Development of a Laboratory Test Stand for Grain Combine Yield Monitoring

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ABSTRACT

Yield monitors come with various technical designs and features. There is a growing need and interest for research-based information about the accuracy and performance of different brands of yield monitoring systems under varying crop yield and different field conditions such as varying terrain. Therefore, a laboratory test stand facility was designed and developed. It is able to provide a wide range of grain mass flow rates and to simulate hillside conditions. The system consisted of a receiving bin that is supported by three 5000-N load cells and a supply bin. A handling system (auger-elevator combination) is used to transfer grain between supply and receiving bins. The effects of grain flow rate and elevator tilt angle simulating pitch and roll on power consumption of the grain elevator was studied. The results showed that any increase in grain flow rate and elevator tilt angle, caused a significant and proportional increase (R^2=0.99) in power consumption of the elevator. Therefore, it can be claimed that power consumption of the clean grain elevator at each tilt angle may be used as a suitable index for predicting grain flow rate through the clean grain elevator of a combine. This goal can be realized by deriving and using a multiple regression equation relating grain elevator power consumption to both grain mass flow rate and elevator tilt angle.
Keywords: *Mass flow rate, yield monitor, grain elevator, elevator tilt angle, test stand, Iran*

1. INTRODUCTION

Yield monitoring, which can be defined as, 'the measurement of the harvested crop over space and time and the summation of those measurements in graphical form' (Pierce, 1997) is the first step toward precision agriculture adoption. The yield variations across a field indicate the potential economic benefits of precise application of inputs. Yield variability is the result of variation in soil and crop variables, such as moisture, nutrients, weeds, and pests. Mapping yield is important since the prescribed rates for many inputs are determined from the expected yield goal. Crop yield could be used as an integrator of varying soil and crop variables. Various approaches have been developed and used for continuous yield monitoring. Yield monitors come with various technical designs and features. Yield sensors reported in the literature or currently available to farmers are based on a wide variety of measurement methods including a paddle wheel volume flow sensor (Schueller *et al.,* 1987; Searcy *et al.,* 1989; Schnug *et al.,* 1993), a pivoted auger (Wagner and Schrock, 1989), a capacitance sensor (Stafford *et al.,* 1991), an ultrasonic sensor (Klemme *et al.,* 1992), a strain gage-based impact sensor (Borgelt, 1993), an elevator-based flow sensor (Howard *et al.,* 1993), a gamma ray sensor (Stafford *et al.,* 1991;

Massey Ferguson, 1993), an infrared sensor (Hummel *et al.*,1995), and x-ray techniques (Arslan *et al.*, 2000).

Successful implementation of precision farming strategies depend on accurate quantification of spatial variation in crop yield within a given field. There is a growing need and interest for research-based information about the accuracy and performance of different brands of yield monitoring systems under varying crop yield and different field conditions such as varying terrain. A yield monitoring system consists of several sensors, one of which is the mass flow sensor. The mass flow sensor measures the rate of grain flow through the combine. Yield monitor accuracy has been investigated since the 1990's. Arslan and Colvin (1998) developed a laboratory test stand for combine grain yield monitors to compare the accuracy of a yield monitor to an electronic scale. Strong correlation was found between the yield monitor and the electronic scale with an R^2 of 0.99, following the calibration of the yield monitor under laboratory conditions. They observed stronger agreement when testing at higher flow rates over a longer duration.

