall costing can then be related to demand and estimations to cost made.

Competitors products and pricing policies require investigation, a summary of which are in Chapter 1. Also an evaluation should be made of possible future pricing trends and offers, will their experience and economies of scale allow a drop in their unit costs? Once aware of competitors prices, these can be used as a guide for the sponsor's price. If this is coupled with a standard mark-up pricing method, adding a standard mark-up as a percentage to the product costs, the final end user price can be found. This however, should not be the only component associated with price. Thought should be given to discounts, allowances, payment period and credit terms as these will could affect cash flow through the company.

- *Place* - The placement of the product is concerned with how the product will be accessible and available to the customer. The main question involved is 'who is the customer?' There are 2 directions, (i) sell product to the combine manufacturer for factory fitment and (ii) sell product to the farmer for a retro-fit. Assuming the second option, the distribution channels within the sponsor's company are established, selling directly to the customer. Very little external transport is used at present as most products are delivered and installed by a skilled technician. The coverage of current products at present is world-wide, but the majority of sales are made in the UK. However, with the reduction of trade barriers, it is envisaged that Europe (which is keen to adopt precision farming technologies) will provide the major market. North America also offers excellent opportunities, with most UK manufacturers selling products through an independent American distributor.

- *Promotion* - Careful thought is needed to promote such a specialised product. If the farmer is considered the customer, he is difficult to impact with any promotional material, as he works long hours, is nearly always at the farm and is generally wary about the uptake of new technology. Despite this, there are still routes to the farmer. Most farmers read the specific agricultural press and advertising in these may attract their attention. Most of these magazines review products (normally farmers experience of a prototype) and if the review is favourable, this free advertising may also attract attention. Another form of advertising used for the sponsor's current product is at the agricultural shows that occur throughout the UK during the summer months. Favoured by farmers as a day away from the farm, potential customers can see the system demonstrated by an experienced sales force. Existing customers could be targeted in two ways. A simple mail-shot could be made, sending information and a reply card for further information and demonstrations. Alternatively, cold calling by a sales representative could be used, however, some farmers do not approve of this practise and care should be taken.

By working through these final stages of the new product development process, the product should have all elements required to prove it successful. The monitoring phase should not be forgotten, carefully analysing competitors products and prices, market trends, customer comments and any relevant information to maintain a competitive advantage.

Finally, when conducting this work 'caution' is an important watch word, as in such a technology led market, the end users may not be aware of the wealth of scientific advancements available. Even if not mentioned by customers an option should not be written off completely but more thoroughly researched.

CHAPTER 7

CONCLUSION

7.0 - CONCLUSION

1. A transducer system based upon the principles of force reaction has been developed, to measure the true mass of "free" flowing granular materials, at flow rates of 1 and 10 kg/s. The final transducer design fully matches the sponsor's core skills of strain gauge technology, providing a simple to manufacture device coupled with relatively low cost. It consists of a double inclined plane (DIP) constructed from aluminium, with sides angled at 55 degrees to the horizontal, mounted upon a horizontal strain gauged beam. The whole transducer system is mounted in the drop box, above the bubble up auger. A DIP transducer provides suitable angular compensation when subject to a crop flow, by generating a higher force from the shallower face and a proportionally lower force from the steeper face.

2. A mathematical model applicable to both single and double inclined plane transducers, based upon flowing material impacting a sloping face and creating an impulse force together with a vertical force resulting from the mass of material sliding down the face of the reaction plate, predict the total force to within 14 % and 1.7 % respectively, at a flow rate of 10 kg/s. These models permit the effects of key variables such as coefficient of friction of the granular material, reaction plate angle, the initial material velocity and the size of transducer to be evaluated.

3. In laboratory studies on a single reaction plate, roll angles of up to 7.5 degrees caused errors up to 33%. In static yard trials, roll angles in the same range caused between –0.9% and 1.7% error, with pitch angles up to 10 degrees causing between –2.8% and 1.5% error.

4. Field beans and oilseed rape require calibration constants 6.8 % and 3.1 % lower than that for 12.5 % moisture content wheat, but with adjusted calibration constants, gave repeatable results. Increasing moisture contents of up to 30 % in wheat resulted in an average reduced output from the transducer of 1.6 %.

5. During harvest field trials, tramline were found to cause both a positive and negative 'spike' of similar amplitude and duration in the DIP transducer output, within a period of two seconds, the net result of which is to cancel any effect from this action, effectively offering "self-compensation".

6. From an analysis performed on the harvest field trial data, to account for all sources of variability tested, the cumulative errors were found to be –4.5 % to 4.3 %. However, these errors were never found to all be present at their maximum values. This is illustrated by the fact that over the total field trial, the transducer exhibited a 0.9 % error on a total accumulated mass of 127 tonnes. As the instrumentation and recording process introduces minor errors of approximately this magnitude, a further improvement in accuracy is not considered to be achievable at present.

7. Estimated manufacturing costs at the time of writing are £154.12 each for 30 units, reducing to £109.59 each for 3000 units.

8. This thesis has provided the systems, data and principles required to create a novel, commercially practical transducer system, based upon the principles of force reaction. The project is still ongoing at the time of writing, the first stages of commercial adoption currently being undertaken by a multi-national agricultural machinery company, who are evaluating a pre-production prototype.

APPENDICES

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APPENDIX 1

Table 1.1 Marking Schedule for Mass Measurement Methods

	Weight	Weighing		Peltonwheel		F = m . a		Gamma		True Mass		Capacitive		NMR		Doppler		Electrostatic		Piezo		Optical	
Marking Criteria	from10	Mark	Total	Mark	Total	Mark	Total	Mark	Total	Mark	Total	Mark	Total	Mark	Total	Mark	Total	Mark	Total	Mark	Total	Mark	Total
Accuracy	9	7	6.3	6	5.4	8	7.2	8	7.2	10	9	7	6.3	9	8.1	5	4.5	5	4.5	4	3.6	8	7.2
Simplicity	7	5	3.5	4	2.8	9	6.3	8	5.6	2	1.4	7	4.9	1	0.7	5	3.5	5	3.5	5	3.5	6	4.2
Cost	6	7	4.2	4	2.4	9	5.4	5	3	3	1.8	7	4.2	1	0.6	4	2.4	4	2.4	5	3	7	4.2
Durability	8	6	4.8	3	2.4	7	5.6	8	6.4	3	2.4	5	4	4	3.2	6	4.8	3	2.4	3	2.4	4	3.2
Failsafe	8	7	5.6	2	1.6	8	6.4	8	6.4	4	3.2	3	2.4	7	5.6	7	5.6	7	5.6	7	5.6	7	5.6
Sensitivity	5	7	3.5	4	2	8	4	6	3	3	1.5	5	2.5	3	1.5	4	2	5	2.5	4	2	4	2
Restriction	6	4	2.4	2	1.2	8	4.8	9	5.4	7	4.2	7	4.2	8	4.8	7	4.2	7	4.2	7	4.2	8	4.8
Re-calibration	4	8	3.2	3	1.2	7	2.8	8	3.2	9	3.6	6	2.4	6	2.4	4	1.6	3	1.2	3	1.2	3	1.2
TOTAL	**53**		**33.5**		**19**		**42.5**		**40.2**		**27.1**		**30.9**		**26.9**		**28.6**		**26.3**		**25.5**		**32.4**
TOTAL AS %			**63**		**36**		**80**		**76**		**51**		**58**		**51**		**54**		**50**		**48**		**61**

