THE DEVELOPMENT OF AN ON-OFF CONTROL SYSTEM
FOR AUTOMATIC SWATHER AND COMBINE HEIGHT-OF-CUT ADJUSTMENT

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by

Tony L. Kaminski

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ABSTRACT

This thesis describes the development of an on-off control system which can be used for automatic height-of-cut adjustment on both swathers and combines. The system was designed to be compatible with the hydraulic and electrical systems already present on most grain harvesting machinery. It can be pre-set by the operator, so that cutter bar movement varies between any desired maximum and minimum positions.

A separate investigation was conducted to determine some of the physical properties of grain plants. The results of this investigation were applied to the design of the sensing elements in the control system.

The performance of the system was determined in the laboratory by mounting grain plants of different heights in a narrow strip around the circumference of a large rotating table. The results obtained from the laboratory study showed that the operation of this system was satisfactory for all practical combinations of ground speed, grain height and density of plant population. A more complete system was then constructed and mounted on a pull-type swather. Field tests showed that this automatic control system performed satisfactorily and could have a number of practical applications.
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1. INTRODUCTION

1.1 Grain Harvesting

Agriculture is one of Canada's most important industries and a large amount of Canada's income is derived from the production and sale of fine quality grain. The majority of this grain is produced by Saskatchewan, the leading grain growing province in Canada. Grain production is climaxed yearly by the harvesting operation.

Crops that have ripened evenly and are free of weeds are usually harvested by straight or direct combining. However, these crop conditions do not usually exist in the field. To facilitate harvesting, a large percentage of Western Canada's grain crop is cut by a swather prior to combining. Regardless of the method used, the grain is cut by a cutter bar whose height must be controlled by the operator.

Crop height usually varies considerably with terrain soil and moisture variations throughout each field. The variations in the height of a crop necessitates frequent manual manipulation of the height of cut. In the early 1940's hydraulic controls replaced the mechanical lifts on grain harvesting machinery and the task of controlling cutter-bar height was eased considerably. However, since then little has been done to improve the system of cutter bar control on swathers and combines.

1.2 Importance of Automatic Control

The continual operator attention required for proper adjustment of cutter bar height when harvesting variable-height crops is believed to be a cause of operator fatigue.
If muscles are to perform an activity properly over a period of hours, the rate at which they are used should be such that fatigue does not become apparent\(^1\). Under conditions of excessive fatigue, the motor nerves become so inactive that they cannot transmit any signals. This of course, affects the action of the muscles, since muscles react only to signals from the nerves.

To minimize grain losses it is important to have the proper height-of-cut adjustment. With higher operating speeds which are possible with modern equipment, the task of properly controlling the cutter-bar height has become more difficult. The total reaction time involved between the time the operator detects an error and the time he makes the control movement is about 1.7 seconds\(^2\). During this time, a machine travelling at 5 mph would have moved a distance of over 12 feet. This total reaction time represents a delay in achieving the desired adjustment. The operator because of neglect, fatigue or lack of time, may not make the required height of cut change and increased grain losses will result. Poor visibility of the cutter bar during night operation makes it difficult for an operator to maintain accurate cutter bar adjustment. An unskilled operator may also experience difficulty in judging what adjustments should be made to minimize grain losses.

It has been found that cutter bar grain losses are extremely high when cutting a relatively high stubble in short grain\(^3\). On the other hand, cutting a relatively short stubble reduces the cutter-bar loss but increases the separation losses. Grain losses are more fully discussed in Appendix B.

* Numbers in parentheses refer to the appended references.
1.3 Limitations of Existing Automatic Header Control System

An automatic header control system for self-propelled combines has been patented* and is manufactured in the United States by at least two companies. This device consists of a feeler system which is mounted directly below the cutter bar so that the feelers or fingers slide along the ground when in operation. The feelers are connected through a cable to control the operation of a hydraulic valve. The valve controls the oil flow to the hydraulic cylinders which in turn maintain the cutter-bar at a given distance above the ground. The cutter bar is held at a fixed minimum distance above the ground which is preset by the operator.

This unit is not suitable for use on combines in Western Canada because in these areas the farmers find it necessary to vary the length of stubble as the grain height changes.

1.4 Purpose of Project

The major objective of this project was to design, to construct and to test a control system for automatic control of swather and combine height of cut in variable height grain crops. A secondary objective was to determine some of the physical properties of grain plants to facilitate a more practical design of the control system.

The work was prompted by the fact that no known system had been devised to sense grain height. The successful development of a control system for automatic adjustment of swather or combine height of cut was considered to be a major contribution toward relieving operator fatigue and in the reduction of grain losses during harvest.

1.5 Control System Considerations

Various means of sensing grain height were considered. Initially a photo-electric system was considered.

*U.S. Pat. No. 2,750,727
No information was found on the effect of dust and of variations in density of plant population on the operation of this system. The photo-electric system was not selected for sensing grain height because of its relatively high cost as compared to other methods.

The next consideration was a system of lever-actuated micro switches operated by the grain plants. No data could be found pertaining to the magnitude of the force resulting from an object striking a head of grain. Hence it was not known whether enough grain force was present to operate a system of this kind. It was necessary to study the structure of a grain plant and to determine some of its physical properties such as weight, bending strength of the stem and the period for free oscillation of the plant. With this data it was possible to obtain various mathematical solutions for the magnitude of the impulse force resulting from an object striking the head of grain and passing over it. The mathematical solutions given in Appendix C showed that there would be sufficient force produced by two grain plants to operate a micro switch with an extended arm. An attempt was made to determine, by experiment, the magnitude of this impulse force. A cantilever beam with strain gages mounted on it, was used to measure the impulsive force of a grain plant striking the beam and passing under it. The results were recorded by an oscillograph. Unfortunately, the readings taken on the oscillograph could not be interpreted due to fluctuating values. These fluctuations were probably due to vibrations associated with the impulsive force and the fact that dynamic loading was being measured by a beam which had been calibrated with a static load.

In the control system the micro-switches were operated by impact with the grain heads and were used to control an electrically-operated hydraulic solenoid valve.
The final-control element was a hydraulic cylinder. Two basic types of hydraulic control systems were considered:

(1) Proportional hydraulic control systems - These systems are very desirable because they permit linear outputs. However, they suffer from three main limitations: complexity, unreliability, and expense(5). Servo transfer valves are used for proportional control. These valves are extremely delicate in construction and consequently expensive. The valve requires special additional equipment with its use. Improper operation occurs whenever foreign material enters the servo-valve and impedes the proper motion of the spool. These limitations did not justify the development of a proportional hydraulic control system.

(2) On-off control systems - On-off control systems are a method of control in which the desired output of an automatic control system is achieved by intermittent corrective efforts of some controlling element within the system. This control system eliminates the disadvantages present with proportional control systems and in addition provides a much faster response. The main disadvantage of on-off hydraulic control is that it does not permit a linear output.