According to Al-Mahasneh and Colvin (2000), the most reliable method of determining accuracy is to compare continuous yield monitor data with an independent reference flow rate measurement on the same grain flow path. Variation in ground slope can affect the accuracy of the mass flow sensor. Sanaei and Yule (1996) found that increasing slope adversely affected the accuracy of the mass flow sensor. The effect of tilting the elevator system on mass flow sensor accuracy was investigated by Kormann *et al.* (1998). The accuracy of combine yield monitors was observed to be significantly affected by variation in hillside conditions with yield monitor errors as high as 18.2% when harvesting uphill and 60.7% when harvesting downhill on 6 to 9% slopes (Kettle and Peterson, 1998). So far, all mass flow sensor accuracy testing has been conducted either under field conditions (Birrell *et al.*, 1996; Prez-Munoz and Colvin,1996; Kettle and Peterson, 1998; Shearer *et al.*, 1997; Al-Mahasneh and Colvin, 2000; Arslan and Colvin, 2002) or in laboratory test facilities (Kormann *et al.*, 1998; Arslan and Colvin, 1998; Arslan and Colvin, 1999; Burks *et al.*, 2003; Loghavi and Ehsani, 2004; Burks *et al*. 2004). Under field conditions, tests have been conducted on combines. The advantage is that the grain is at field moisture content, but the tests can not be replicated due to the inability of providing a constant grain flow rate or slope. Conversely, in laboratory test facilities, the advantage is that the tests can be replicated for a constant flow rate or a given slope. The objectives of this work was to build an easily transportable test rig capable of testing and evaluating the accuracy of various grain mass flow sensors which can accommodate a tiltable elevator support fixture. The test rig can be used at farm shows, extension meetings, and workshops as a teaching tool to visually enhance the understanding of the principles of yield monitoring systems. The test rig can also be used for research on and development of yield monitors. The specific objectives of this research were to use the test rig to investigate the possibility of correlating the grain mass flow rate to the power consumption of the clean grain elevator at different levels of steady-state mass flow rates. This approach could be very valuable and practical for the farmers in developing countries who can never afford the high cost of equipping their combines with the commercial yield monitoring sensors. And further to use the test rig to study the effect of simulated ground slope on power requirements of the clean grain elevator at different mass flow rates under steady-state flow by inclining the clean grain elevator in two planes simulating pitch and roll.

2. MATERIALS AND METHODS

2.1 Design and Development of the Test Rig

The mechanical components of the test rig shown in figure 1 include the frame, two grain bins, an auger-type conveyor system, a clean grain elevator and a hood housing the mass flow rate sensor. The frame is made of 80 x 80 x 5 mm rectangular steel tubing with a load capacity of 1200 kg supported on four 5.60-13 pneumatic tires (not shown in this figure). The supply bin and a receiving bin, are capable of holding about 0.68 and 0.56 cubic meters of grain (about 500 kg and 420 kg of wheat), respectively.