APPENDIX 2

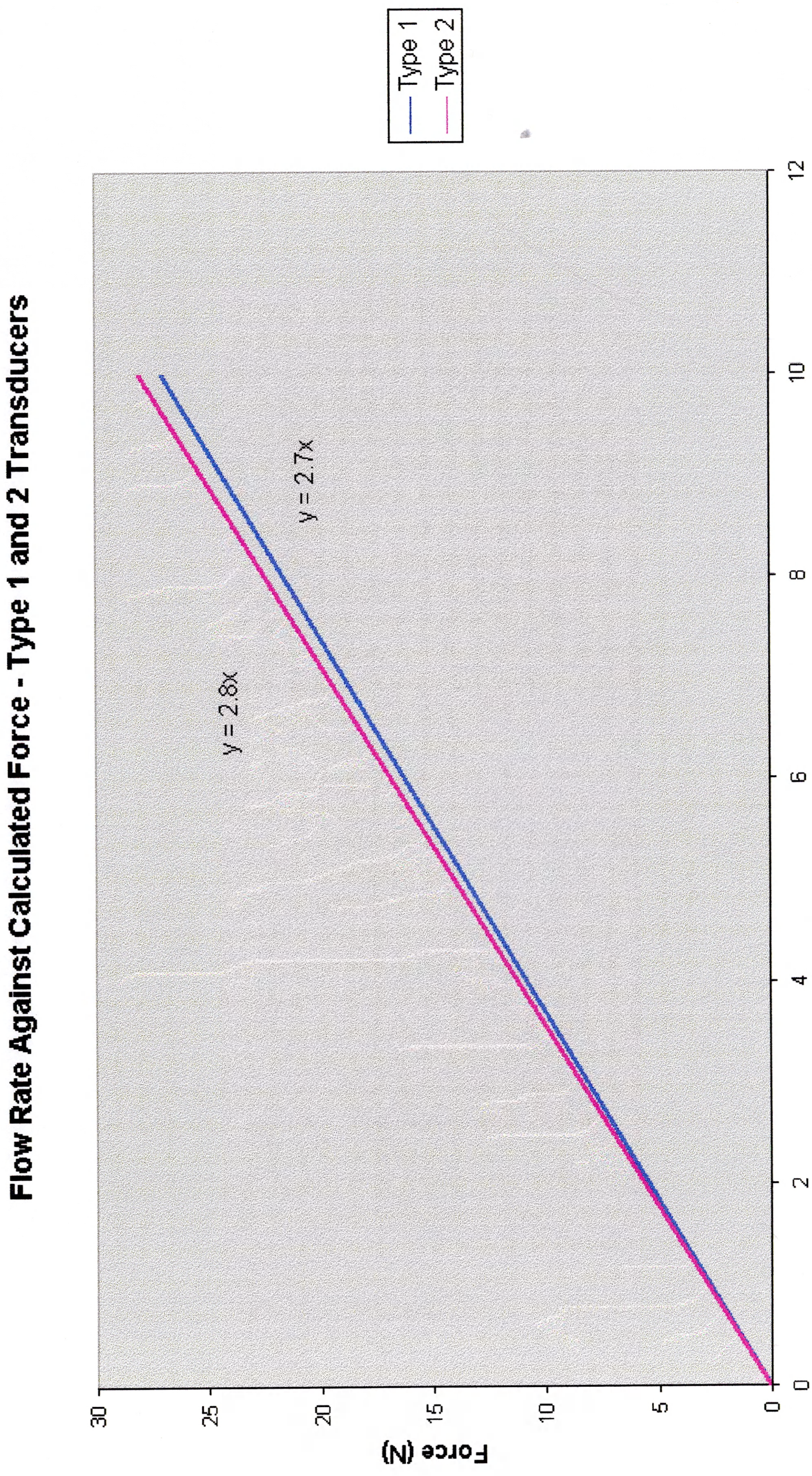


Figure 2.1 Flow Rate Against Calculated Force

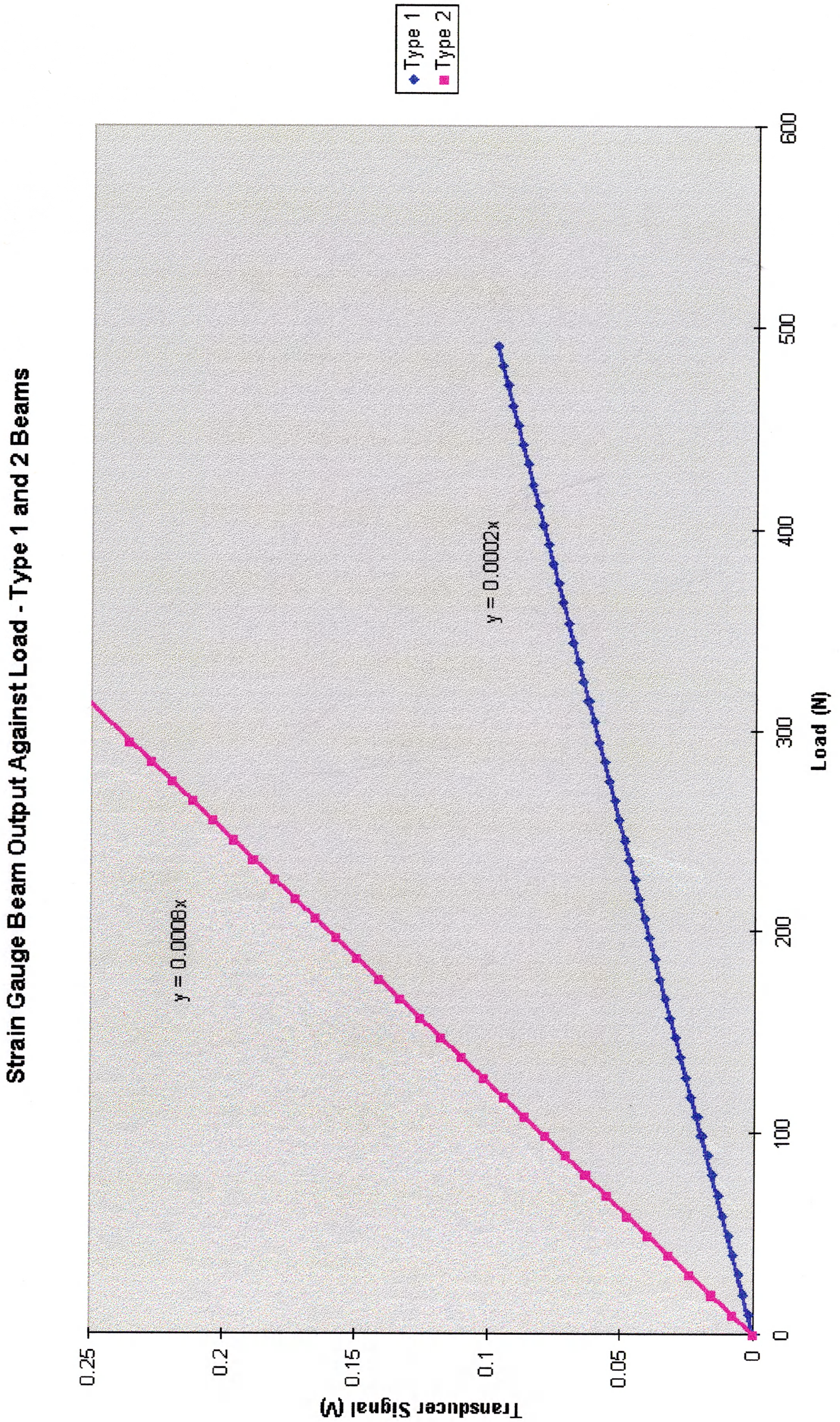


Figure 2.2 Calibration Curves for Type 1 and 2 Transducers

APPENDIX 3

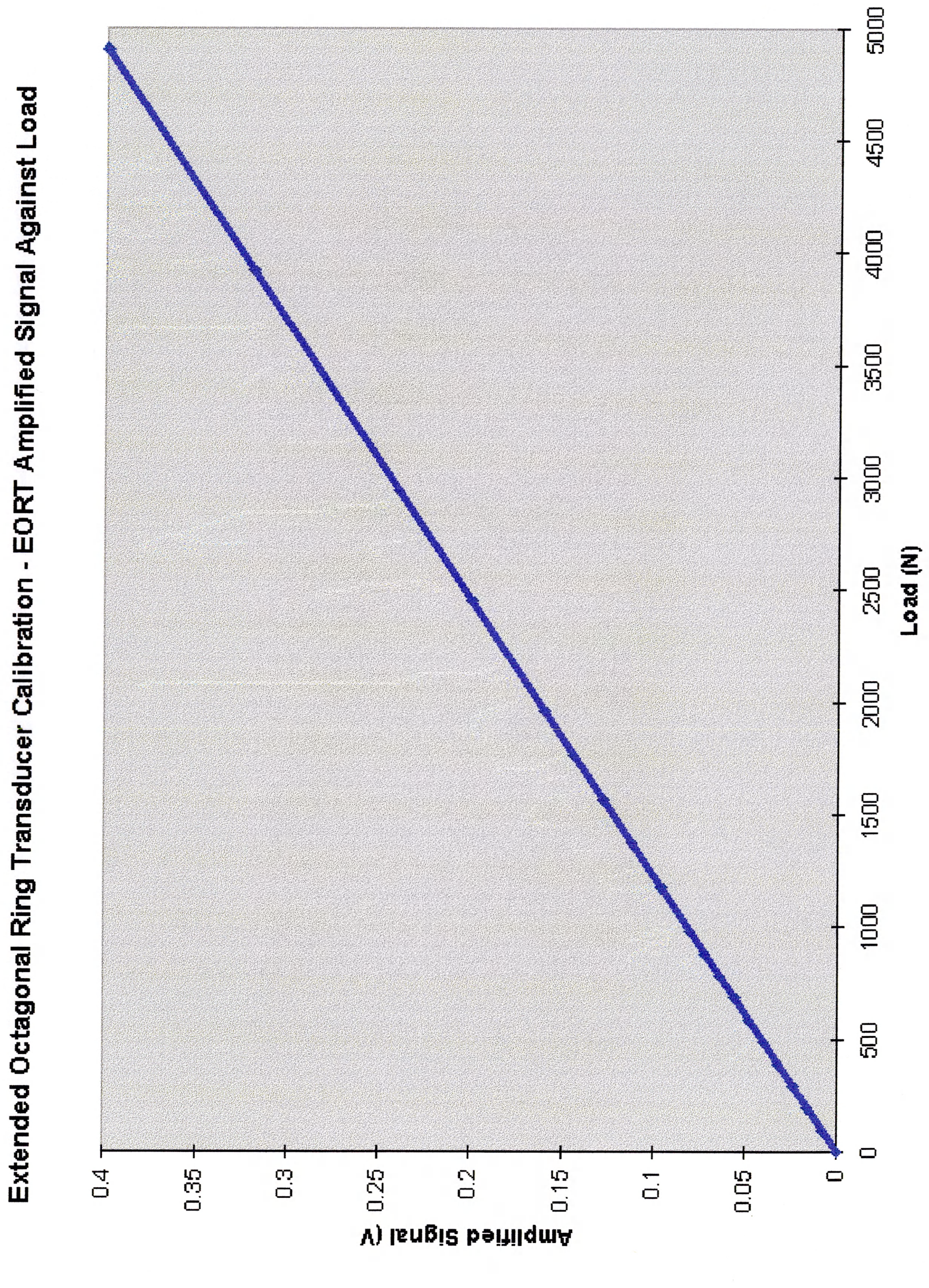


Figure 3.1 Static Calibration of EORT

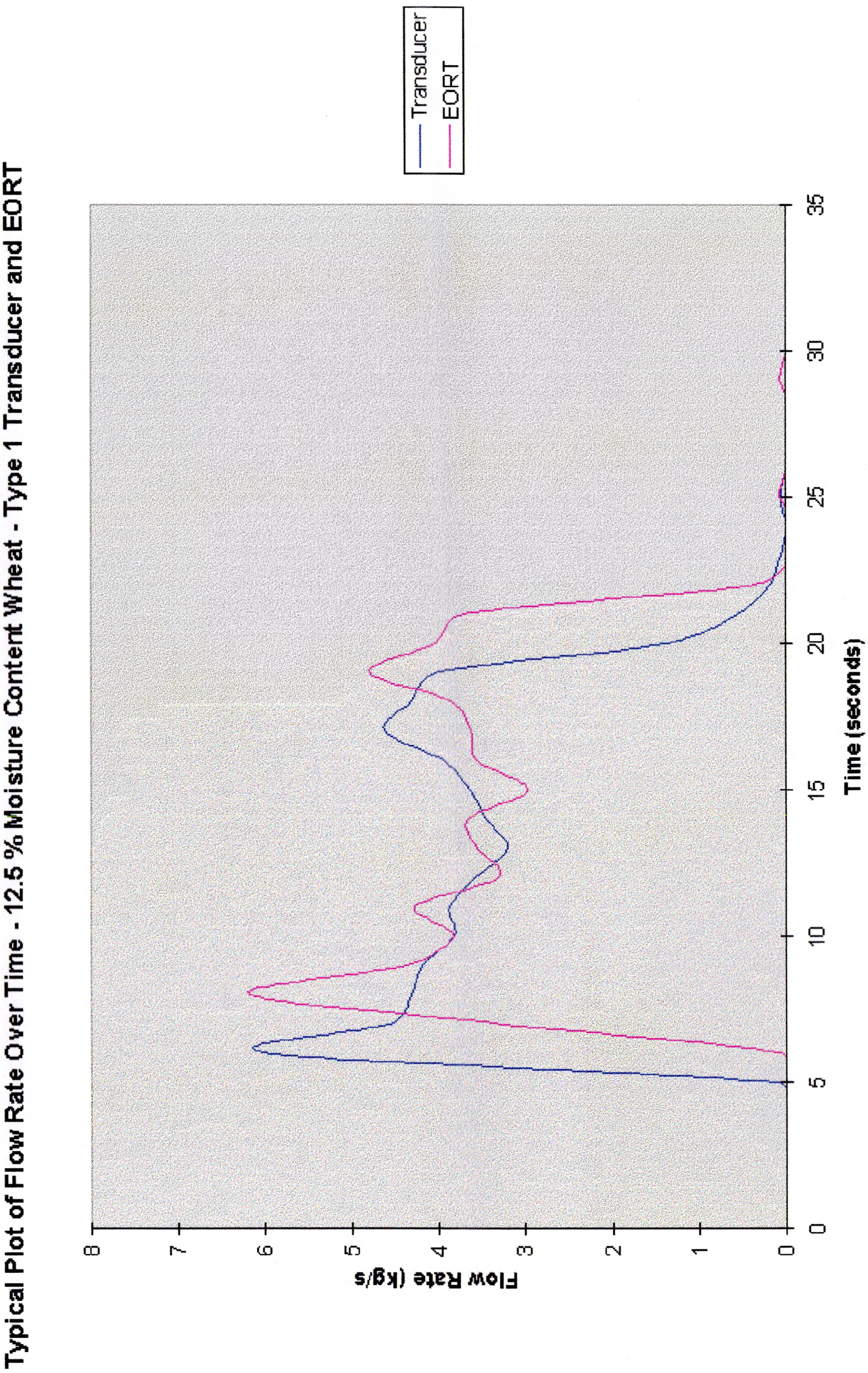


Figure 3.2 Typical Plot of Flow Rate Over Time, 12.5 % Moisture Content Wheat - Type 1 Transducer and EORT

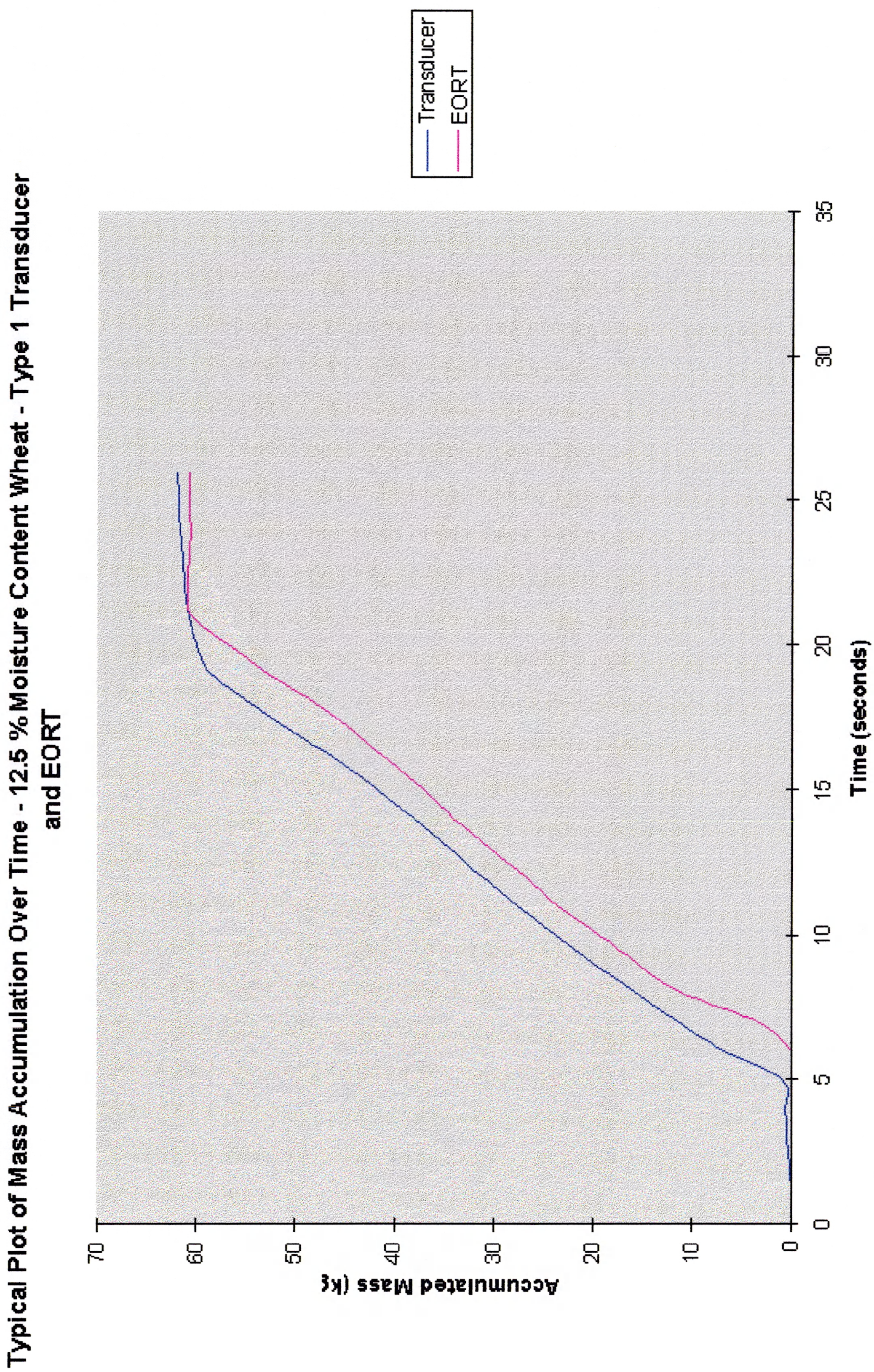


Figure 3.3 Typical Plot of Mass Accumulation Over Time - 12.5 % Moisture Content Wheat - Type 1 Transducer and EORT

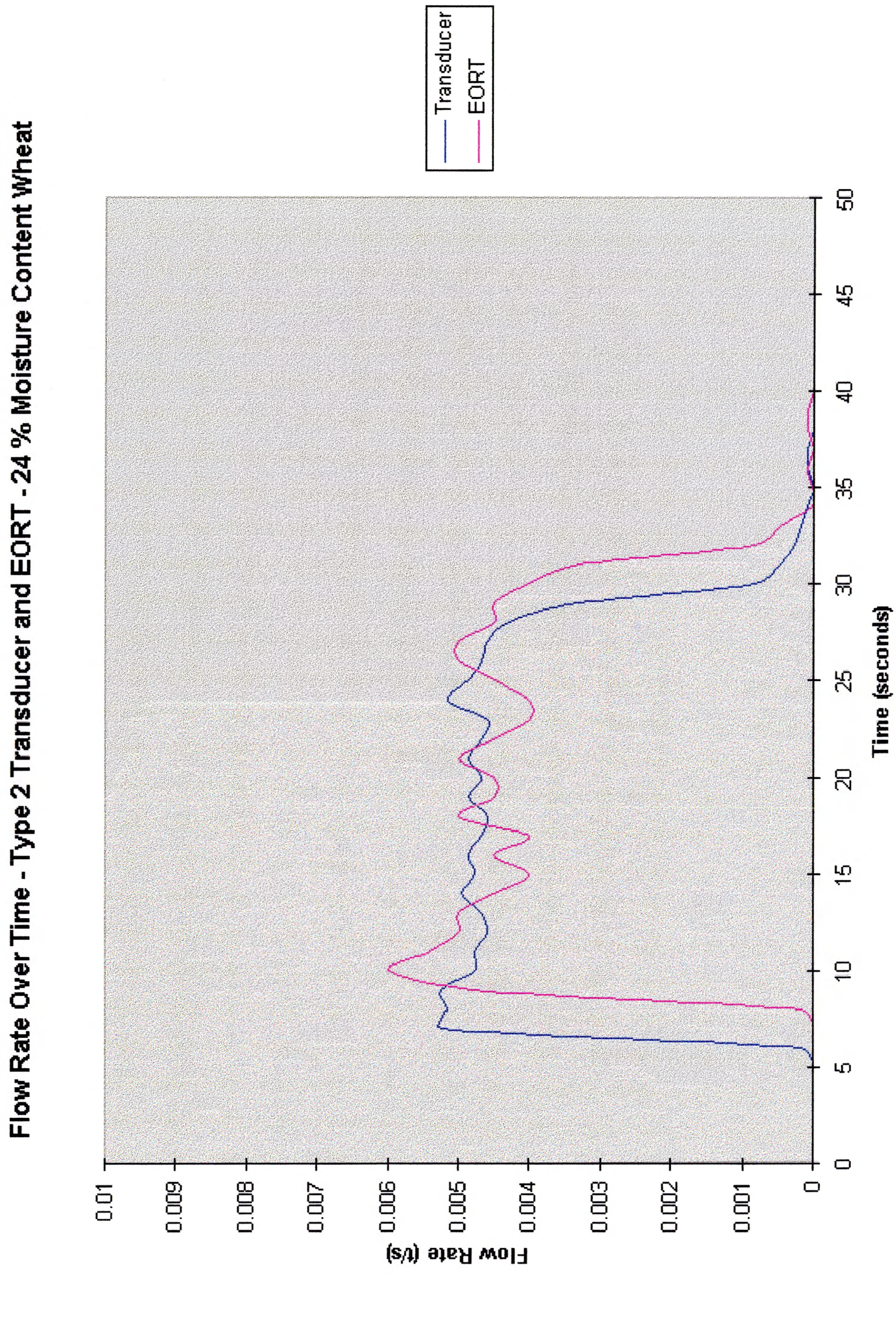


Figure 3.4 Flow Rate Over Time - Type 2 Transducer and EORT
24 % Moisture Content Wheat