It was decided that an on-off control system employing a hydraulic solenoid valve was more suitable for this application. The hydraulic valve required suitable solenoids to enable it to be operated with the D.C. power obtained from the battery on the tractor or combine. Also, the valve had to be of sufficient size to assure its use with conventional farm hydraulic systems. A four-way valve was necessary to operate a double acting cylinder. It was decided to incorporate a dead zone into the control system to limit the frequency of operation of the solenoid valve. This necessitated the use of a three-position spool in the valve with a spring return to the center or neutral position.
An open-center type of spool was selected because it permitted oil circulation through the valve when in the neutral position.

Relays were used because they limited the amount of current through the micro-switches. The micro-switches operated relays which controlled power to the solenoids.

A laboratory apparatus was constructed and used to determine the performance of the system in various crop conditions. The effect of wind on the operation of the micro-switches was also considered. The system was then subjected to field tests in order to determine its practical use.
2. **ON-OFF CONTROL**

2.1 **Definition of On-Off Control**

This type of control is known as discontinuous control(6). It is a method of control in which the desired operation of an automatic control system is obtained by intermittent corrective efforts by some controlling element within the system. The controller action is such that the manipulated variable is quickly changed to either a maximum or minimum value(7) as shown in Figures 1 (b) and (c). The principle of on-off control is further illustrated by the schematic diagram of Figure 2 which shows a two-position on-off control system. In this diagram, the height of the grain is sensed by one micro switch which is moved in a direction perpendicular to the plane of the paper and actuated by the force resulting from striking the grain plants. This micro switch causes the solenoid on the hydraulic control valve to be suddenly energized and then de-energized. The correction signal in this system has two distinct values as the top of the grain passes above and below the lever arm of the micro switch. This results in a non-linear movement of the final control element, the hydraulic cylinder.

2.2 **Two-Position On-Off Control**

The expression "two-position control" refers to the two position or values which the manipulated variable can assume. In operation two-position control is very simple, but in theory the action is hard to analyze because of the discontinuous nature of changes in the manipulated variable. There are two forms of two-position control.

2.2.1 **Two-Position Control Without Dead Time** *

This form of control uses only positive and negative corrections

* A delay between two related actions caused by a dead zone
as required and is shown graphically in Figure 1 (b). An automatic control system employing this form of control is illustrated by the height-of-grain sensing system in Figure 2. In this type of system the components never remain at rest(7) and there is continuous corrective action. In Figure 2 the micro switch moves in a direction perpendicular to the standing grain. The micro switch operates a relay which controls power to a hydraulic solenoid valve. The lever arm of the micro switch hunts continuously about the top of the grain plants. When the lever is above the grain, the switch contacts are closed, the solenoid is energized and the resulting cylinder action causes the micro switch to lower. As soon as the lever of the micro switch strikes the top of grain plants, the switch contacts are opened, the solenoid is de-energized and the cylinder action results in the raising of the micro switch. This form of control is simple but results in excessive operation of the elements comprising the system.

2.2.2 Two-Position Control With Dead Time

In this form of on-off control the corrective signal is zero when the control signal is less than some critical value and becomes a definite value when the control signal exceeds the critical value as shown in Figure 1 (c).

A two-position temperature-controlled process is illustrated in Figure 3. The controller is a thermostat with electrical contacts that connect when the temperature drops a certain number of degrees, then after sufficient heating the electrical contacts will break again. When the temperature is between these two limits there is no corrective signal produced, with a resulting dead zone in the system(8). These contacts control the electrical circuit which energizes the heater element and
thereby regulates the heating of the bath. This type of action is illustrated in Figure 1 (c). The actuating signal is the mechanical motion of the bimetallic strip, induced by the decrease in temperature. There is positive or forward correction, but no negative or reverse correction.

2.3 Three-Position On-Off Control

This form of control is used partly to eliminate the power loss, but mainly to eliminate the inherent hunting characteristic of the two-position positive-negative type of on-off control.

The characteristic curve of a three-position on-off element is shown in Figure 4 (b). The correction signal can be one of any three values. The signal can be positive, zero or negative. Between the positive and negative corrective signals lies an inactive or dead zone in which no corrective signal is produced. When the limits of this dead zone are exceeded, a corrective signal in either the positive or negative direction is applied to the system.

The two-position on-off control system shown in Figure 2 has been changed into a three-position on-off control system and is shown in Figure 5. Both systems are being used to sense grain height. The three-position system requires the use of two micro switches, two relays and a double solenoid valve. A dead zone exists in the system. If the top of the grain plant is located between the two lever arms of the micro switches there is no corrective signal produced. The lower micro switch is held open by the force of the grain plants and the upper micro switch is normally open. When the top of the grain is below the lower micro-switch, a negative signal is produced and the micro switches are lowered by the hydraulic cylinder until the lever of the lower micro switch strikes the grain plants. A positive signal is produced if the top of the grain is above the upper
micro-switch lever. This results in the raising of the micro switches.

In three-position control the presence of a dead zone reduces the frequency of operation of the elements and produces an inherent error in the control system. This form of control does however provide both negative and positive corrections.

2.4 Advantages of On-Off Control

On-off control systems have wide industrial and domestic use because they are simple, cheap, reliable and fast acting.

On-off control systems employ a fewer number of components as compared to a linear continuously-acting control system. The components used in on-off control systems are simpler in design and construction than required in linear systems. This fact of employing a fewer number of simpler components results in lower initial costs and lower maintenance costs for the on-off system.

There is better utilization of power in an on-off control system. Full power is applied to the final-control element during corrective action by the on-off system, whereas in a linear system there is a gradual increase in the power applied during a corrective action. The result is that an on-off system produces faster corrective action than a linear system.

2.5 Disadvantages of On-Off Control

On-off control systems have a number of disadvantages, one of which is that their use seldom results in smooth control performance because of the abrupt action of the manipulated variable. The sudden large withdrawal of energy from the power source may also be undesirable. In addition the frequent and violent operation of the system may result in considerable wear and tear of the control system.
Another disadvantage is that a dead zone has to be incorporated into the control system if continuous hunting of the system is not permissible. This dead zone results in a range of error in which no correction is made. In two-position action the correction cannot be exact and must be either greater or less than exact (8). Thus an inherent error is present in the control system.

In theory on-off control is difficult to analyze because of the discontinuous nature of the changes in the manipulated variable. The mathematical methods available are not simple and can only be used for the analysis of very simple control systems.
3. **DESIGN AND CONSTRUCTION OF LABORATORY APPARATUS**

3.1 **Overall Design Considerations**

It was decided to use a three-position control system, of the type shown in Figure 5, for the laboratory apparatus. This decision was based on the fact that this type of system was simple and durable.

Grain plants of various heights and arranged to represent different plant densities were placed on a rotating table. This simulated grain field was used to test the operation of the control system under varying crop conditions. The complete laboratory set-up is shown in Figure 6 and additional views of the apparatus are shown in Figures 7 and 8.