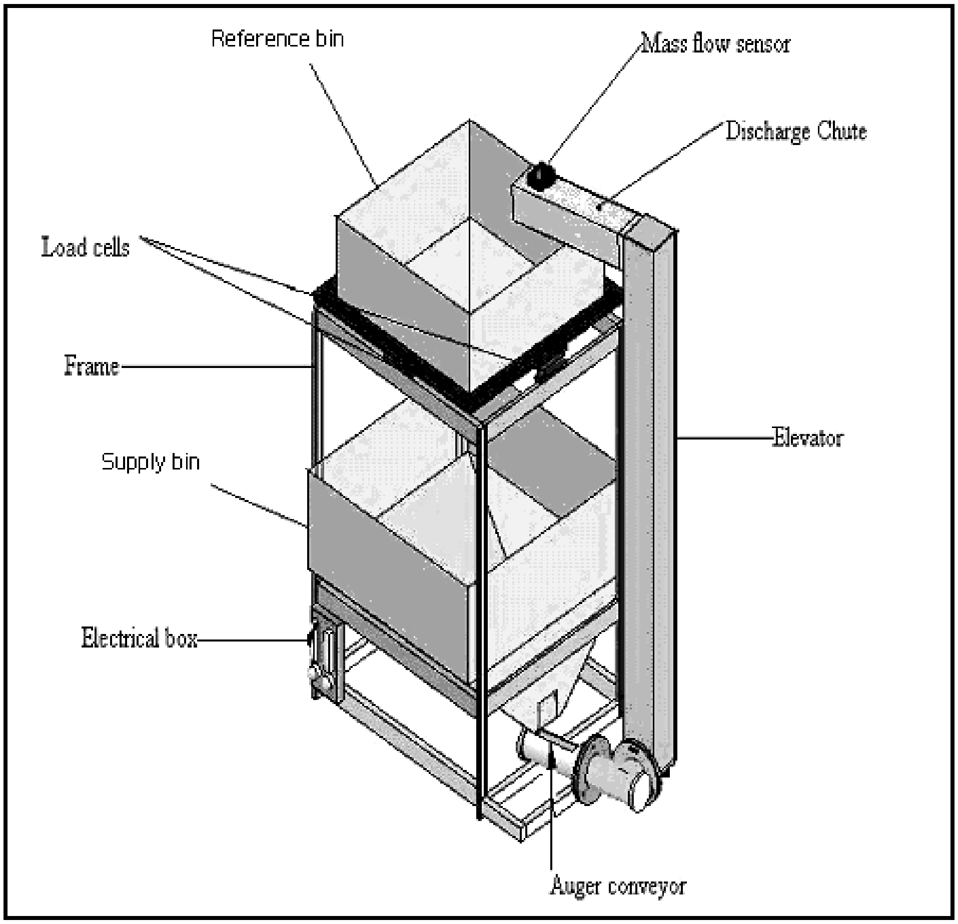

Figure 1. Schematic diagram showing mechanical components of the test rig.

In order to facilitate the grain flow out of the bins, the sides and bottom of t the bins were sloped at 30° which is greater than the angle of repose of most grains. To develop a grain metering system capable of varying grain flow rate, a vertical sliding door was provided for the rectangular orifice gate at the bottom of the supply bin (figure 2). The operator can increase or decrease the flow rate as needed by opening or closing the gate through the use of a simple lever mechanism. The mass flow rate through the gates can be varied from 0 to about 15 kg s^{-1} for wheat. A graduated scale was installed to indicate the degree of orifice opening and a series of calibration tests were conducted to establish a calibration curve relating the flow rate to the gate opening.

Figure 2. The vertical sliding door on rectangular orifice gate at the bottom of the supply bin.

For continuous yield monitoring and assessment of the yield monitors, the system needs to be able to transfer grain from the supply bin to the clean grain elevator equipped with a mass flow sensor and then to a reference system consisting of a receiving bin mounted on a scale that senses the actual weight of the grain at that point. The data from the scale can be compared to the data recorded by the yield monitor system to assess the accuracy of the mass flow sensors. The scale consisted of three load cells manufactured by TEDEA Company (model No. 3410), each having a 5000 N load capacity. Each load cell is supported as a cantilever beam by being bolted to the reference bin frame at one end and a ball and socket on the main frame as shown in figure 3. A translating screw is provided next to each ball support for unloading the load cells during transportation. The load cells are located in such a way that the center of gravity of the bin provides equal forces on them. A load cell transmitter provides a stable 10-V DC excitation voltage to the load cells with line length compensation. The load cell outputs were matched and summed in the transmitter and then sent to be displayed on a TEC-800 indicator. The display was also able to provide an RS232 output of the weight to a computer.

The cross auger assembly transporting grain from the supply bin to the grain elevator consists of a 132-mm diameter auger with a 140-mm pitch, 1.10 m of auger housing, and a 0.60m rotatable sleeve to accommodate grain elevator roll of 10° in either direction. The overall length of the cross auger is 1.75 m, consisting of 1.45 m of flighting and 0.30 m rubber paddles (figure 4), designed to flip the grain into the bottom of the elevator.

A 140×400 mm opening was cut on top of the auger housing to receive the grain flow out of the supply bin (figure 5). The auger was supported by two self-aligned bearings at the ends and was driven by a 0.5 kW single phase AC electric motor through a V-belt drive system with the speed ratio of 6:1, resulting in the final auger speed of 250 rpm.