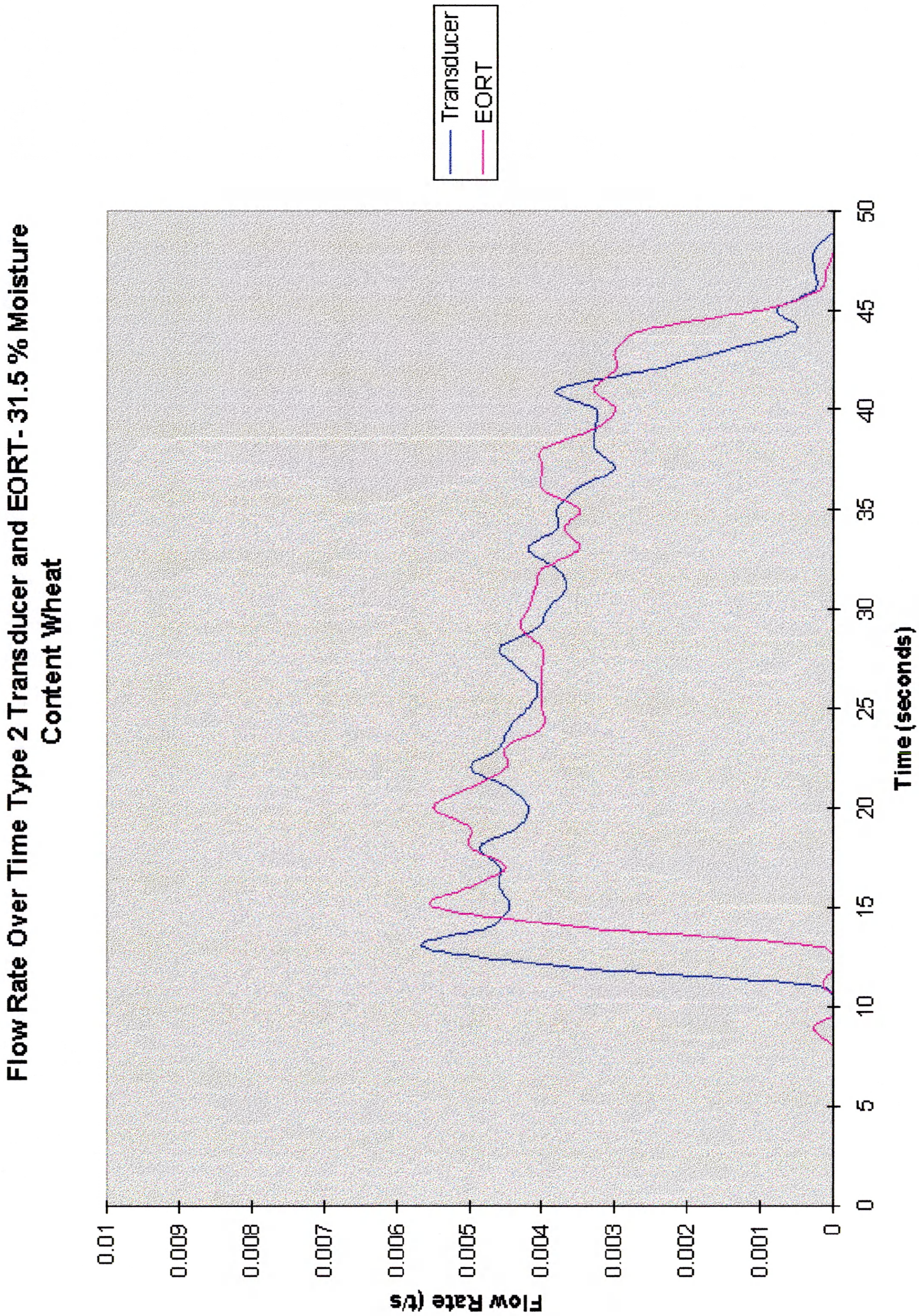


Figure 3.5 Flow Rate Over Time - Type 2 Transducer and EORT 31.5 % Moisture Content Wheat