As can be seen from Figure 6, the apparatus consisted of a hydraulic section, an electrical section, a mechanical linkage and a simulated grain field. The hydraulic section consisted of a hydraulic pump driven by an electric motor, a solenoid valve, various lengths of hydraulic hose, a hydraulic cylinder and an oil filter. The electrical section consisted of two micro switches, two relays, two condensers, a control box and a battery. The mechanical linkage was a simple lever pivoting about an upright frame. The simulated grain field consisted of three rows of wheat mounted around the outer edge of a rotating table.

3.2 **The Hydraulic System**

3.2.1 **The Hydraulic Pump**

A Saginaw power steering pump equipped with an oil reservoir and pressure relief valve was obtained in the laboratory and used in this apparatus. The pump was driven by a one h.p. electric motor and was rated at 2.5 gpm at pressures up to 900 psi.
This pressure was more than necessary to do the small amount of work applied to the system.

3.2.2 **The Hydraulic Cylinder**

A Dowty double-acting hydraulic cylinder was used in the hydraulic system. The cylinder had a 2 3/8 in. bore and 7 1/2 in. stroke with a capacity of 4040 lbs. at 1000 psi oil pressure.

3.2.3 **The Oil Filter**

A Char-Lynn Model 240 full flow, in-line oil filter was used in the hydraulic circuit to remove any particles from the oil which might impede the operation of the control valve.

3.2.4 **The On-Off Hydraulic Control Valve**

It was necessary to select and purchase a hydraulic solenoid valve which could be used for both the laboratory and the field tests. A large control valve had to be selected because most tractor hydraulic systems have ratings of 10 to 12 gpm in the 1000 to 2000 psi pressure range and the valve had to be sized accordingly. In addition this valve had to be a three-position, four-way type with open center ports to allow oil circulation through the valve when in the neutral position.

The control valve that was selected was a Beckett Harcum Model B2A-3S, 3/8 in. four-way, three-position solenoid valve, complete with number four spool and 12 volt D.C. solenoids. Its maximum operating pressure was 2000 psi. and its power requirement was 36 watts (3 amps at 12 volts D.C.). A schematic diagram of the valve and the appropriate J.I.C.* symbol are shown in Figures 9 (a) and (b) respectively.

*J.I.C. refers to the Joint International Conference on Hydraulics.
Two solenoids, one on each end of the valve, move the spool to its operating positions. When neither solenoid is energized, the spool is returned by springs to its centre position. The spool travel is $\frac{1}{4}$ in. on each side of center when a solenoid is energized. The time required for valve movement was stated by the manufacturer to be 16 milliseconds. The manufacturer's specifications for the head loss through the directional control valve is shown in Figure 10.

3.3 The Electrical System

3.3.1 The Micro Switches

General-purpose lever-actuated micro switches were selected because of their low cost and low operating forces. A Unimex ZHBT-1 S.P.D.T. switch and a Licon switch of the same type were used in the electrical system. These switches required maximum operating forces of 1 to $2\frac{1}{2}$ oz. and had a spring to return the lever to its normal position. The switches were rated $\frac{1}{2}$ amp. at 125 volts D.C. Two 10-inch lengths of spring steel bars were used to extend the lever arms already present on the switches. One bar was $\frac{1}{32}$ in. by $\frac{1}{8}$ in. in cross section and the other one was $\frac{1}{32}$ in. by $\frac{1}{16}$ in. in cross section. These two different widths were employed so that the effect of wind on the operation of the switches could be determined. The switches were mounted so that one was two inches above and one inch ahead of the second switch. The difference in height provided a dead zone to the system.

3.3.2 The Relays

The high power requirement of the solenoids would have limited the life of the contacts in the micro switches and hence the micro switches were not used to directly control the operation of the solenoids.
This problem was overcome by employing two relays in the electrical circuit as shown in Figure 11. Two Potter & Brumfield type KL11D 12 volt relays were used. These general-purpose, multiple-contact relays were selected because they could be adapted for other purposes. The coil resistance was 11/0 ohms and their power requirement was 1.1 watts. The silver contacts were DPDT and rated at 5 amps. The use of these relays resulted in a maximum current flow of less than 1/10 amp. through the micro switches.

3.3.3 Additional Electrical Accessories

Power was supplied to the electrical circuit by a 12 volt storage battery. A five amp. fuse was placed in the main power supply line to protect the various components of the circuit. Two toggle switches were used so that manual or automatic control could be employed in the system. A two-position on-off toggle switch was employed as shown in Figure 11 to provide manual or automatic control of the system. A three-position on-off-on toggle switch was used to control the two solenoids when the system was placed on manual control.

Operation of the control system revealed considerable arcing across the contact points of the relays. This arcing was almost completely eliminated by using condensers which were sized by trial and error.

3.4 The Mechanical Support

A mechanical arrangement was used to relate cylinder movement to the positioning or control of the micro switches. The linkage, as shown in Figure 7, was such that it permitted greater micro-switch movement for a certain amount of cylinder movement. This was required so as to compensate for the low capacity hydraulic pump which was used in the laboratory control system.
3.5 Simulated Grain Field

Two 4 ft. by 8 ft. sheets of 3/4 in. plywood were used to construct a circular table 8 ft. in diameter. A large diameter table was used so that for a given linear velocity the centrifugal force on the grain plants was very small when the table was rotated, and little bending of the plants resulted. The table was mounted on a steel frame and was coupled directly to an 80:1 worm-gear speed reducer. Power was supplied by a 1/3 hp electric motor with a multiple-sheave V-belt pulley which permitted various operating speeds of the table.

The grain plants were supported by a perforated framework placed on the outer edge of the table. This framework consisted of 2 layers of 1/4 in. plywood separated by small pieces of 3/4 in. plywood. The stems of the grain plants were placed in 9/64 in. diameter holes which were drilled through the two pieces of 1/4 in. plywood.

The laboratory tests were conducted during the spring season and hence it was impossible to obtain mature grain plants from a field. However the Field Husbandry Department at the University of Saskatchewan was able to provide sheaves of club wheat which had been cut in the Fall of 1961 and then stored in a shed. This grain was taken and sorted by hand and the plants having relatively straight stems were retained and grouped according to their length. The plants varied in length from about 18 to 30 inches, consequently it was possible to obtain net grain heights of 16 to 28 inches for the tests.

It was difficult to determine what grain plant densities should be used in the laboratory experiments. Grain yield is determined both by the number of tillers produced and by the number of kernels present in each head. It was finally decided to use 1½ plants per square foot to
represent a light crop, 22 plants per square foot to represent an average crop and 30 plants per square foot to represent a heavy crop. This decision was based on the fact that the heads on the wheat plants used, contained an average of 20 kernels per head. Thus these densities of plant population represented crop yields of 10 to 12 bus./acre, 18 to 20 bus./acre and 25 to 30 bus./acre, respectively.
4. DESIGN AND CONSTRUCTION OF FIELD CONTROL SYSTEM

4.1 Design Considerations

The control system which was constructed for the laboratory tests had to be altered considerably before it could be used in the field test. The laboratory system was unstable because the lower micro switch was normally closed and one solenoid was energized to cause lowering of the hydraulic cylinder. A system of this kind, if used in the field, has to be manually controlled when the switches are removed from the grain or if there was no relative motion between the switches and the grain plants. Another switch had to be used to provide power to the control system only when the micro switches were moving in some grain.