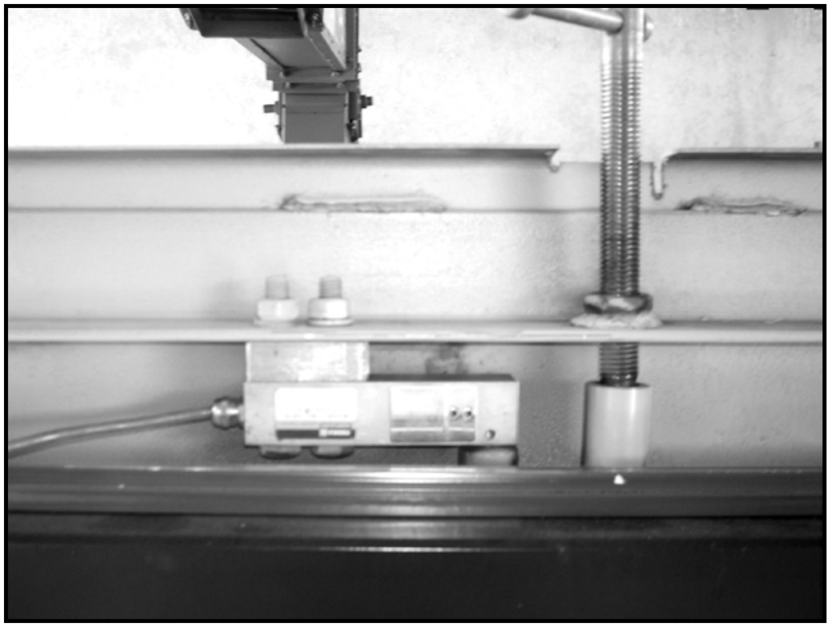

Figure 3. One of the three load cells used to measure the weight of the reference bin.

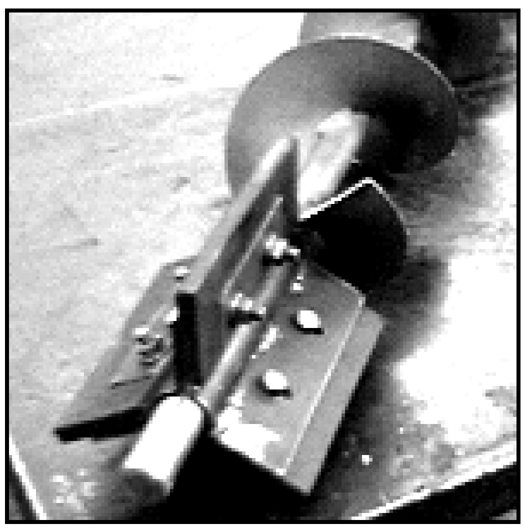

Figure 4. Rubber paddles for flipping grain into the grain elevator.

The clean grain elevator from a John Deere 955 combine was used to transfer the grain delivered by the cross auger into the reference bin and to allow simulation of a real combine in hillside conditions. The later is accomplished by tilting the elevator in a three-dimensional rotation representing hills and hillsides. To accommodate this motion, the joint between the elevator and the auger assembly should resemble a T-fitting, allowing fore and aft movement. Due to the three-dimensional motion requirements, the elevator is only supported at the base by a circular face flange on the rotating sleeve of the auger assembly. With this configuration, the elevator is simultaneously capable of pitch and yaw of 10° in either direction. The elevator could be rotated and held in any desired position by loosening and tightening two sets of three bolts on the circular face flanges at both ends of the rotating sleeve of the auger assembly. On the other side of the elevator, located on the base plate, a cantilever box with two bearings is mounted to support the lower elevator shaft and to counterbalance the forces applied on the shaft due to the tension in the elevator chain. In order to provide adjustment of the elevator chain tension, the bearings of the upper sprocket shaft are mounted on two sliding plates as shown in figure 6.

Figure 5. The opening cut on top of the auger housing to receive grain flow.

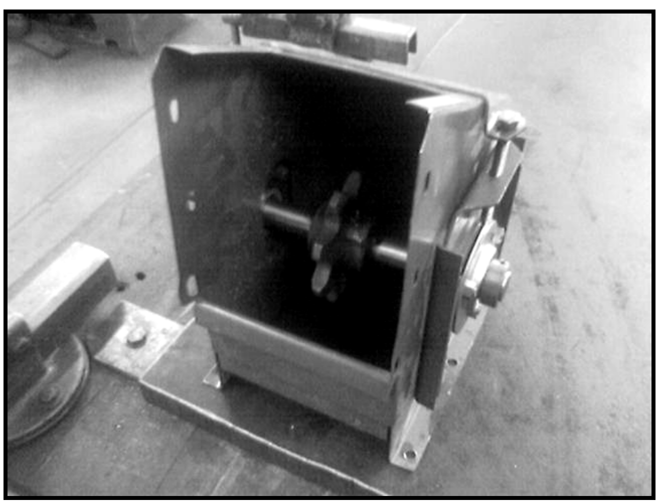

Figure 6. Mounting of the upper sprocket shaft bearings on two adjustable sliding plates.