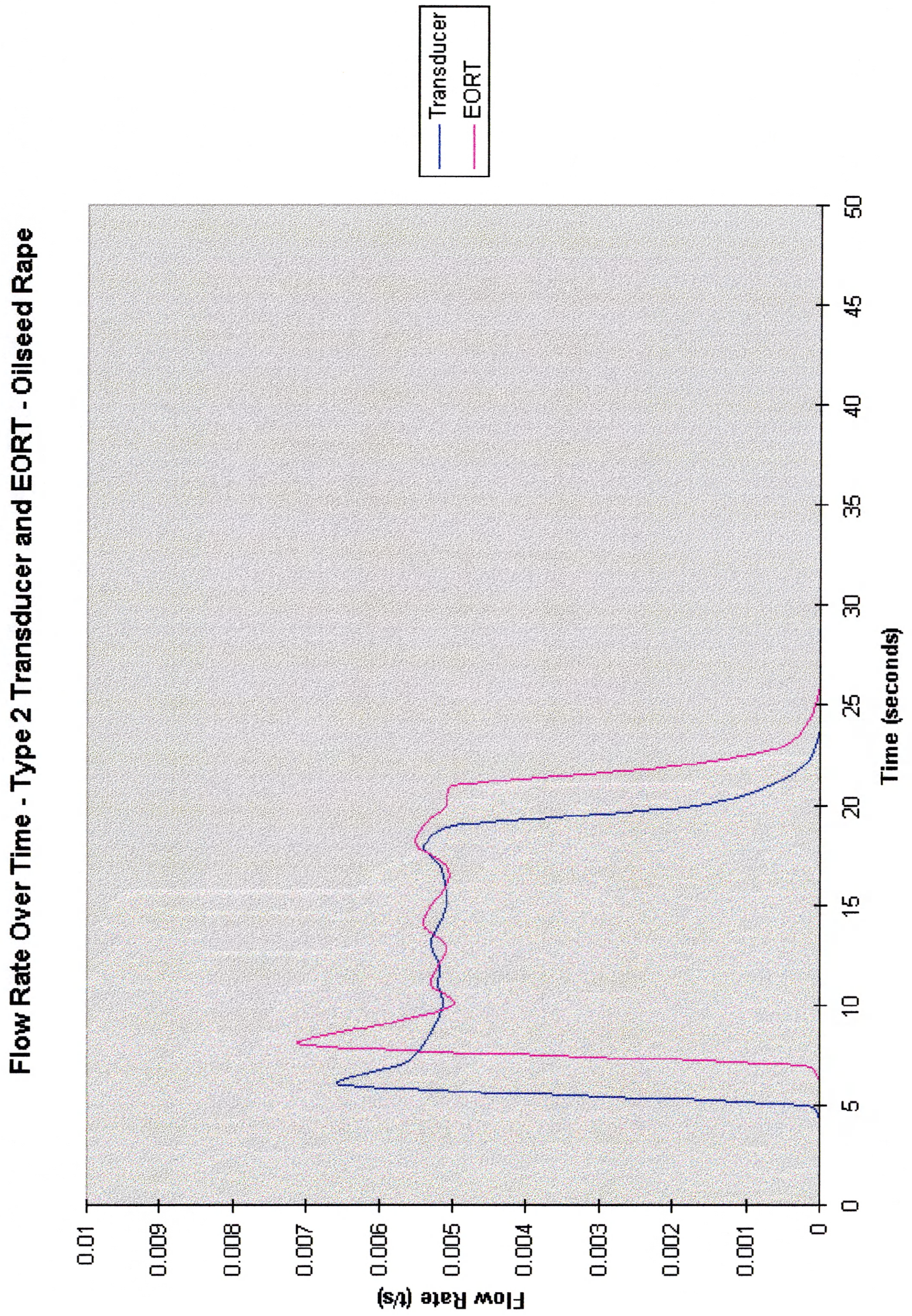


Figure 3.6 Flow Rate Over Time - Type 2 Transducer and EORT Oilseed Rape

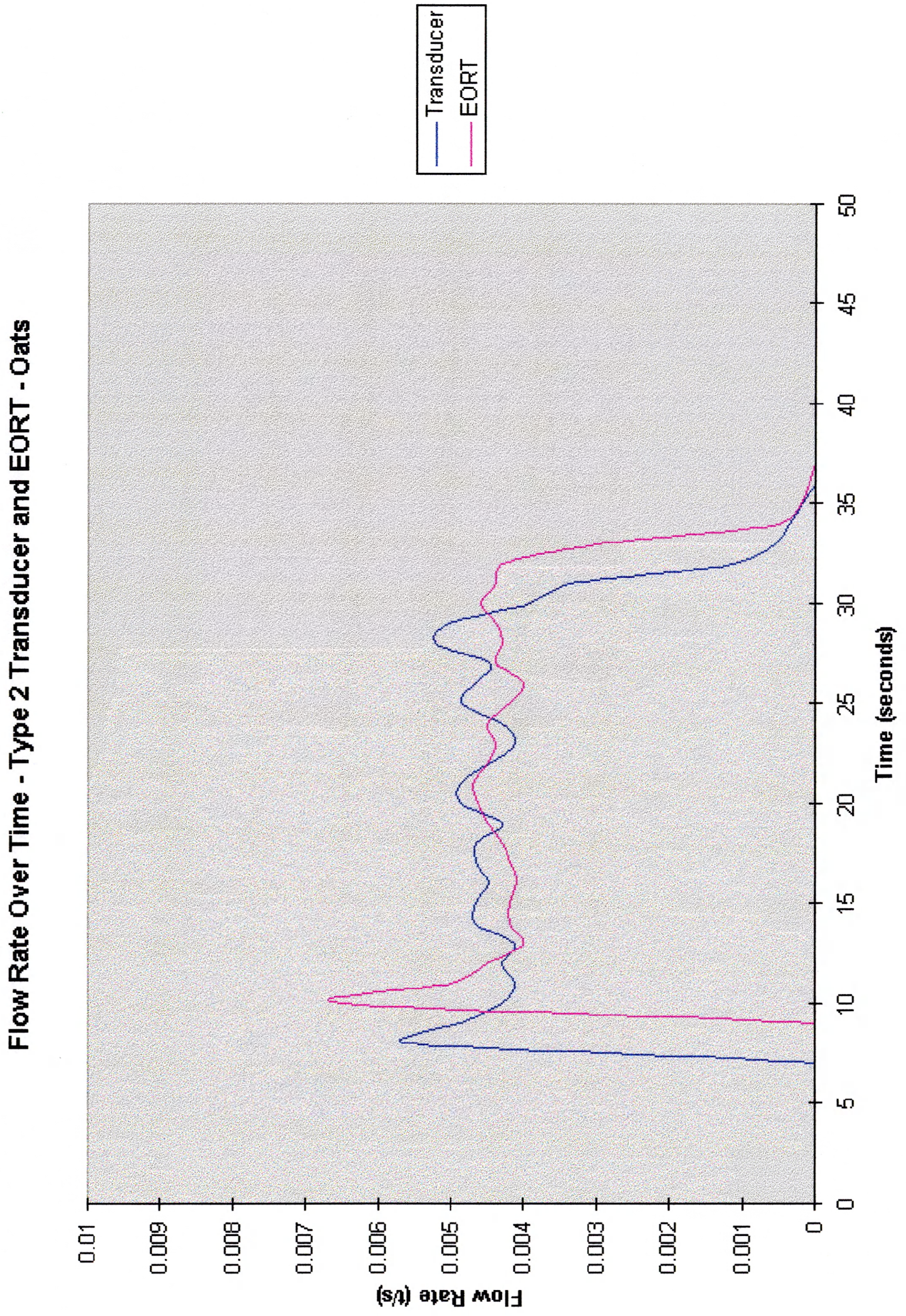


Figure 3.7 Flow Rate Over Time - Type 2 Transducer and EORT - Oats

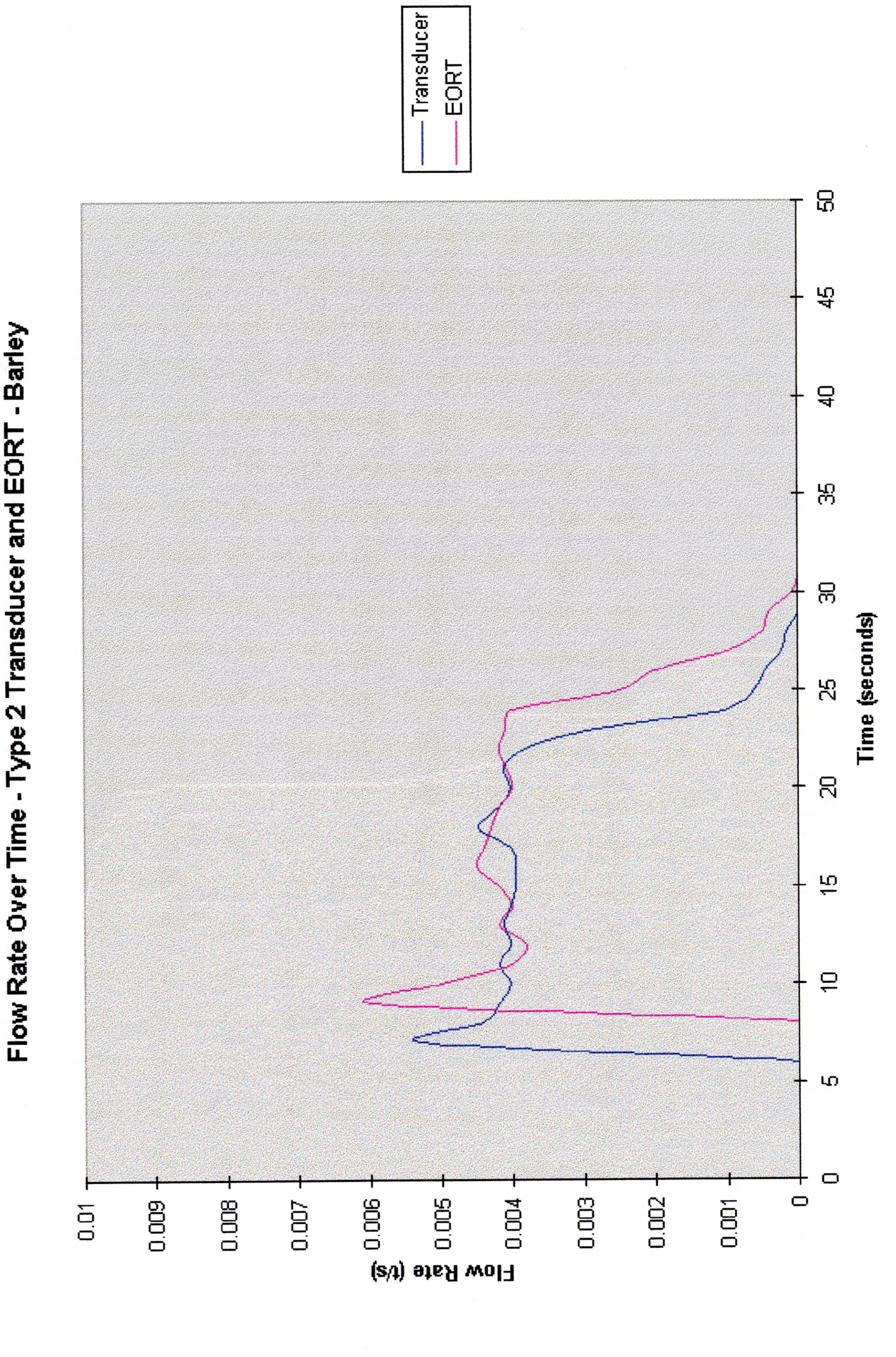


Figure 3.8 Flow Rate Over Time - Type 2 Transducer and EORT - Barley

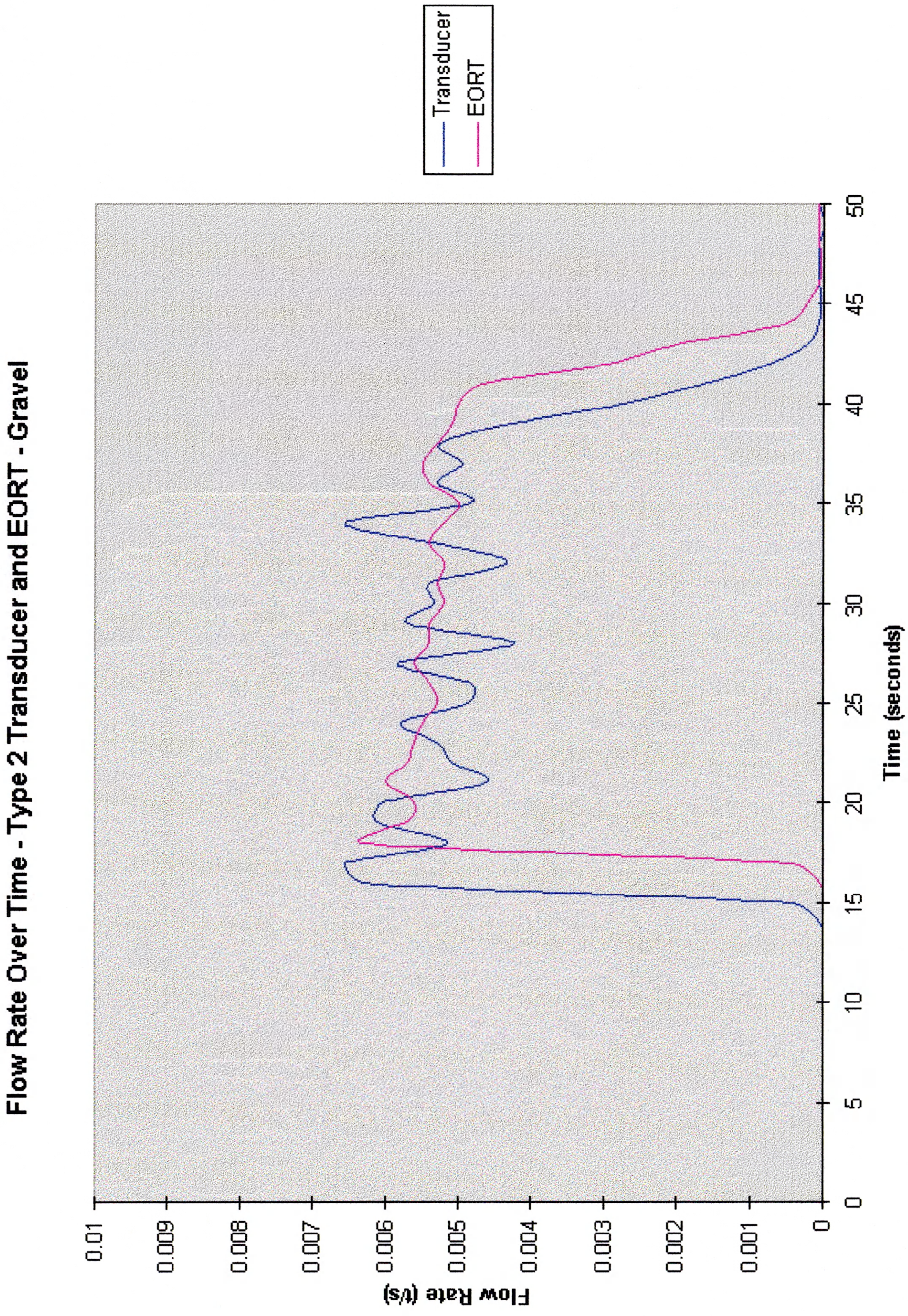


Figure 3.9 Flow Rate Over Time - Type 2 Transducer and EORT - Gravel

APPENDIX 4

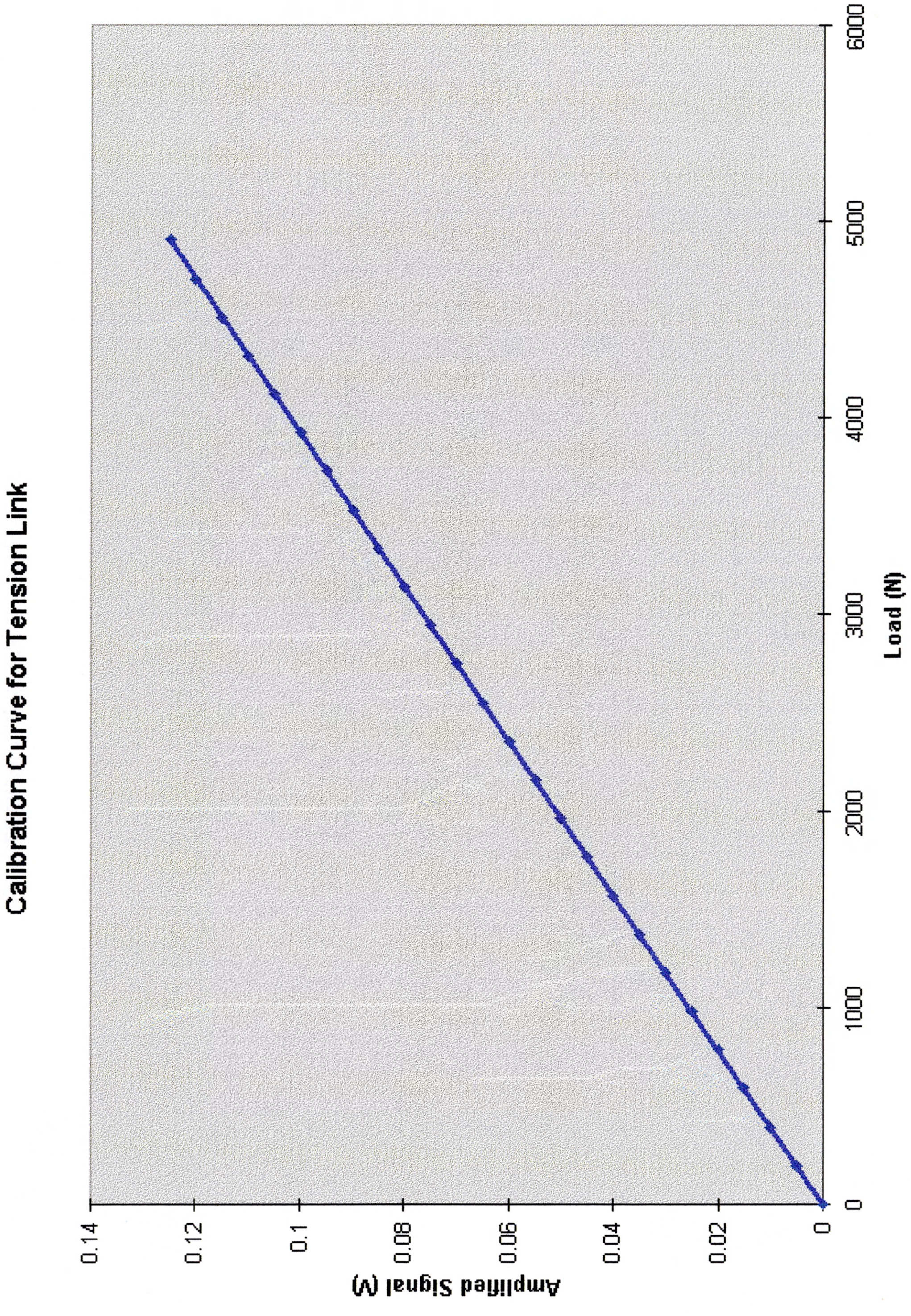


Figure 4.1 Calibration Curve for Tension Link

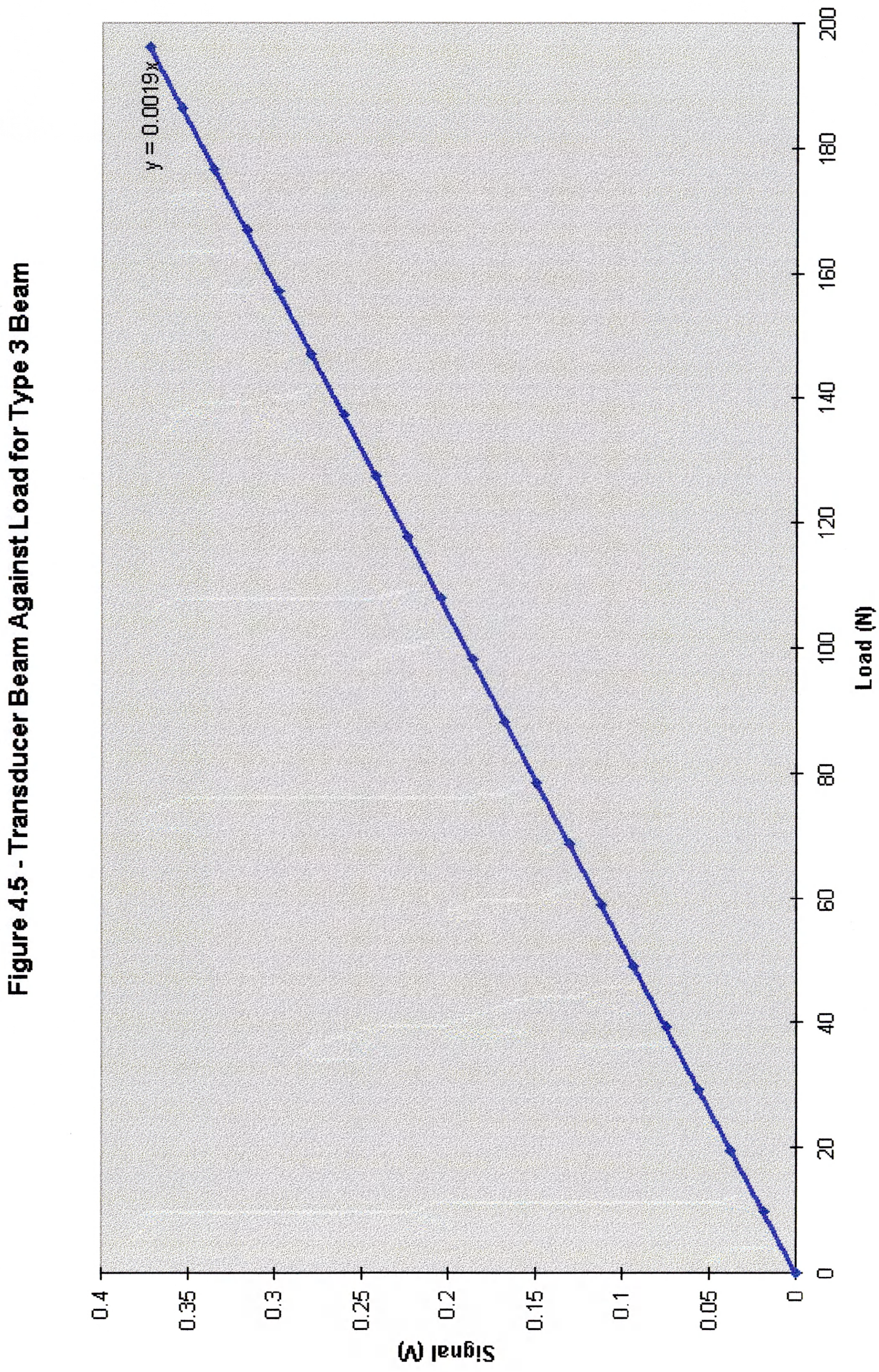


Figure 4.2 Calibration Curve for Type 3 Strain Gauge Beam

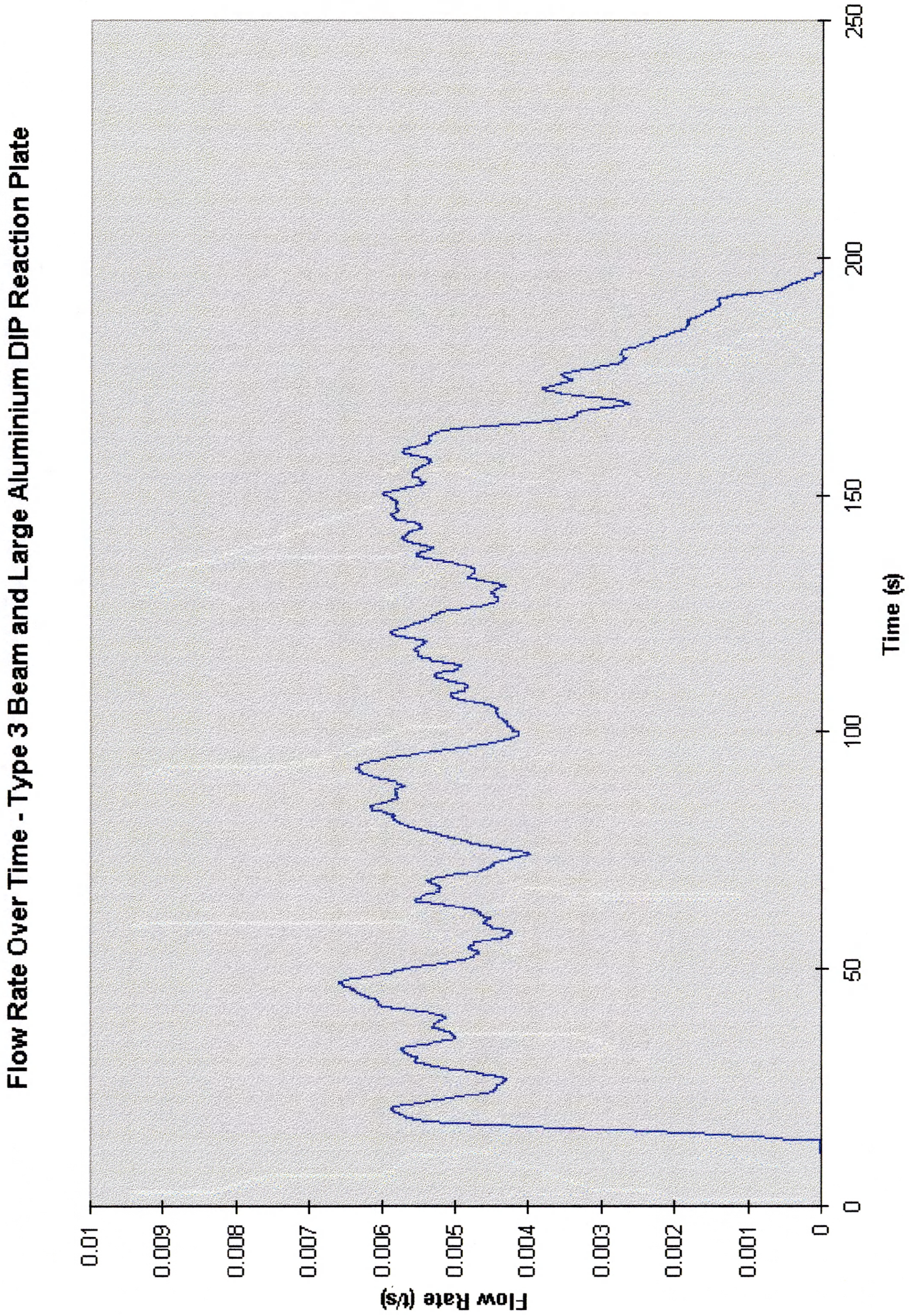


Figure 4.3 Flow Rate Over Time - Type 3 Beam and Large Aluminium DIP Reaction Plate