It was difficult to establish the optimum stubble height for various grain heights. A detailed discussion of grain losses in harvesting is given in Appendix B. For windrowed grain, the stubble height should be about 1/3 the total length of the straw (10). The conclusion reached by one experimental station (3) was that to have minimum grain losses the stubble height should be 1/3 the total length of the straw, for average to heavy crops, and approximately 1/4 the total length of the straw, for thin straw-broken crops. The field tests with the automatic control system were done in a plot of oats having large variations in height. For these tests, the height of cut for different lengths of grain are those as shown in Figure 12.

Arrangements were made with the Field Husbandry Department at the University of Saskatchewan to use a conventional pull-type swather. The power source was a Fordson Major diesel tractor.

The design of an appropriate control system and of a suitable mechanical mounting for the swather was next considered.
As can be seen in Figure 12 the micro switches following the top of the grain had to move about three to four times the distance the cutter bar moved. It was decided to use a simple mechanical linkage which followed along the ground and provided the required micro-switch movement. The complete sensing unit was mounted ahead of the cutter bar.

An average height of grain was sensed by the system since two micro switches were used on each side of the mechanical linkage. Limit switches for maximum and minimum cutting heights were operated by the position of the mechanical linkage. Two other switches were required in the control system. One was used to control the operation of the automatic system and the other was used as a safety switch to prevent the cutter bar from striking the ground.

The control signal from these on-off sensors was used to operate a hydraulic solenoid valve. Oil from this valve was directed to the hydraulic cylinder to control the cutter bar height. Under varying crop heights the mechanical linkage followed along the ground surface and automatically maintained the proper height ratio, standing grain to stubble.

A control box was mounted on the tractor and provided a manual override so that the operator could manually control the hydraulic system at any time, if desired.

4.2 Detailed Description of the Control System

4.2.1 Micro Switches

The sensing unit, which was mounted ahead of the cutter bar, contained eight lever actuated micro switches as shown schematically in Figure 13. Ten-inch lever arms, made of 1/32 in. by 1/16 in. spring steel bars were used on micro switches 1, 2, 3, 4 and 5. Laboratory tests showed that these switches were operated easily with the force
developed by moving them through the standing grain plants at conventional operating speeds. These eight switches were general purpose Unimax switches which required a maximum operating force of five ounces.

Switch 5 was normally open and was connected in series with the main power supply line as shown in Figure 11. This switch was located ahead and below switches 1, 2, 3 and 4. The purpose of switch 5 was to close the circuit and thus place switches 1, 2, 3 and 4 into operation for automatic height control. Switch 5 was located ahead of the other switches so that it closed as soon as the switch moved in the grain crop, and opened when the swather stopped moving or came out of the grain.

Switches 3 and 4 were normally closed and were connected in parallel with the lowering circuit of the system. Switches 1 and 2 were normally open and were connected in series with the raising circuit. Two switches were used in each circuit so that an average height of grain was sensed.

As soon as Switch 5 strikes some grain it closes the circuit and the hydraulic cylinder lowers the swather platform until the grain strikes both switches 3 and 4 to open the lowering circuit. The system will then be stationary. When the grain plants become taller to close both switches 1 and 2, the swather (cutter bar) is raised by means of the solenoid valve directing oil to the hydraulic cylinder. The swather platform rises, lifting both its cutter bar and micro switches 1 and 2 until the grain plants no longer strike these two switches.

Switches 1 and 2 were located above and slightly ahead of switches 3 and 4. The difference in height between switches 1 and 3 or 2 and 4 provided a dead zone which made the system inactive within this set range of grain height. The greater the dead zone selected, the less frequent was the on-off operation of the hydraulic solenoid valve.

It is desirable when cutting grain to limit the stubble height within a certain range. Minimum stubble height is usually considered to be
from 5 to 6 inches while maximum stubble height is about 10 to 12 inches regardless of how tall the grain crop becomes.

Switch 6 was normally closed and was placed in series with the raise circuit as shown in Figure 14. The position of this switch is initially set or adjusted by the operator and is used to control the maximum height of stubble. This switch was used to open the raise circuit and prevent the cutter bar from lifting above the desired maximum height (12 inches), although switches 1 and 2 are still closed by contact with the grain.

Switch 7 was normally closed and was placed in series with the lowering circuit. The purpose of this switch was to control the minimum height of stubble. In the case where the grain height suddenly decreases, the swather lowers since switches 3 and 4 are normally closed. In order to maintain the minimum stubble height of about 5 inches where the grain was short (say less than 2½ inches) it was necessary to stop the lowering action at the desired minimum cutter bar height with switch 7 rather than allow the machine to continue to lower until switches 3 and 4 encounter the grain.

Switch 8 was normally open and was placed in parallel with the raising circuit as shown in Figure 14. This switch acted as a safety switch to prevent the cutter bar from striking the ground in rough topography. For example, if the swather was operating at its minimum set height of cut of five inches and one wheel dropped into a hole or depression, switch 8 will close the raise circuit and the machine will raise until switch 8 is again open.

4.2.2 Mechanical Support for the Sensing Unit

A mechanical linkage was used in front of the swather to provide the required micro switch movement as the cutter bar position was changed.
The mechanical linkage consisted of a support arm attached to the swather and a movable lever arm with a heavy narrow shoe at the lower end made to slide along the ground. The upper end of this lever arm was used to support micro switches 1, 2, 3, 4, and 5 (see Figure 13). A design procedure for constructing the mechanical linkage and for determining the location of the sensing unit is given in Appendix D. Various holes were drilled in the movable lever arm so that the location of the pivot point could be altered to permit the required relationship between the upper micro switch movement and the cutter bar movement. The support arm with switches 6, 7, and 8 was bolted directly below the cutter bar. A grain divider was required on the front part of this support arm to prevent uncut grain from being run over by the shoe. Increased grain losses would result if uncut grain plants were left standing in the field.

4.2.3 The Hydraulic System

The hydraulic system is shown in Figure 15. A 3/8 in. four-way, three-position hydraulic solenoid valve with 12 volt D.C. solenoids was used to direct oil flow from the hydraulic pump to a standard 3 in. by 8 in. hydraulic cylinder which raised and lowered the cutter bar. Other component parts of the system included an oil filter placed in the return line to the hydraulic pump and hydraulic couplings used so that this hydraulic system could be easily attached to the hydraulic system on the tractor. The hydraulic control valve on the tractor was held in an open position to permit continuous oil flow to the hydraulic solenoid valve.