The power requirement of the grain elevator with the maximum transporting capacity of 0.023 $m^3\,s^{-1}$ ($51 ft^3\,min^{-1}$) was calculated as 1.4 kW for handling wheat. The lower shaft of the elevator chain was driven by a 3-phase, 1.5 kW electric motor through a V-belt drive with a speed ratio of 3:1, resulting in operational speed of 450 rpm.

The grain hood at the top of the original elevator was removed and replaced with a hood made of light weight steel angle bar with clear polycarbonate side plates, capable of accommodating various types of mass flow sensors (figure 7). This enables viewers to observe the grain flow and how it interacts with the yield monitoring sensors. The length of the hood was extended long enough in order to provide possibility of discharging grain into the receiving bin when the elevator is in tilt back position.

Figure 7. The grain hood equipped with clear polycarbonate plates to allow visibility of sensors.

2.2 Test Procedure

2.2.1 Grain Mass Flow Rate Calibration

A series of calibration tests were conducted to establish a calibration curve relating the grain flow rate to the supply bin gate opening. A graduated scale, ranging from 0 (gate closed) to 20 (wide open) with 1-cm spacing was installed at one edge of the supply bin outlet next to the sliding gate to indicate the degree of orifice opening. At each height of the gate opening, at one centimeter increments, the grain flowing out of the opening during a 5-second period was collected and weighted. This test was replicated three times at each gate opening and the data was used to construct a calibration cure.

2.2.2 Reference Bin Scale Calibration

Multiple point calibration of the reference bin's electronic scale was performed according to the user’s manual, by loading the bin with accurately measured known weights in the appropriate loading range, and entering their exact values to the scale indicator. The electronic scale proved to be accurate within ±0.05% of the applied load or ±1 increment division, whichever was greater.

2.2.3 Steady State Grain Mass Flow Tests with the Elevator at Vertical Position

A series of grain mass flow tests at different levels of flow rates were conducted to investigate the possibility of correlating the electric power consumption of the grain elevator with the mass flow rate of the grain being transferred from the cross auger to the reference bin. In this stage, the grain elevator was set at vertical position, simulating grain harvesting on a flat (zero slope) field. Preliminary calibration tests showed that the maximum material handling capacity of the test stand was limited to about 6 kg s^{-1} of sample wheat at 12% moisture content. Tests were conducted at four target material flow rates including 25%, 50%, 75% and 100% of the simulator maximum flow capacity. This was in compliance with the ASABE X578 Yield Monitor Performance Test Standard. The calibration curve relating mass flow rate with the sliding gate position showed that values of the gate opening set at 4.34, 6.1, 7.9 and 9.7 cm would provide average flow rates of 1.5, 3, 4.5 and 6 kg s^{-1}, respectively which represent the above target flow rates. Each test was replicated three times. An individual steady state flow test at each of the target flow rates was run by first turning on power to the reference bin electronic scale system and the grain transport system components (auger and elevator). Then the grain metering gate of the supply bin was opened and set at the prescribed gate opening to supply the flow of wheat at the target flow rate. After about 10 seconds, when the grain flow was stabilized, the references bin scale indicator was tarred to initiate the data logging. The mass of the wheat (in kg) delivered to the reference bin during a 5-second period was read and divided by 5 to determine the actual grain mass flow rate (kg s^{-1}). At the same time, the voltage supplied to and the current drawn by the electric motor driving the elevator chain were read from the ammeter and the volt meter properly connected to the electric power circuit. The electric power consumption of the grain elevator was calculated at each grain mass flow rate by using the following formula.

$$P = 1.73 VI \cos\varphi \qquad [1]$$

Where:

P = electric power consumption in kW

V = voltage supplied to the motor (V)

I = current drawn by the motor (A)

φ = phase angle between the voltage and current

2.2.4 Steady State Grain Mass Flow Tests with the Elevator at Tilted Position

To simulate the ground slope, the grain elevator was tilted forward and backward (i.e. pitch) and sideway (i.e. roll), each at three tilt angles of 2, 5 and 8 degrees. In each tilted position, tests were conducted at the same four percentages of the maximum mass flow rate as those of the elevator vertical position tests.