APPENDIX 5

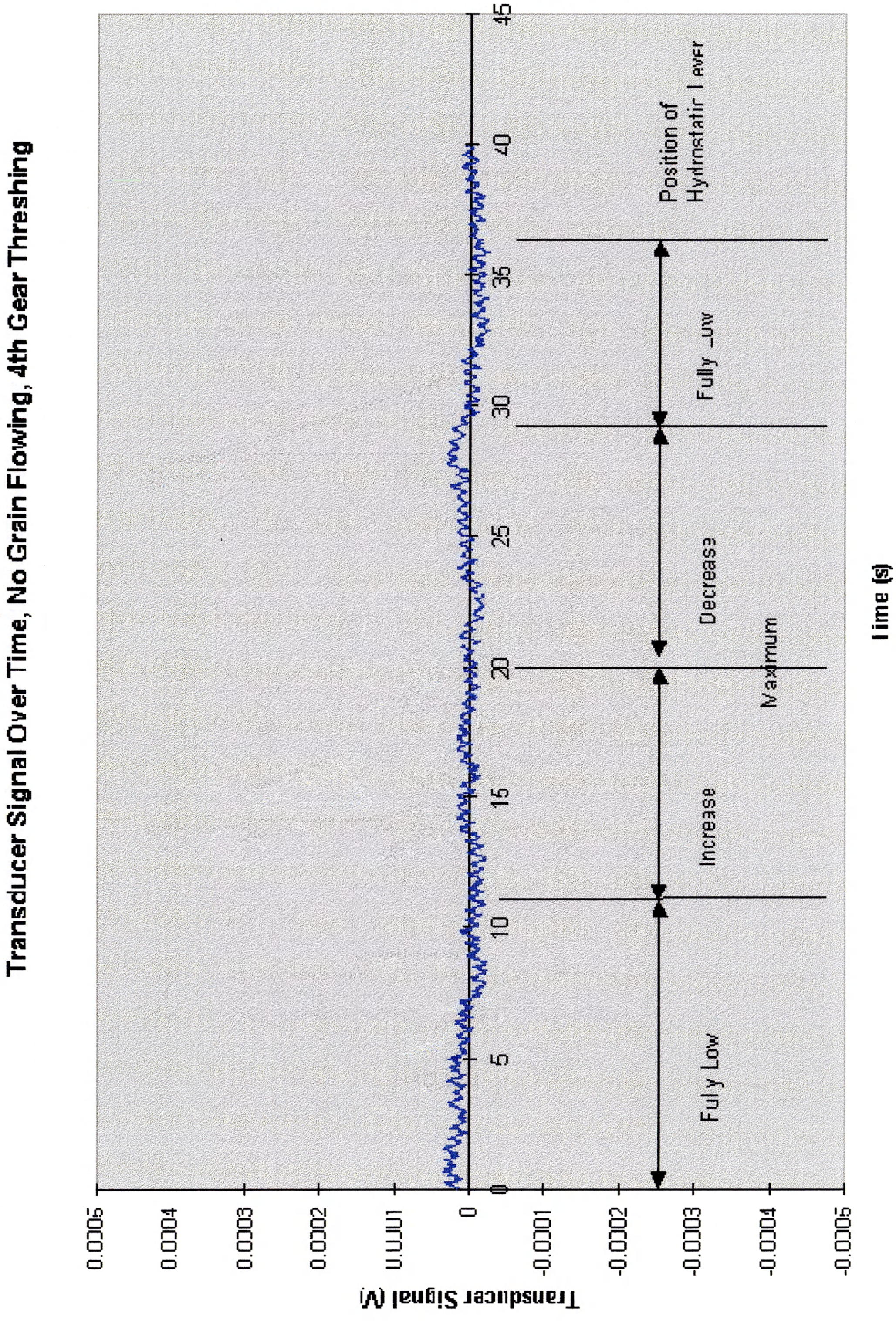


Figure 5.1 Transducer Signal Over Time - No Grain Flowing
4th Gear, Threshing

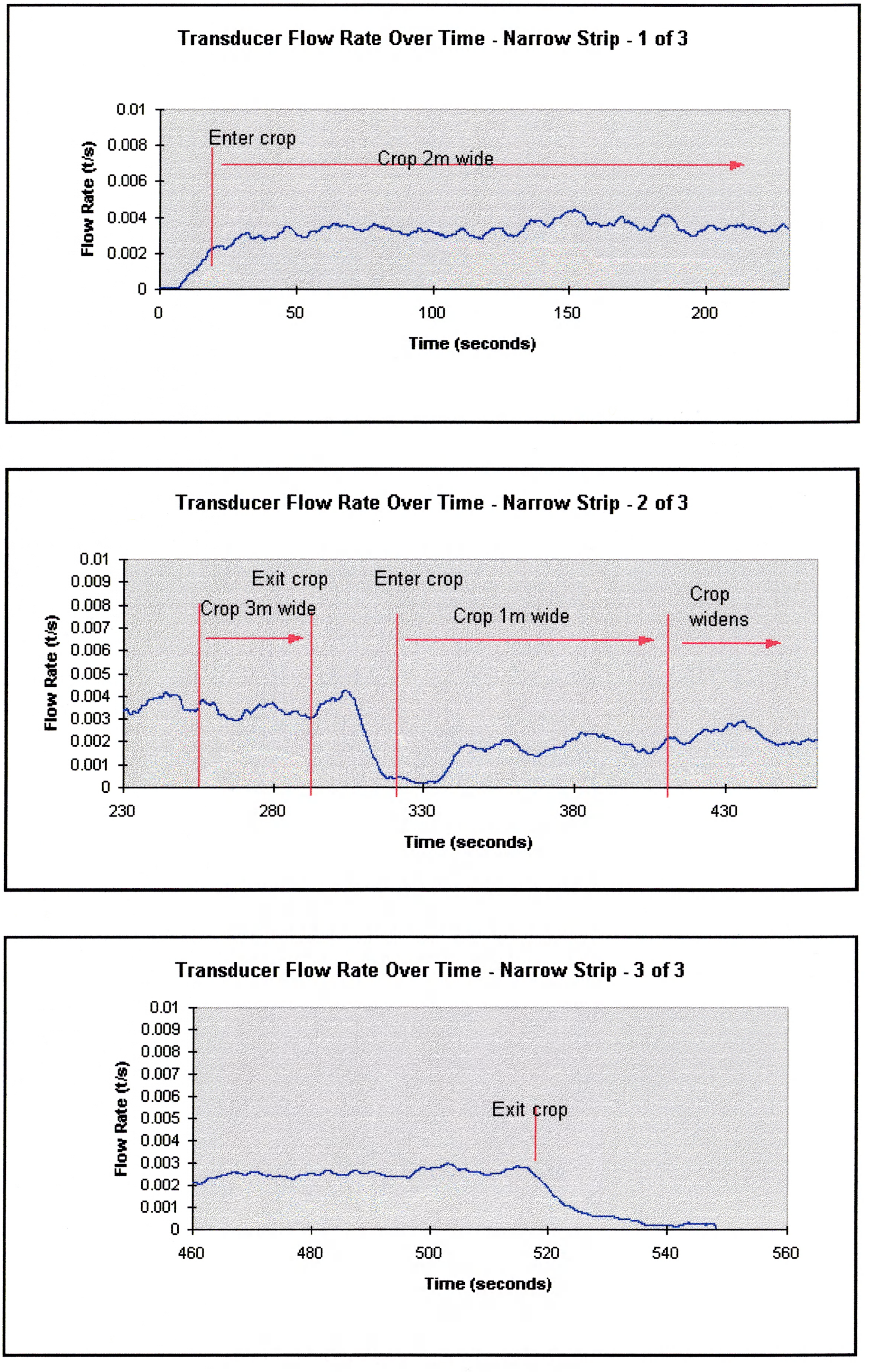
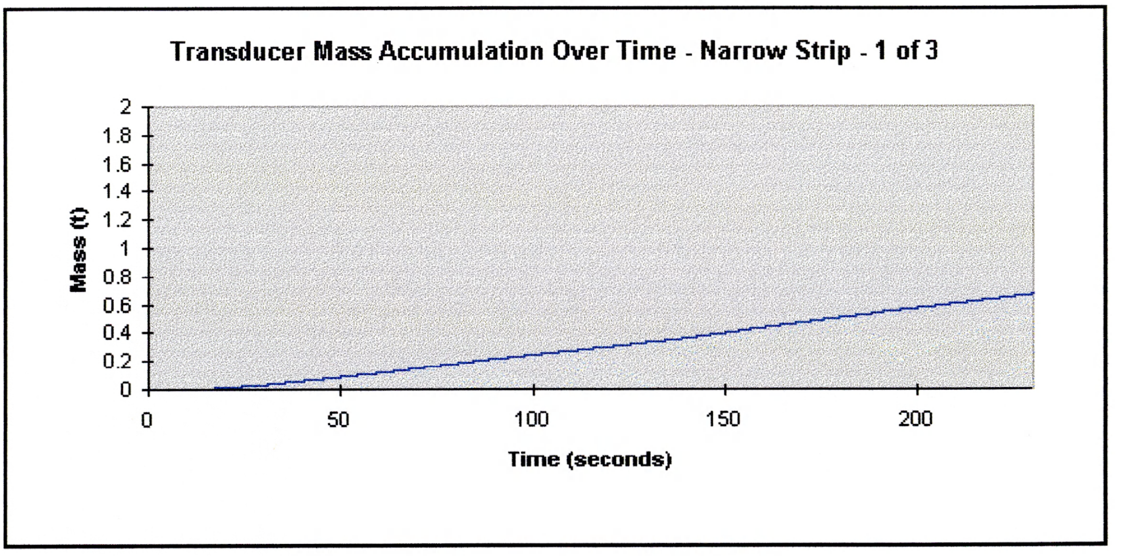
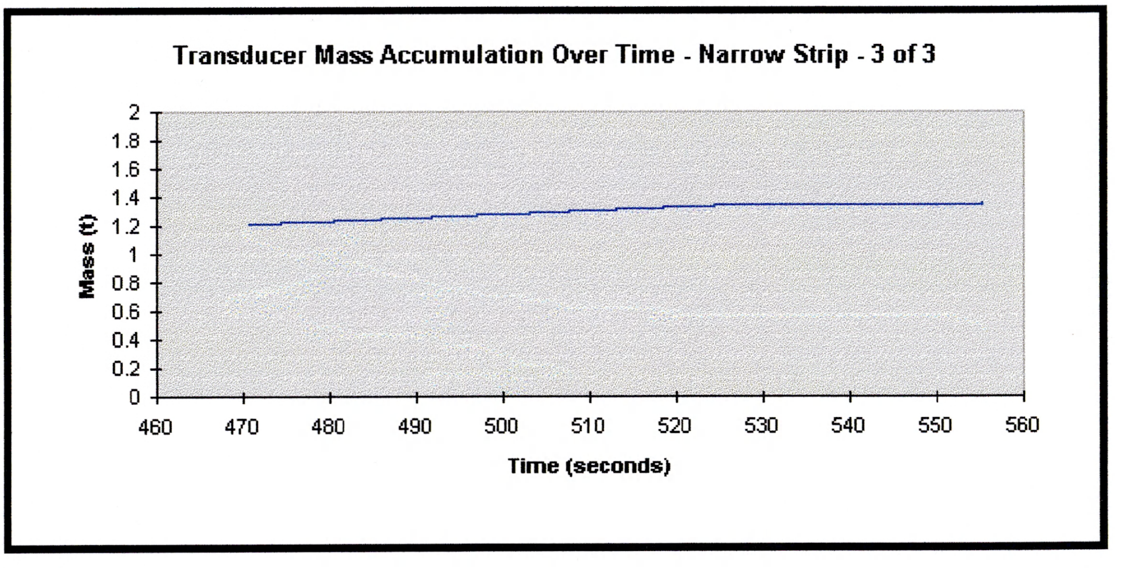


Figure 5.2 Transducer Flow Rate Over Time - Narrow Strip





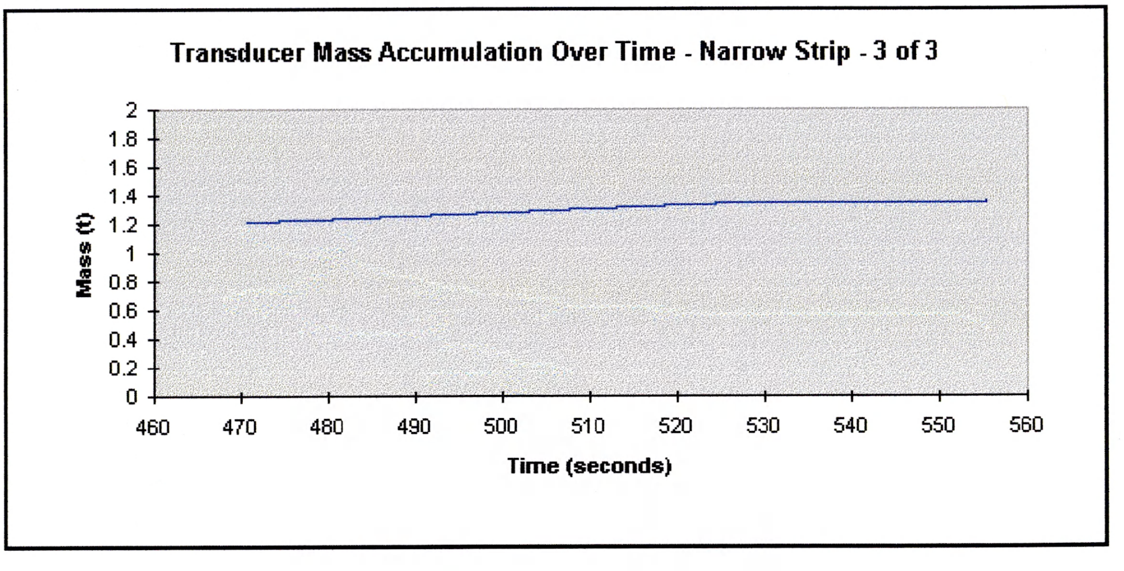
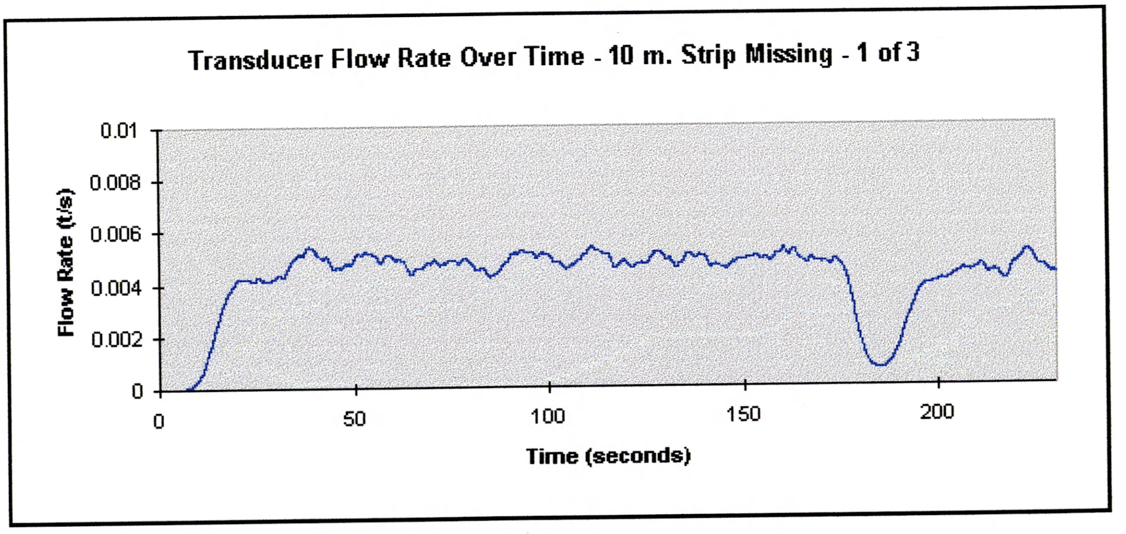
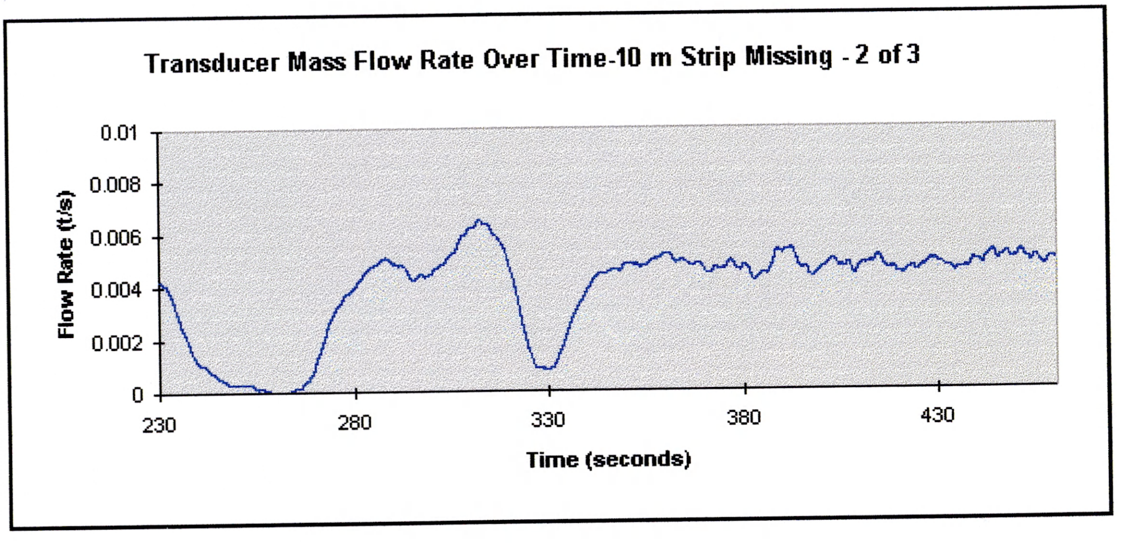