4.2.4 The Control Box

A control box consisting of two toggle switches, a fuse holder, two alligator clips, two relays, two condensers and necessary lead wire,
was mounted beside the tractor seat (see Figure 14). The two alligator clips were used to obtain power from the tractor battery whereas the two toggle switches were used so that the operator could manually control the cutter bar height. The two-position on-off switch was used to maintain either manual or automatic control and the three-position on-off-on toggle switch was used to manually control the hydraulic solenoid valve. Two 12-volt relays were used to limit the current flowing through the micro switches and condensers were used to reduce arcing across the points of the relays.

4.2.5 Economics of the Field Control System

The cost of the complete control system was approximately $190.00 of which $154.00 was for the hydraulic solenoid valve. The wholesale cost on original equipment manufacturer (O.E.M.) price to a manufacturer should be about half of this amount, i.e. approximately $100.00. There is little labor required in the assembly of the control system since only a few simple components are used. Also, no machined parts are required.

The initial cost of a new swather will range from $1,000.00 to $3,500.00 depending on the size of the unit and whether it is a pull-type or a self-propelled unit. A new combine will cost from $5,000 to $11,000.00 depending upon its size and type. Hence, the cost of this automatic height of cut control system is only a small percentage of the initial cost of the machine.

4.3 Field Tests

The control system was mounted on a pull-type swather and its performance was tested in a field of oats on the University of Saskatchewan farm. This crop was of average yield with the height of stand varying from 16 to 50 inches. The field had a considerable number of straw-broken oat plants.
5. EXPERIMENTAL EVALUATION

5.1 General

In the development of a new automatic control system it was necessary to evaluate experimentally the performance of the system. Careful evaluation provided the basic information necessary to determine what functions the control system could perform satisfactorily. It was felt that the success of this control system depended mainly upon the effectiveness of grain plants for controlling the actuation of the micro switches and thus it was necessary to check the performance of the control system by subjecting it to a wide range of operating conditions.

The tests conducted in the laboratory with the rotating grain table consisted of observing the overall performance of the control system when subjected to a moderate slope in grain height. Further tests were conducted to determine the type of control which could be obtained in the various grain conditions.

These laboratory tests were designed to determine how accurately the system could sense grain height in various grain conditions when operating at different forward velocities. Since a relatively large lever arm was used on the micro switches, it was also necessary to determine the effect of wind on this lever arm as it affected the operation of the micro switches.

After the laboratory tests were completed, the control system was modified and adapted to a conventional grain swather. Various field tests were conducted to determine the overall field performance of the control system.
5.2 Laboratory Testing Procedure

The preliminary laboratory tests were designed to determine the overall operating characteristics of the control system. These tests were conducted using three rows of wheat plants mounted to represent a plant density of 30 plants per square foot (2 in. by 2 1/2 in. plant spacings). These grain plants were mounted so that there was a uniform height variation in the grain crop equal to one inch per linear foot of travel (+ 9% slope). The mean circumference of the rotating table was 24 feet, hence the grain height increased from 16 inches to 28 inches around one half of the table, then decreased from 28 inches back down to 16 inches in the second half of the table circumference.

A multiple sheave pulley used on the electric motor made it possible to operate the grain table at four speeds; 2 1/2 mph., 3 1/2 mph., 4 3/4 mph., and 5 3/4 mph.

Further laboratory tests were conducted with uniform heights of grain. Three series of tests, employing grain heights of 16 inches, 22 inches and 28 inches were carried out. In each series of tests, different densities of plant population and various table speeds were used.

The first series of tests consisted of using wheat plants 16 inches long placed at spacings to give a plant density of 30 plants per square foot (25-30 bus/acre). Then, the table was operated at one of the four speeds. These tests were run starting with the slowest table speed, then increasing the speed in steps until the maximum speed was used. After the table was placed in motion, the manual control was used to lower both micro switches until the lever arm of the upper switch was at least two inches below the top of the grain, then the system was placed on automatic control. The upper micro switch, which is normally open, becomes closed by the force of the grain and causes the hydraulic cylinder to raise the
sensor unit until the grain has insufficient force to actuate the upper micro switch. The position of the upper micro switch was then recorded. This distance was called the minimum height of the upper micro switch for open contacts. If this distance was decreased, then the contacts of the upper micro switch would become closed again and raising would result.

After the grain population of 30 plants per square foot was subjected to all four table velocities, the grain population was reduced to 22 plants per square foot (18-20 bus/acre) and then finally to 14 plants per square foot (10-12 bus/acre). Twelve test runs were made with each grain height.

The same series of tests were conducted with a grain height of 22 inches and finally with a grain height of 30 inches.

Further laboratory tests were conducted to determine the effect of wind on the operation of the micro switches. One micro switch had a lever arm which was 10 inches long, 1/16 in. wide and 1/32 in. thick. The other micro switch had a lever arm of the same length and thickness, but it was twice as wide i.e. 1/8 in. wide. Both switches required the same operating force to be actuated. A blower was used to provide air of sufficient velocity, over the entire length of the lever arm, to actuate the switch having the wider lever arm. The air velocity was measured with an Alnor velocity meter. The micro switch with the narrower lever arm was also subjected to the same air velocity to observe the effects. The experimental results obtained are discussed later.

5.3 Field Testing Procedure

The control system was mounted on a Cockshutt No. 4114 nine-foot, pull-type swather. A Fordson Major diesel tractor was used to pull the swather and also to provide electrical and hydraulic power to the control system.
The field tests consisted of operating the system in the variable height grain crop and carefully observing the complete operation. The pivot point on the mechanical linkage was adjusted so that the desired stubble height (see Figure 12) was obtained.

5.4 Discussion of Laboratory Experimental Results

Preliminary laboratory tests showed that the on/off control system performed satisfactorily. The two micro switches were easily actuated by the impact of their lever arm with the grain plants and they were able to follow the changes in grain height (+ 9% slope) very well when the table was operated at 2 1/2 mph. However, when the table was operated at a speed of 3 1/2 mph., there was a slight lag in the control system when following the increasing grain height or positive slope. This lag was caused by the low capacity pump used in the hydraulic system. Higher table speeds resulted in increased system lag. This lag was smaller when the system followed decreasing grain height or a negative slope because the hydraulic system provided faster cylinder movement in this direction.

Most of the laboratory tests were done to determine how accurately the system could sense various heights in different densities of plant population and moving at various forward velocities. The results of these tests are given in Tables 1, 2 and 3 (page 28) and graphical representations are shown in Figures 16, 17 and 18.