3. RESULTS AND DISCUSSION

3.1 Calibration of the Supply Bin Discharge Gate

The results of the calibration tests relating the grain mass flow rate to the supply bin discharge gate opening as shown in figure 8 indicates that the discharge rate is not a linear function of the gate opening, but a polynomial function best fits the data points with a very high correlation (R^2=0.99).

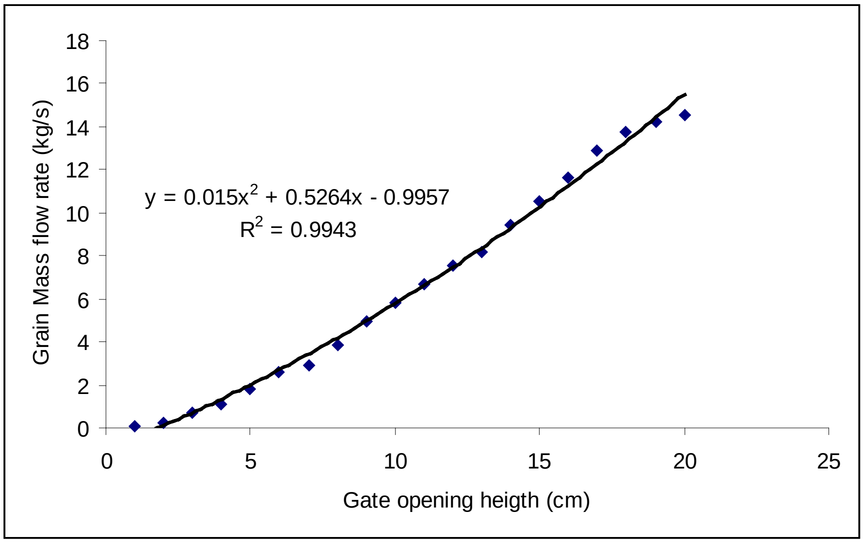

Figure 8. The calibration cure correlating grain mass flow rate with the supply bin discharge opening.

The analysis of variance of the data on elevator electric power consumption (table 1) revealed that grain mass flow rate and elevator tilt angle both had significant effect on elevator shaft power requirement.

The means of grain elevator power requirement as affected by mass flow rate and tilt angle (forward, backward and sideways) are compared in tables 2, 3 and 4, respectively. The comparisons reveal that the elevator power requirement increases significantly as mass flow rate or elevator tilt angle are increased independently or simultaneously, in either direction (forward, backward or sideways). The patterns of changing grain elevator power requirement with increasing mass flow rate at various levels of elevator tilt angle (backward) have been shown in figure 9. Similar figures can be shown for tilting the elevator forward or sideways. In figure 10 mean values of the elevator power consumption versus tilt angle at different directions show that the effect of tilt angle is highest when the elevator is tilted to either side (i.e. roll) and lowest when it is tilted forward (i.e. pitch down).

In figure 11 mean values of the grain elevator power consumption (in vertical position) have been plotted against grain mass flow rates as measured by the reference bin scale system. The high linear correlation (R^2=0.99) suggests that the measured values of elevator power consumption could be used for predicting the rate of grain mass being transferred from the cross auger to the grain bin in a combine harvester. Similar figures could be created by plotting grain mass flow rate against power consumption at other tilt angles using the data of tables 2 to 4. Figure 11 was presented as a typical representative.

Table 1. Analysis of variance for the effects of elevator tilt angle and mass flow rate on elevator power consumption.

		Mean squares		
Source	*df*	*ETF*	*ETB*	*ETS*
Tilt angle (Φ)	3	547847**	866221**	1369813**
Mass flow rate (Q)	3	2258064**	603339**	577614**
Φ × Q	9	1727**	448**	6412**
Error	30	151	48	197

** Significant at P<0.01

ETF *Elevator tilted forward*

ETB *Elevator tilted backward*

ETS *Elevator tilted sideway*

Table 2. Comparison of mean values of grain elevator power requirement (W) as influenced by mass flow rate and elevator tilt angle (forward).