Figure 5.3 Transducer Mass Accumulation Over Time - Narrow Strip





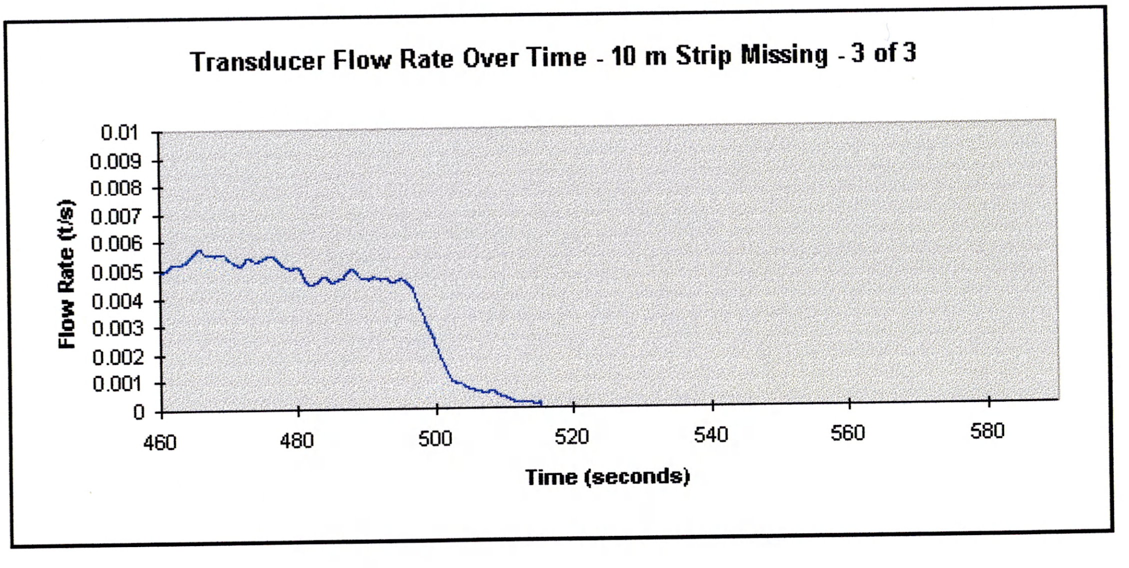


Figure 5.4 Transducer Flow Rate Over Time - 10m Strip Missing

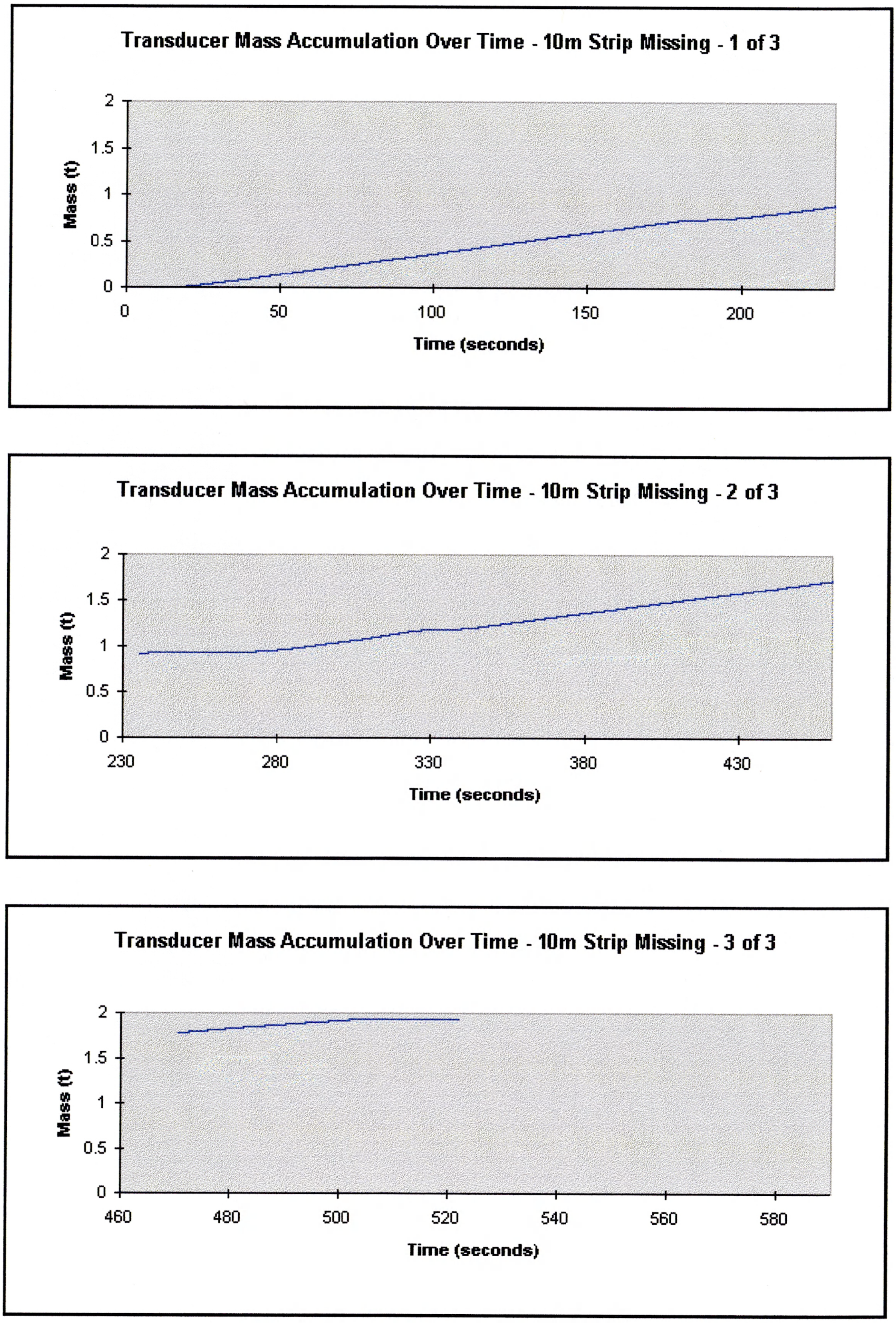
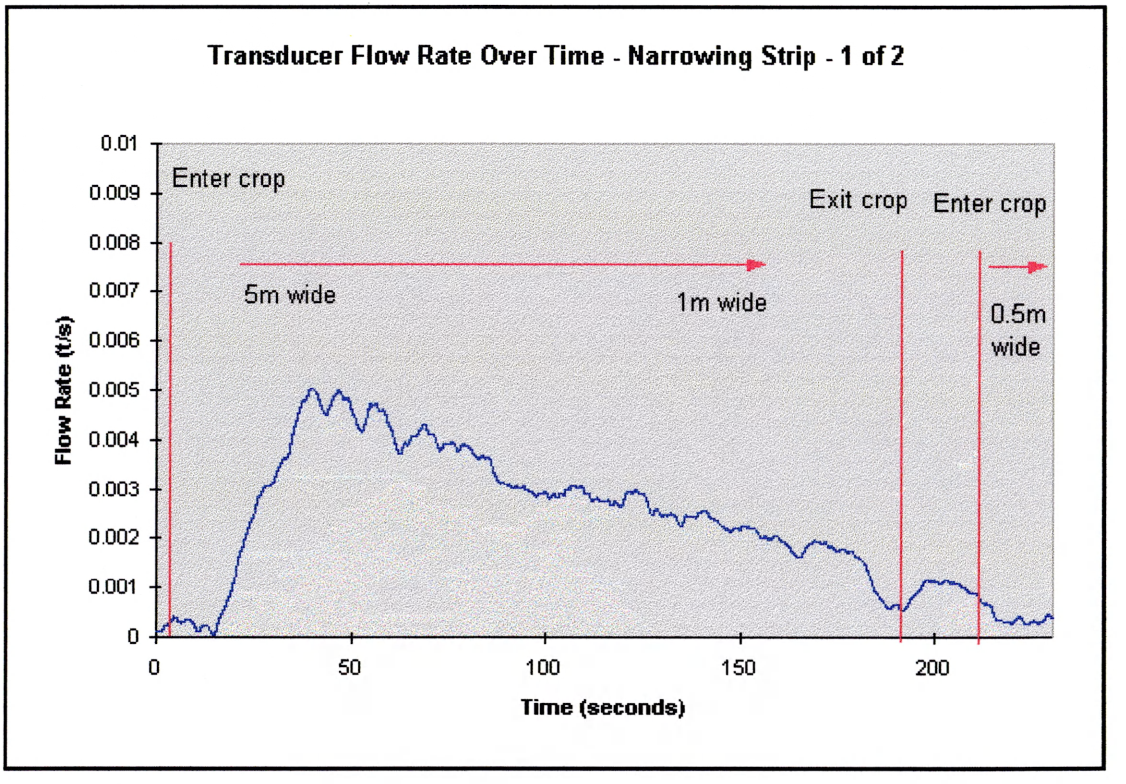


Figure 5.5 Transducer Mass Accumulation Over Time - 10m Strip Missing



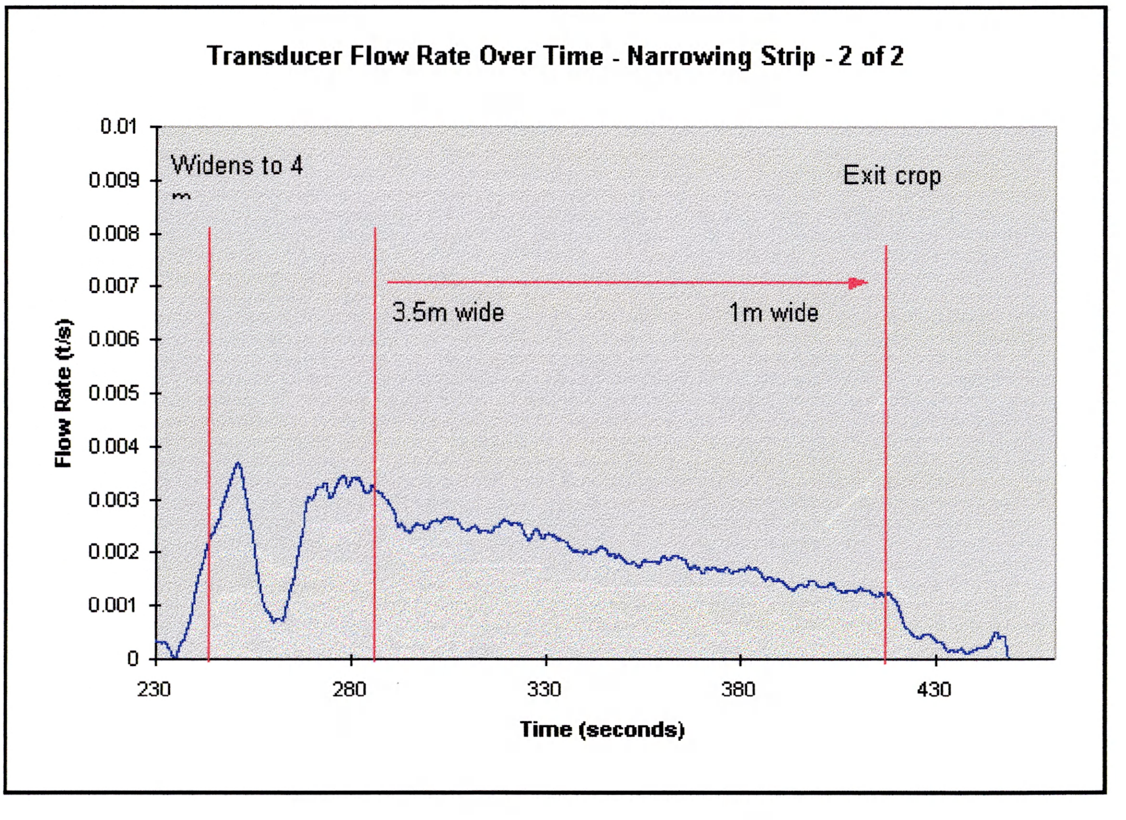
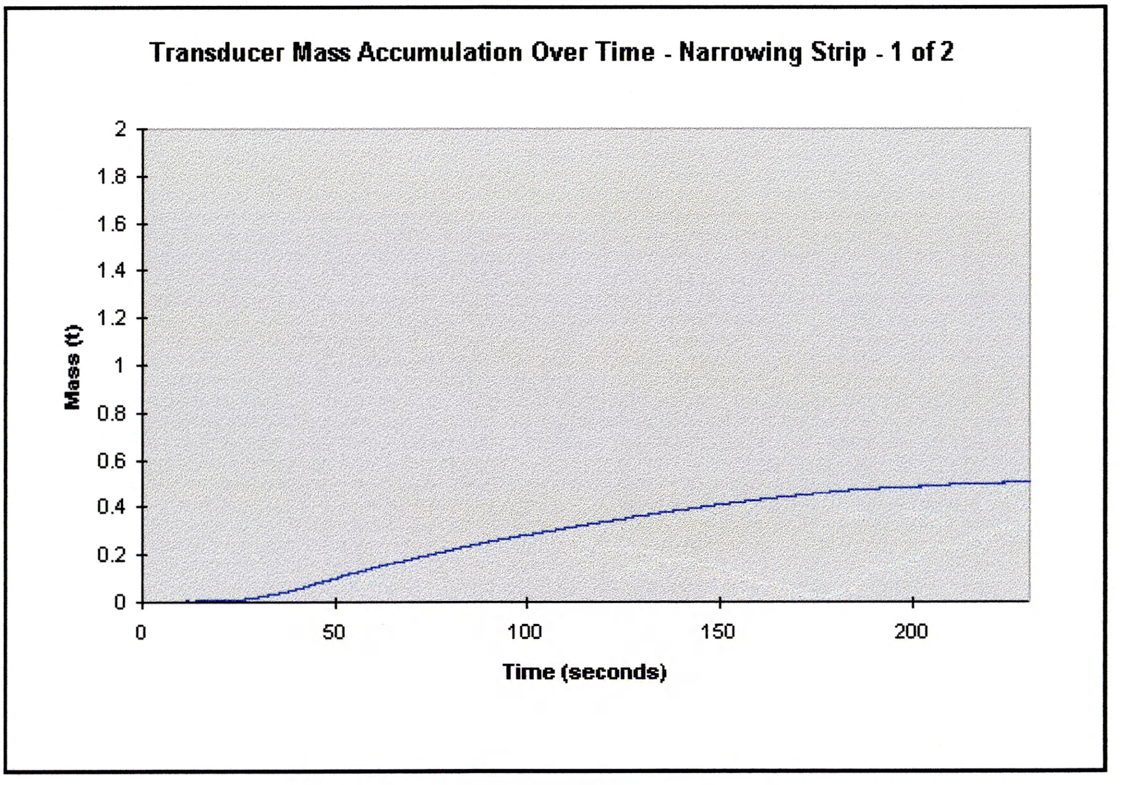