In Figure 16, a grain height of 16 inches was used for the tests. The figure shows that the upper micro switch was more easily actuated at higher operating speeds and in denser plant populations. This same relationship was also true for the lower micro switch. It should be noted that if there is sufficient force present to actuate the upper micro switch, then there is more force than is necessary for the actuation of the lower micro switch.
Table 1: Minimum Height of Upper Micro Switch For Open Contacts in Grain 16 Inches High (inches)

<table>
<thead>
<tr>
<th>Table Speed</th>
<th>Density of Plant Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>mph.</td>
<td>1½ Plants/ Ft.²</td>
</tr>
<tr>
<td>2 1/2</td>
<td>14.5</td>
</tr>
<tr>
<td>3 1/2</td>
<td>14.8</td>
</tr>
<tr>
<td>4 3/4</td>
<td>15.0</td>
</tr>
<tr>
<td>5 3/4</td>
<td>15.1</td>
</tr>
</tbody>
</table>

Table 2: Minimum Height of Upper Micro Switch For Open Contacts in Grain 22 Inches High (inches)

<table>
<thead>
<tr>
<th>Table Speed</th>
<th>Density of Plant Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>mph.</td>
<td>1½ Plants/ Ft.²</td>
</tr>
<tr>
<td>2 1/2</td>
<td>20.0</td>
</tr>
<tr>
<td>3 1/2</td>
<td>20.6</td>
</tr>
<tr>
<td>4 3/4</td>
<td>21.0</td>
</tr>
<tr>
<td>5 3/4</td>
<td>21.2</td>
</tr>
</tbody>
</table>

Table 3: Minimum Height of Upper Micro Switch For Open Contacts in Grain 28 Inches High (inches)

<table>
<thead>
<tr>
<th>Table Speed</th>
<th>Density of Plant Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>mph.</td>
<td>1½ Plants/ Ft.²</td>
</tr>
<tr>
<td>2 1/2</td>
<td>26.0</td>
</tr>
<tr>
<td>3 1/2</td>
<td>26.6</td>
</tr>
<tr>
<td>4 3/4</td>
<td>26.8</td>
</tr>
<tr>
<td>5 3/4</td>
<td>27.0</td>
</tr>
</tbody>
</table>
The results in Figure 16, showed that when the system was operated at a low speed of 2\(\frac{1}{2}\) mph and in a poor crop represented by a plant population of 14 plants per square foot (10-12 bus./acre), then the upper micro switch lever had to strike the grain plants 1\(\frac{1}{2}\) inches below the top of the heads before it obtained enough force from the grain for actuation. On the other hand, if the same system was operated at 5 3/4 mph, in a heavy crop as represented by a plant population of 30 plants per square foot (25-30 bus./acre), the upper micro switch was actuated as soon as its lever arm was positioned just below the top of the heads of the grain. Similar results are shown in Figures 17 and 18. In these figures curves are given to show the performance of the control system in grain heights of 22 and 28 inches respectively. No significant changes in control system operation were noted in the various grain heights. However in taller grain plants it can be seen from Figures 17 and 18 that when the system was operated at a slow speed of 2\(\frac{1}{2}\) mph, in a poor crop, the upper micro switch had to strike the grain plants more than 2 inches below the top of the head before it was actuated by the impact of the grain plants against the lever arm.

These graphical representations showed that the control system can perform satisfactorily in various grain conditions and at different travel speeds. In thin crops or at low operating speeds the micro switch has to drop further below the top of the grain before its lever arm obtained enough force from the grain plants to actuate the switch. The control system operated with less lag in dense grain and at higher operating speeds.

In the laboratory experiments used to determine the effect of wind on the operation of the micro switches, it was found that an air velocity of
30 mph. was sufficient to actuate the switch with the lever arm 1/8 in. wide. The same air velocity of 30 mph. on the narrow lever arm (1/16 in. wide) produced little or no effect. It was thus decided that lever arms 1/16 in. wide and 1/32 in. thick should be used in the field tests to prevent any interference by the wind.

5.5 Discussion of the Field Tests

In the initial field test, the abrupt action of the hydraulic cylinder caused by the on-off corrective action, produced excessive vibration of the mechanical linkage. To remedy the excessive vibration an additional brace was placed below the platform of the swather and was used to strengthen the means of support for the mechanical linkage. The initial sensor unit tested had no grain divider mounted on its front section and a wheel was used on the lower end of the lever arm to follow the ground. This resulted in a narrow strip of grain being left uncut behind the swather. To remedy this situation the small wheel in front of the cutter bar was replaced by a thin steel shoe which slid along the ground between the grain plants. Further field tests showed that this was not a satisfactory solution. The field operation was improved considerably but there was still some uncut grain being caused by the sensor unit being mounted ahead of the cutter bar.

Closer observation revealed that there were a considerable number of straw-broken grain plants in the test field. The sensor unit passed over these plants and they remained uncut. It was then decided that a large grain divider should be mounted ahead of the sensor unit. This grain divider was constructed to operate with its point close to the ground.
This action raised the broken or leaning plants and separated them before they were run over. Further field tests showed that the addition of the grain divider prevented grain plants from passing below the cutter bar and thus being left in the field uncut. Figure 19 shows the complete sensor unit mounted on the swather and Figure 20 shows the upper micro switches following the top of the grain plants during a field test.

The field of oats used for the tests had wide variations in grain height. In one small area in the field there was only short weed growth present. The automatic control system which was devised for the field tests was able to provide good cutter bar control in all crop conditions encountered. In the very short crop and in the area of weed growth, the limit switch (switch No. 7) maintained a minimum stubble height of five inches as was desired. The manual override, provided in the control box, could have been used to raise the cutter bar and prevent the swather from cutting the weeds but this type of area provided a further test to check the operation of the control system. As the crop height changed, the system sensed and followed the change in height. The mechanical linkage employed in the sensor unit automatically maintained the proper stubble ratio i.e. the ratio of stubble height to uncut grain height. When extremely tall grain (over 40 in. high) was encountered in the field, a limit switch (switch No. 6) provided a maximum stubble height of 12 inches as was desired.

The two limit switches can be preset by the operator to provide the desired maximum and minimum stubble heights. The limit heights used in the field tests were chosen because they would permit minimum grain losses. Grain losses are discussed fully in Appendix B.
6. CONCLUSIONS

On the basis of the laboratory and field tests, the following conclusions are presented:

1. A three-position on-off control system, employing lever-actuated micro switches to control a hydraulic solenoid valve, provided a simple means of controlling cutter bar height.

2. When 10-inch lever arms were used on the micro switches, the operation of the system was satisfactory for ground speeds of $2\frac{1}{2}$ mph to 5 3/4 mph, for grain heights of 16 in. to 28 in. and for plant population densities of 11 plants/ft.² to 30 plants/ft.² (10-30 Bus/acre).

3. The depth of penetration of the sensor below the top of the grain required to actuate the micro switches decreased with increasing forward speed and with increasing density of plant population. Changes in grain height affected the performance of the control system slightly.

4. A narrow lever arm (1/16 in.) was required on the micro switches to prevent switch actuation caused by the wind.

5. Field tests showed that the control system varied the cutter bar position in the desired range and automatically provided the required stubble length in a variable height crop.
RECOMMENDATIONS FOR FUTURE STUDY

1. Field test the control system for extended periods of time to determine the durability of the component parts.

2. Design a different mounting for the sensing unit so that the control system could be easily adapted to all types of swathers and combines.