	Grain mass flow rate (kg s^{-1})			
Tilt angle (degree)	1.5	3	4.6	6
0	240^{j}	450^{h}	650^{f}	846^{d}
2	351^{i}	543^{g}	747^{e}	947^{c}
5	550^{g}	743^{e}	950^{c}	1150^{b}
8	750^{e}	940^{c}	1160^{b}	1257^{a}

Means followed by the same letter are not significantly different at P<0.01 (DMRT)

Table 3. Comparison of mean values of grain elevator power requirement (W) as influenced by mass flow rate and elevator tilt angle (backward).

	Grain mass flow rate (kg s^{-1})			
Tilt angle (degree)	1.5	3	4.6	6
0	240^{k}	450^{j}	650^{h}	846^{f}
2	545^{i}	750^{g}	905^{e}	1047^{d}
5	760^{g}	952^{e}	1050^{d}	1243^{c}
8	951^{e}	1057^{d}	1253^{bc}	1443^{a}

Means followed by the same letter are not significantly different at P<0.01 (DMRT)

Table 4. Comparison of mean values of grain elevator power requirement (W) as influenced by mass flow rate and elevator tilt angle (sideway).

	Grain mass flow rate (kg s^{-1})			
Tilt angle (degree)	1.5	3	4.6	6
0	240^{l}	450^{k}	650^{j}	846^{h}
2	745^{i}	951^{g}	1048^{f}	1268^{cd}
5	960^{g}	1065^{f}	1277^{c}	1427^{b}
8	1060^{f}	1280^{c}	1453^{b}	1500^{a}

Means followed by the same letter are not significantly different at $P<0.01$ (DMRT)

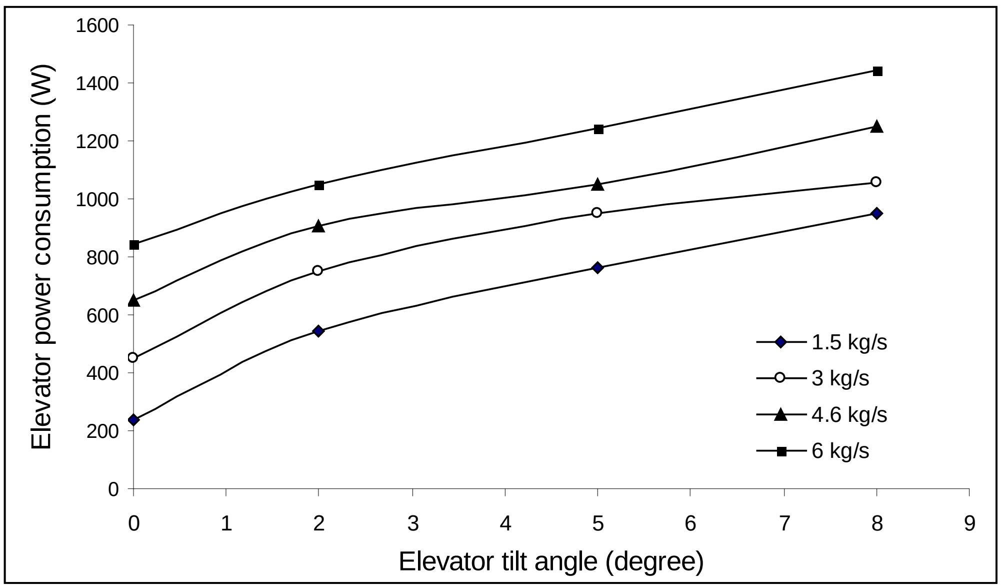

Figure 9. Grain elevator power consumption versus elevator tilt angle (backward) at different levels of grain mass flow rates.