Figure 5.6 Transducer Flow Rate Over Time - Narrowing Strip



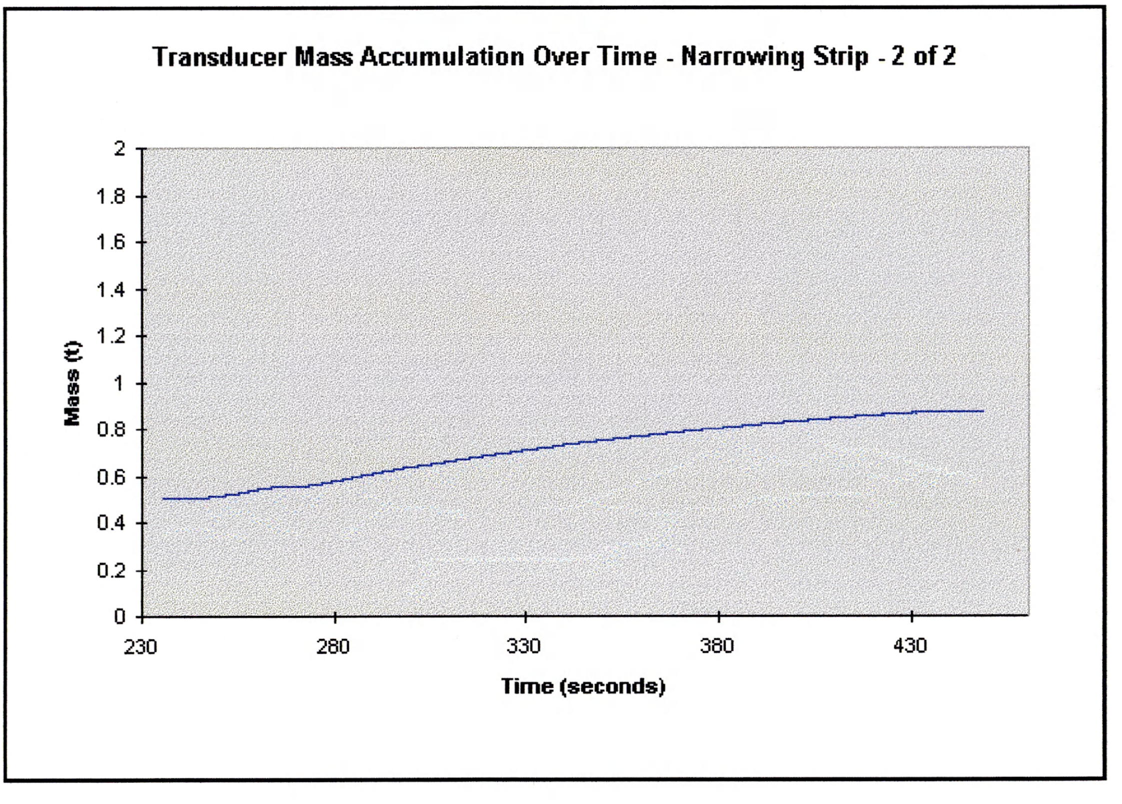
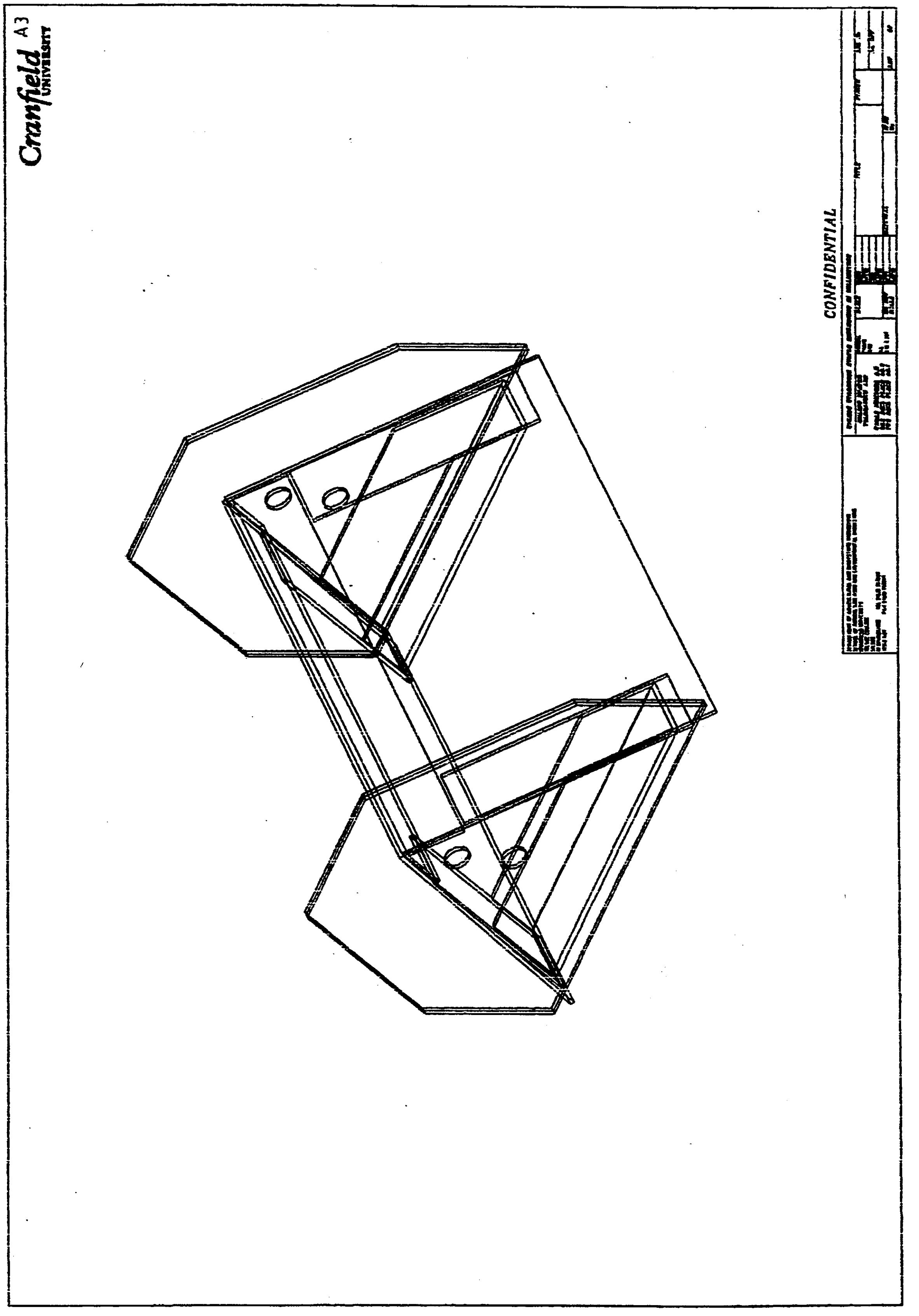


Figure 5.7 Transducer Mass Accumulation Over Time - Narrowing Strip

APPENDIX 6

PART NO	PART NAME	MATERIAL	No OFF	TOTAL COST	PROPRIETARY SUPPLIER
1	END PLATE	NS4 HALF HARD	2		
2	CENTER SUPPORT	NS4 HALF HARD	1		
3	END PLATE MOUNT	NS4 HALF HARD	2		
4	ROOF SIDE	NS4 HALF HARD	2		
5	BRACE	NS4 HALF HARD	2		
			TOTAL COSTS		CARRIED FORWARD

DRAWN	APPD	CHKD		PROJECT NAME	Cont. Mass Flow Measurement
S.P.S.			DEPARTMENT OF AGRICULTURE & ENVIRONMENTAL ENGINEERING	PROJECT No	664
			SILSOE COLLEGE, SILSOE, BEDFORD, MK45 4DT	DRAWING No	
DATE	DATE	DATE	TEL 0525863000 FAX 0525863001		SHEET 1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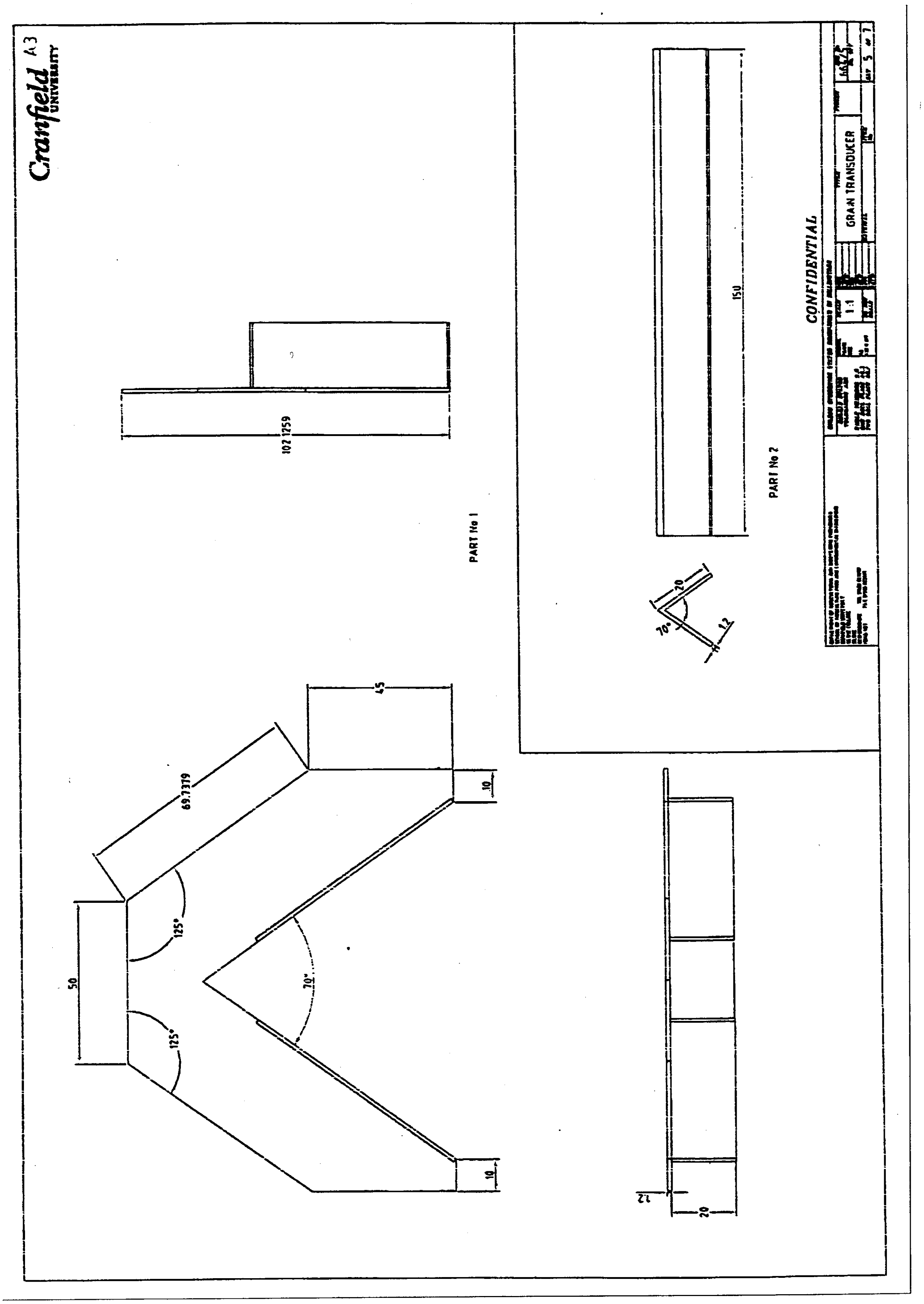
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GRAIN TRANSDUCER
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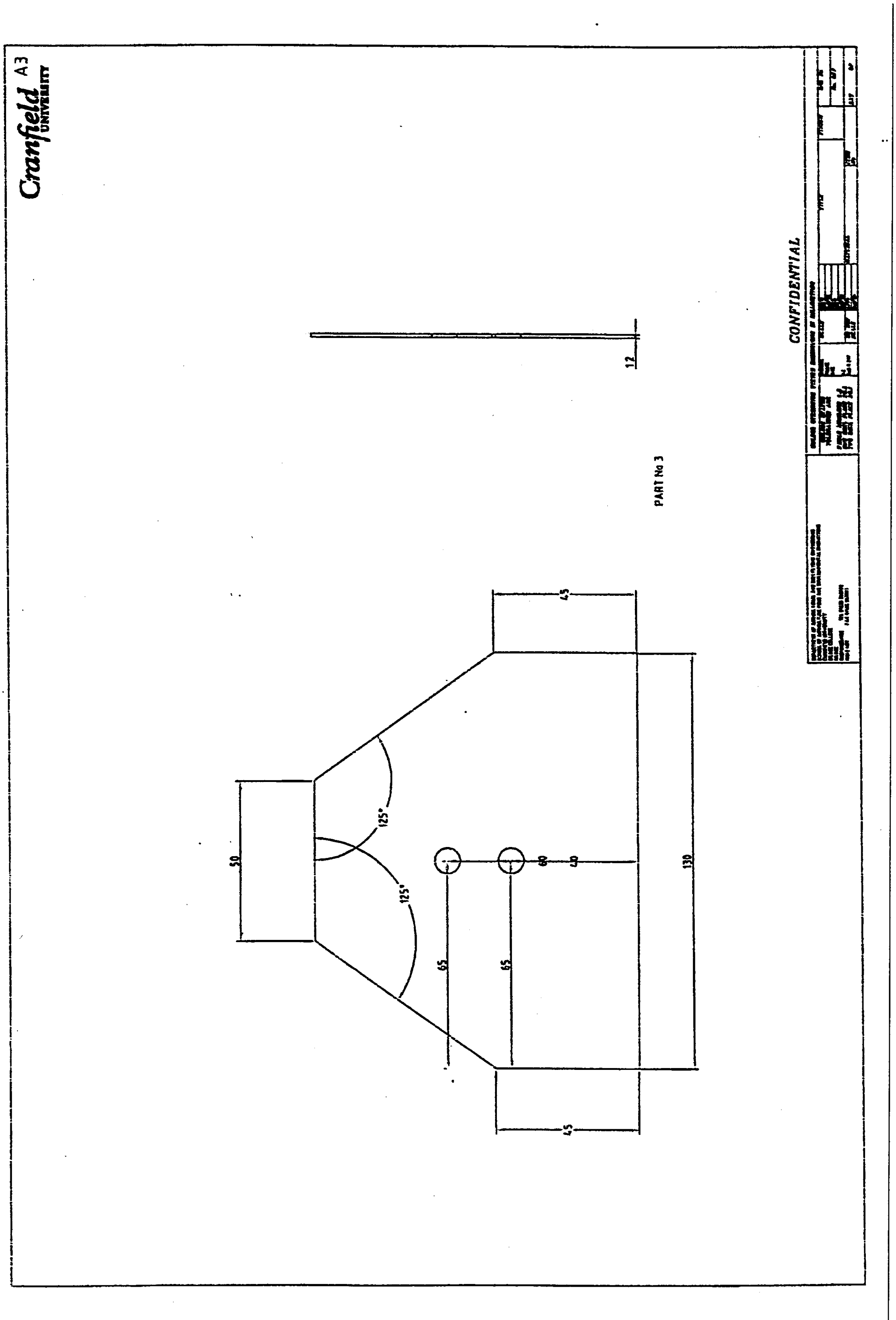
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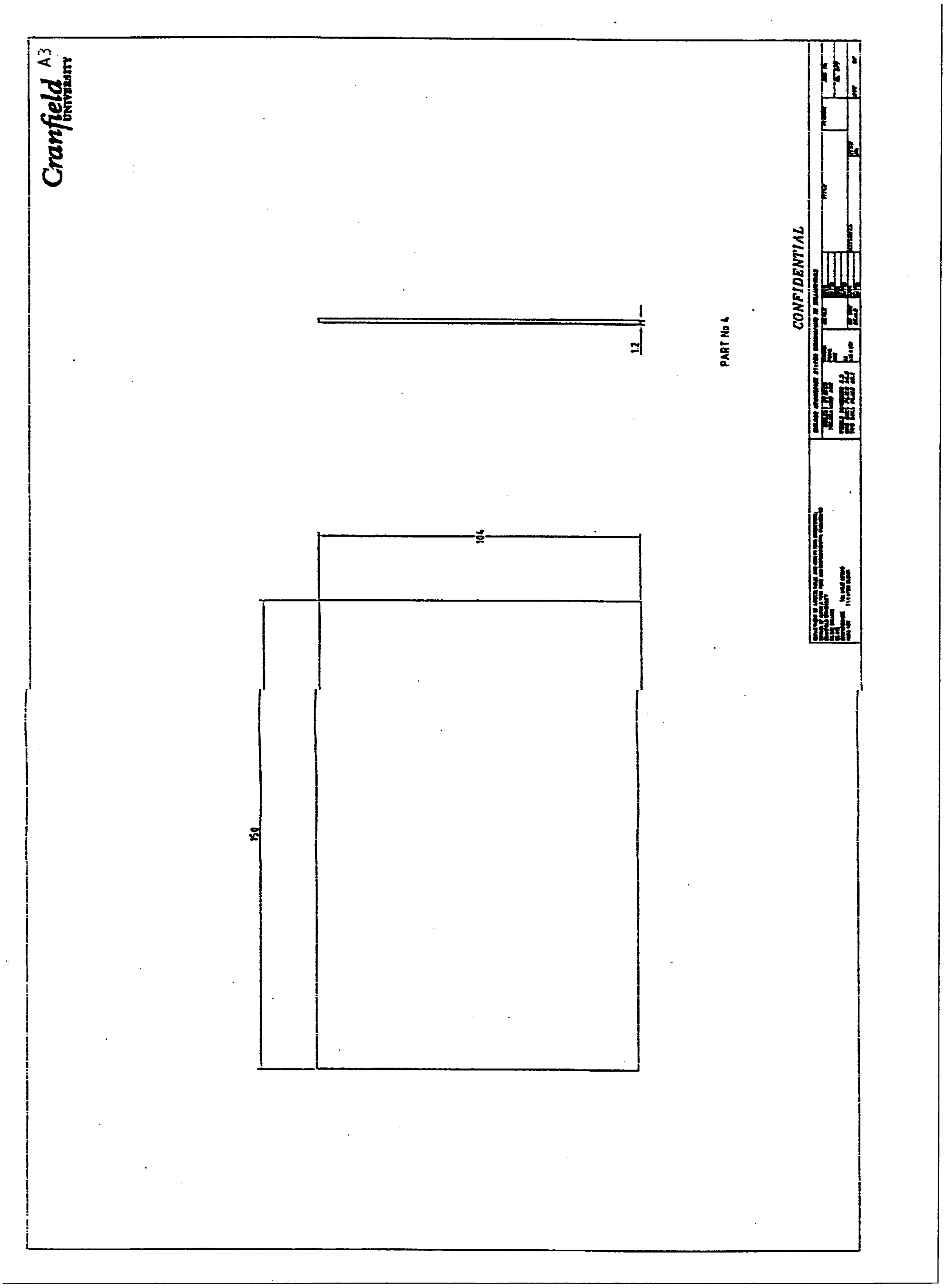
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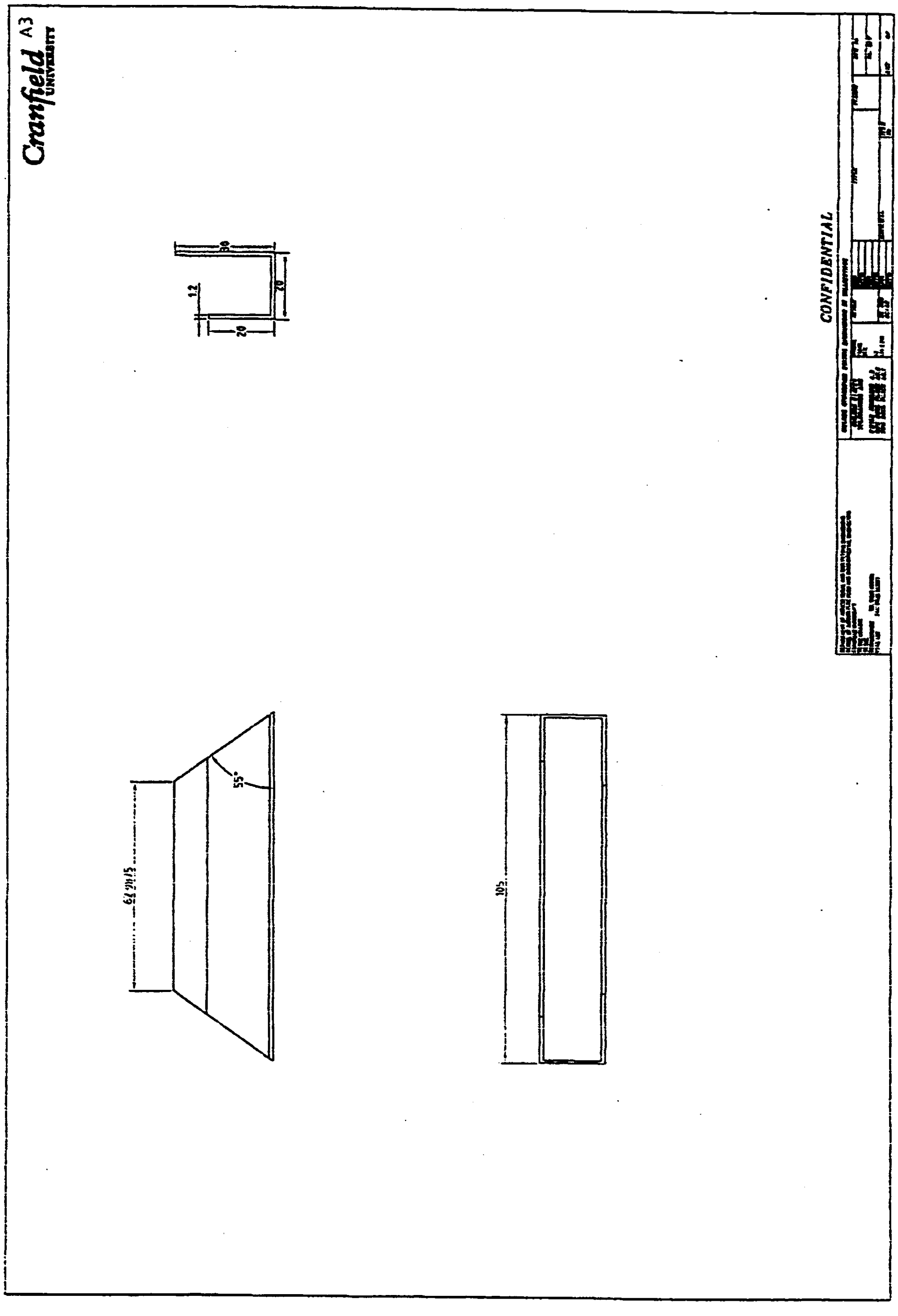
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APPENDIX 7