3. Test the control system to determine the effect of vibration on its operation.

4. Evaluate the fatigue reduction associated with the application of the automatic control system.
REFERENCES


(a) INPUT AND OUTPUT SIGNALS

(b) TWO POSITION ACTION WITH NO DEAD TIME

(c) TWO POSITION ACTION WITH DEAD TIME

Figure I Two Position On-Off Elements
Figure 2 Schematic Diagram of a Two-Position On-Off Height of Grain Sensing System With No Dead Zone.
Figure 3  Schematic Diagram of a Two Position On-Off Temperature Controller with a Dead Zone.
(a) INPUT AND OUTPUT SIGNALS

(b) THE THREE POSITION ON-OFF ELEMENT

Figure 4  The Three Position On-Off Element
Figure 5  Schematic Diagram of a Three-Position On-Off Height of Grain Sensing System
1. Electric Motor
2. Hydraulic Pump
3. Hydraulic Cylinder
4. Mechanical Support Arm
5. Oil Filter
6. Hydraulic Solenoid Valve
7. Battery
8. Control Panel
9. Sensor Unit
10. Rotating Grain Table

Figure 6 Complete Laboratory Testing Apparatus.
Figure 7  Hydraulic and Electrical Systems Used in the Laboratory Apparatus

Figure 8  Sensing Unit of the Laboratory Control System
Figure 9  Details of 4-way Control Valve.
Figure 10  Hydraulic Flow Chart for the Directional Control Valve.
Figure II  Schematic Diagram of Electrical Circuit and Hydraulic Components of Laboratory Control System.
STUBBLE HEIGHT FOR AVERAGE TO HEAVY CROP
(Stubble height = \( \frac{1}{3} \) total crop height)

STUBBLE HEIGHT IN OAT FIELD
(Average straw-broken crop)

STUBBLE HEIGHT FOR THIN STRAW-BROKEN CROPS
(Stubble height = \( \frac{1}{4} \) total crop height)

Figure 12 Schematic Diagram Showing Positions of Cutter Bar in a Variable Height Crop.
Figure 1: Schematic Diagram of Electrical Circuit for Field Control System.
Figure 15  Schematic Diagram of Hydraulic System for Field Control System.
Figure 16  Position of Upper Micro Switch for Open Contacts with Various Grain Speeds and Densities of Plant Population.
Figure 17 Position of Upper Micro Switch for Open Contacts with Various Grain Speeds and Densities of Plant Population.
Figure 18 Position of Upper Micro Switch for Open Contacts with Various Grain Speeds and Densities of Plant Population.
Figure 19  Control System Sensing Device and Mechanical Linkage Attached to Swather.

Figure 20  Swather with Control System Operating in a Field of Oats.
EXAMPLE:

If \( M = 20\% \)

\[ V = 100 \text{ in/sec} (5.7 \text{ mph}) \]

\[ K = 3 \]

Then \( L = 5'' \)

---

Figure D1  Nomogram for the expression \( L=\frac{M}{V}-5K \)
EXAMPLE:
If \( L = 5 \) inches
\( K = 3 \)
\( V = 100 \text{ in./sec (5.7 mph)} \)
Then \( D = 33'' \)

Figure D2  Nomogram for the Expression \( D = \frac{vL}{5K} \)
APPENDIX A

GLOSSARY OF TERMS

Many terms which are not commonly known have been used in the writing of this thesis. Some of these terms are associated with the grain harvesting operation, others apply to the field of automatic control. The terms are divided into two sections. Section 1 deals with those terms which apply to grain harvesting, while Section 2 deals with those terms which apply to the field of automatic control.

1. Terms Applicable to Grain Harvesting

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combine</td>
<td>A machine used for harvesting and threshing grain. It is essentially a header attached to a threshing machine.</td>
</tr>
<tr>
<td>Concave</td>
<td>A curved grate placed below the threshing cylinder.</td>
</tr>
<tr>
<td>Cutter Bar</td>
<td>That part of the header which is used to cut the grain.</td>
</tr>
<tr>
<td>Cutter-Bar Losses</td>
<td>Free seeds and grain heads that have been cut off by the knife and dropped to the ground during the cutting operation.</td>
</tr>
<tr>
<td>Cylinder Losses</td>
<td>Kernels of grain which are left in the heads and are carried out over the rear of the straw rack.</td>
</tr>
<tr>
<td>Header</td>
<td>That part of the combine which cuts the grain and conveys it to the thresher. It consists of a reel, sickle, conveyor and other parts making up the platform assembly.</td>
</tr>
<tr>
<td>Header Losses</td>
<td>Grain heads and free seeds that are lost during the cutting and conveying operations or during the pickup and conveying operations in windrow combining.</td>
</tr>
</tbody>
</table>
Rack Losses  -- Loose kernels of grain that are carried over the rear of the straw rack with the straw.

Shoe Losses  -- That part of the combine which separates and cleans the threshed seed and returns partially threshed heads to the cylinder and disposes of the remaining debris. It consists of sieves, a fan, a chaffer extension and conveying augers.

Shoe Losses  -- Loose kernels of grain that are carried over the rear of the cleaning shoe with the chaff or blown over by an excessive air blast.

Straw Rack  -- A straw carrier used behind the threshing unit (cylinder and concaves) in a combine harvester.

Stubble  -- The basal portion of the stems of plants left standing after cutting.

2. Terms Applicable to Automatic Control

Actuating Signal  -- Is the quantity actuating the control element. In a simple system it is equal to the error signal.

Controlled Variable  -- That quantity or condition of the controlled system which is measured and controlled.

Correction Signal  -- Is the signal at the output of the control element (micro switch). The signal can be positive, negative or equal to zero.

Dead Zone  -- Is the range over which a control signal may vary without having a correction signal applied to the control system.
<table>
<thead>
<tr>
<th><strong>Final Control Element</strong></th>
<th>Is the final controlling means in the system, such as a control valve to change flow or a control cylinder to vary position.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Manipulated-Variable</strong></td>
<td>That quantity or condition which the controller applies to the controlled variable.</td>
</tr>
<tr>
<td><strong>Proportional-Control</strong></td>
<td>The control action producing a controller output proportional to the size of the deviation.</td>
</tr>
<tr>
<td><strong>Ramp Change</strong></td>
<td>A change which varies linearly with time—a straight line increase or decrease in a variable.</td>
</tr>
<tr>
<td><strong>Signal</strong></td>
<td>Information transmitted from one part of the control system to another by some change in energy or material.</td>
</tr>
</tbody>
</table>
Grain Losses in Harvesting

1. General

Grain losses are influenced by two general factors; the operation and the adjustment of the machine and the condition of the crop (B1). The combine grain losses can be described as header, cylinder, rack and shoe losses (B2).

Maximum harvesting efficiency can be attained usually by carefully balancing the losses occurring at the various places (B3). For example, the performance of the shoe is affected by the performance of the straw rack since the material which falls through the straw rack must be handled by the shoe. The relative load handled by the rack and the shoe is affected by the type of crop, the condition and length of the cut grain and the threshing condition produced by the cylinder.