4. CONCLUSIONS

By conducting a series of grain flow tests at different mass flow levels, power consumption of the electric motor driving the grain elevator was highly correlated with grain mass flow rate (R^2=0.99). The results also showed that any increase in tilting angle of the elevator in two planes simulating pitch and roll, caused significant and proportional increase in power consumption of the elevator at the four mass flow rates tested. Therefore, it can be claimed that power consumption of the clean grain elevator may be used as a suitable index for predicting grain flow rate through the clean grain elevator of a combine. This technique seems to be promising and in a real grain combine rotational speed and torque transmitted by the grain elevator shaft can be measured to calculate power consumption as a measure of grain mass flow rate. Of course, this approach is only appropriate for developing countries like ours in which farmers can never afford the cost of equipping their combines with expensive imported yield monitoring sensors.

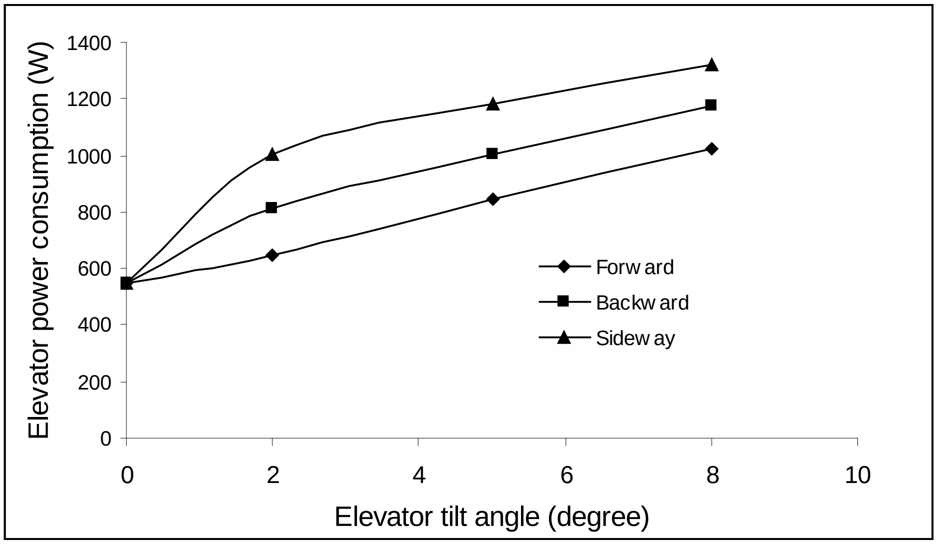

Figure 10. Grain elevator power consumption versus elevator tilt angle at different directions (forward, backward and sideways).

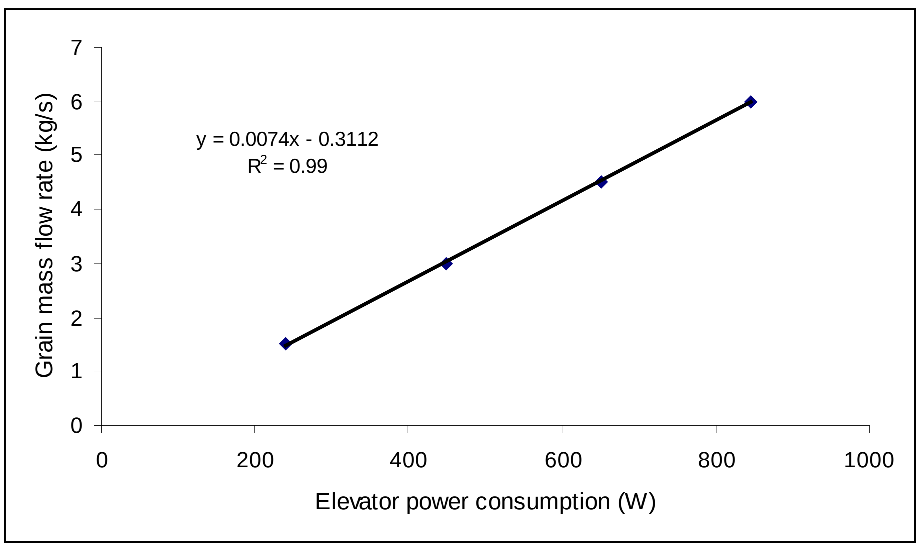

Figure 11. Grain mass flow rate as a function of elevator power consumption (Elevator in vertical position).

5. ACKNOWLEDGEMENTS

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