PATENT SPECIFICATION

DRAWINGS ATTACHED

(21) Application No. 55323/68

(22) Filed 1 Nov 1996

(43) Application published 1 Feb 1997

(45) Complete specification published 1 April 1997

(51) International Classification B 65 h 45/101

(52) Index at acceptance DIS 23B

(72) Inventors STUART SAUNDERS and RICHARD GODWIN

(73) Proprietor Griffith Elder & Co Ltd, Bury St Edmunds

(54) A DEVICE FOR MASS MEASUREMENT OF FLOWING PARTICULATE MASSES

(71) We, Griffith Elder & Co. Ltd, a United Kingdom company of Bury St Edmunds, England, do hereby declare the invention for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement : -

The invention relates to a device for measuring the true mass flow rate of particulate masses (herein referred to as *material*), including biological materials, using a double inclined plane type material interface (herein referred to as DIP) and a strain gauged beam.

Measurement of a flowing materials mass has been accomplished by several methods but these are relatively expensive and can contain errors due to varying material density and moisture content.

An object of this device was to reduce costs whilst improving measurement stability due to material variations.

In accordance with the invention, material is flowed across the surface of the DIP causing a vertically downward force. This is transferred directly to the supporting beam which is fitted with strain gauges, allowing an electrical measurement equivalent to mass flow rate.

The DIP structure consists of two flat plates, both angled at fifty five degrees to the horizontal. This results in the DIP having an internal angle of seventy degrees. Side supports are provided to contain the flowing material to the faces of the DIP and additional supports are used to provide structural rigidity to the whole assembly.

Flowing material is dropped onto the DIP structure and flow is divided evenly across both sides of the DIP. The impact of material onto the DIP contributes some two-thirds towards the overall vertical force, the other third is given by the mass of the material as it flows down the side of the DIP.

The strain gauge beam is mounted solidly to the DIP structure, either on the end face or directly underneath, and consequently receives all the vertical force from the DIP. The strain gauge beam is fixed solidly in the horizontal plane.

Figure one is a perspective view of the complete assembly, showing the DIP structure (1) and strain gauge beam (2).

Figure two is a sectioned end elevation of the DIP structure, viewed in direction of arrow 'X' shown in figure one. This illustrates the angles of the flat plates constituting the DIP sides.

Figure three is a side elevation of the DIP structure, viewed in direction of arrow 'Y' shown in figure one. It illustrates the material flow.

Figure four is a perspective view of the complete assembly illustrating the two options for mounting the strain gauge beam to the DIP structure.

WHAT WE CLAIM IS : -

1. A device for measuring the mass flow rate of particulate masses which uses a DIP type material interface mounted on a strain gauged beam.

2. A device as claimed in claim 1 which uses a lightweight DIP type material interface having the DIP sides at an angle of 55 degrees from the horizontal, fitted with sides to retain the flowing material.

3. A device as claimed in claim 2 over which material flows evenly either side of the DIP type material interface.

4. A device as claimed in claim 2 that solidly mounts the DIP type material interface to the strain gauge beam.

5. A device as claimed in claim 1 that uses a centrally or end, horizontally mounted strain gauge beam.

6. A device as claimed in claim 5 that receives approximately 33 % of its deflection from material present on the DIP and 66 % of its deflection from impact of the material onto the DIP.

7 A device substantially as herein before described with reference to and as shown in Figures 1, 2, 3 and 4 of the accompanying drawings.

For the Applicants,

Godwin Saunders & Elder
Chartered Patent Agents
SAFE, Cranfield University
Silsoe
BEDFORDSHIRE
MK45 4DT

PATENT No. - **COMPLETE SPECIFICATION**

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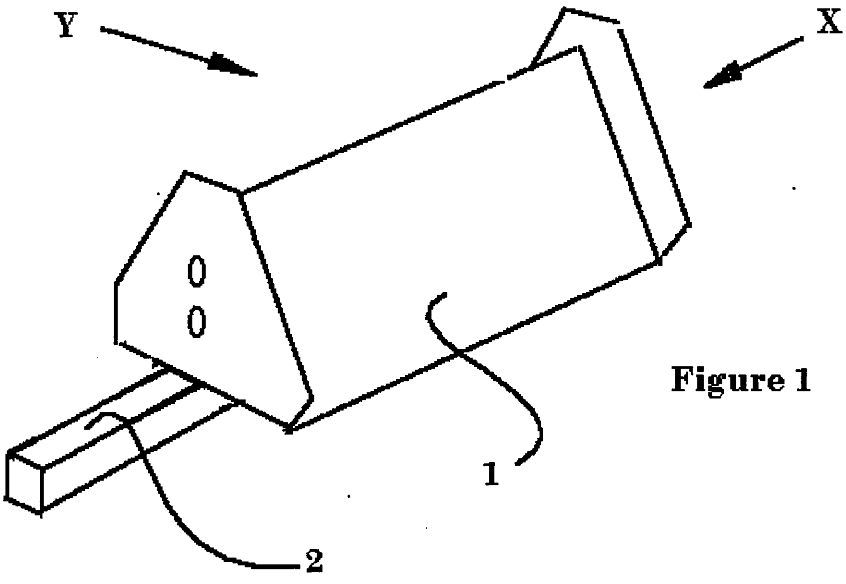
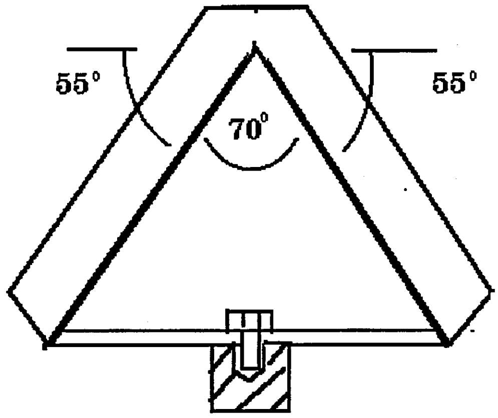


Figure 1

Figure 2



3 SHEETS **SHEET 2**

Figure 3

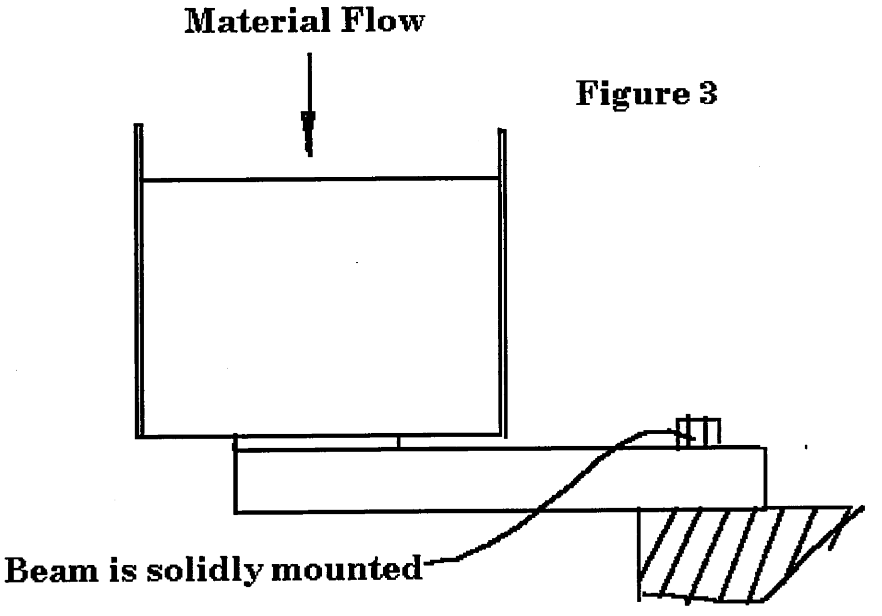
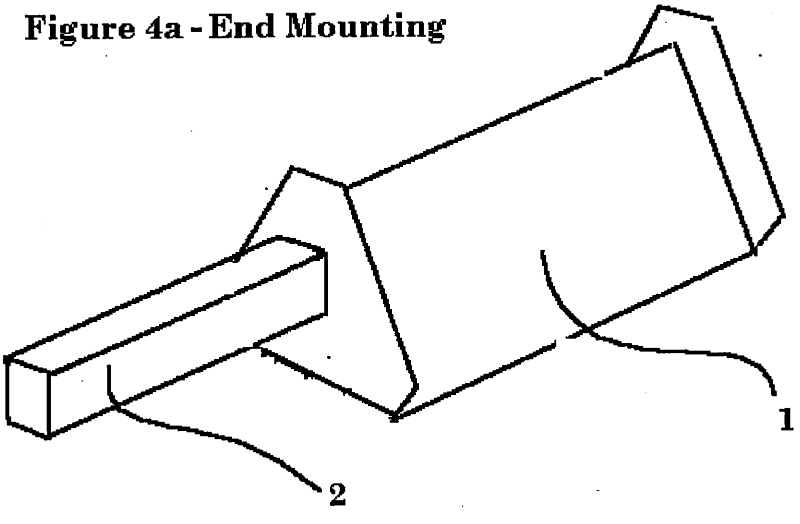
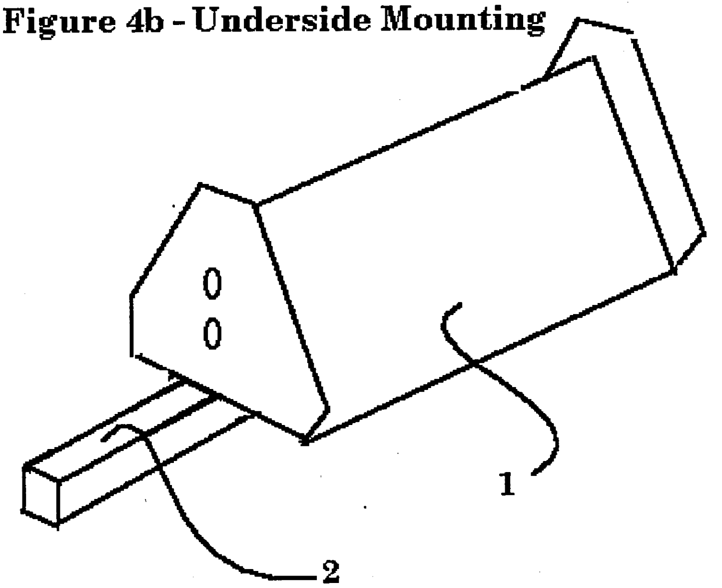


Figure 4a - End Mounting



3 SHEETS **SHEET 3**

Figure 4b - Underside Mounting



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