2. Checking Grain Losses

In order to determine the total grain losses in harvesting, the grain losses resulting in the various parts of the machine have to be considered. Simultaneous collections of material from the various parts are usually made while the machine is operating at a constant speed.

Cutter-bar loss is found by counting loose kernels and heads of grain on the ground beneath the combine. A check should be made in the standing grain to see how many kernels are on the ground prior to harvesting. If there has been some shattering of the grain prior to cutting, a preharvest count is necessary to permit determination of the additional losses resulting from the cutter bar. The approximate grain loss can be determined by
counting the number of kernels found on one square foot beneath the machine, making allowance for the shatter loss if any exists. About 18-20 kernels of wheat per square foot or 12-16 kernels of oats per square foot is equivalent to a grain loss of one bushel per acre (Bu).

Cylinder loss is determined by looking for unthreshed kernels in the heads. This form of grain loss is usually the smallest, regardless of the crop condition or the correctness of machine adjustments.

Rack loss is checked by catching in a box or on a canvas the material coming off from the rack. The grain is then separated from the straw. By measuring the area over which the straw sample was taken and then determining the number of kernels per square foot, the rack loss can be obtained.

The shoe loss can usually be measured by catching with a canvas or a box the material coming over the rear of the cleaning shoe. The grain is then separated and the shoe loss is determined, as described for rack loss. It is difficult with some combines to catch the material from the shoe without catching the straw from the racks at the same time. The shoe loss can then be calculated by subtracting the rack loss from the rack and shoe losses combined, as measured by catching all of the material leaving the rack and shoe.

3. Grain Losses in Straight Combining

In general when a heavy weed growth is present, increased grain losses result. It is necessary to cut at increased height to eliminate most of the weeds, therefore higher cutter-bar losses result. Grain losses can also increase because of a heavy mat of green material which may form on the rack and shoe. The grain kernels held by this material are lost because they slide over the shoe and racks.
When direct combining is done in a relatively weed-free crop, the total grain loss can often be reduced by cutting a higher stubble to reduce the load on the rack and shoe, even though the header loss is increased somewhat. Tests in Ohio with bearded wheat (B5) showed that reducing the length of straw cut from 38 inches to 26 inches reduced the over-all grain losses from 302 to 73 lb. per acre. Increasing the stubble height resulted in lower cylinder loss, much lower rack loss, lower shoe loss but slightly higher cutter-bar loss. Decreased grain losses will also be obtained, by using a slower rate of travel. A combine becomes overloaded if the rate of travel is too fast or if the cutter bar is placed too low. Overloading is one of the most common causes of high rack and shoe losses. A similar effect to overloading is obtained when the straw is badly broken up when the cylinder-concave setting is too close or by too high a cylinder speed.

Cylinder adjustments are important because they affect rack and shoe losses. If the grain is properly dried, it threshes easily and a wide setting of the cylinder and concave is desirable. Overthreshing the grain heads causes increased rack and shoe losses.

The air blast from the fan should be directed upward to lift the material from the sieves at the front end of the shoe. If chaff is allowed to settle solidly on the sieves, large shoe losses will result. The air blast should not be strong enough to blow the grain out, but it should lift the chaff off of the sieve.

Improper reel adjustment and operation will increase header losses. The peripheral speed of the reel should be about 25 to 50 percent greater than the forward speed of the machine (B3). Faster reel speeds will usually result in excessive shatter loss. The reel height should be such
that the bottom edge of the bat at its lowest point of travel will be a little below the lowest head of the uncut grain. The reel axis should be from 6 to 12 inches ahead of the cutter bar(B3).

4. Grain Losses in the Windrow-Pickup Method of Harvesting

The windrow-combine method involves an extra operation as compared with direct combining. The main advantage of windrowng is that it permits the curing of green weeds and unevenly ripened crops before threshing. Tests conducted in Ohio(B1) showed that windrows on grain stubbles 9 to 12 inches tall cured more rapidly than standing grain. The windrow has to be held and supported above the ground by the stubble(B6). If the grain is not properly windrowed, the windrow or swath of grain will fall to the ground making it difficult to pick up. Wet weather may also damage the crop to a great extent.

A series of tests were conducted in Ohio(B1) on a light wheat crop with an average height of 38 inches. The crop was windrowed at various heights to establish a windrow on stubble from 6 to 18 inches in height. The crop was then threshed with a combine. The results showed that the cutter-bar loss increased almost linearly from 1 to 4% as the stubble height increased from 6 to 18 inches. This grain loss became greater with the longer stubble because of the increasing number of heads of grain slipping by under the cutter bar. The tests also showed that with increasing stubble height the separation losses decreased and the cylinder loss increased slightly. The pick-up loss increased with extreme lengths of stubble and was a minimum (less than 1%) when the stubble height was from 8 to 12 inches. The minimum total loss of 4% occurred when the stubble height was 9 inches for the thin straw-broken wheat crop. Cutting below or above this stubble height resulted in larger grain losses.
When the windrow was placed closer to the ground, larger pick-up losses resulted because the pick-up fingers did not get under the windrow properly and small bunches of grain were left behind. On the other hand, if the stubble was too long, the short cut plants produced a windrow that was open and loosely put together. The long stubble was flexible and did not support the windrow properly. The heads of grain dropped to the ground and made it impossible for the pick-up fingers to pick it up.

Tests were also conducted with heavy crops of barley and oats. A short stubble resulted in large total grain losses. However, with a thin crop, the grain losses were not as severe when a short stubble was left.

It was stated (Bl) that minimum grain losses will result if grain is cut so that the stubble height is equal to 1/3 the total length of the straw for average to heavy crops, and approximately 1/2 the total length of the straw for thin straw-broken crops.
REFERENCES


APPENDIX C

Grain Property Determination

1. General

In the design of an automatic control system to sense grain height it was desirable to know some specific grain properties such as the mass of the grain plant, the stem spring constant and the free period of oscillation. This information was necessary for determining the magnitude of the impulse force resulting from an object striking a head of grain and then passing over it. Since the sensing devices in this control system were actuated by this impulse force, it was necessary to know this quantity to facilitate selection of suitable micro switches.

2. Physical Grain Properties

The required grain properties were determined in the laboratory. Representative samples of mature wheat plants were obtained from the Field Husbandry Department, University of Saskatchewan. Weights were determined by using a small scale and the bending strength of the straw was obtained by applying a known load to the head of the grain plant and measuring the resulting deflection. The free period of oscillation was determined experimentally by counting the number of free vibrations of an erect grain plant during a known time.

It was decided to use an average value of each property in the mathematical determination of the impulse force. These values are given in Table C1. These results were obtained by using wheat plants which were 28 inches long.
Table C1  Average Values of Certain Grain Properties for Mature Wheat Plants

<table>
<thead>
<tr>
<th>Grain Property</th>
<th>Mature Wheat Plant (28 inches long)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Weight</td>
<td>$6 \times 10^{-3}$ lb.</td>
</tr>
<tr>
<td>Weight of Head</td>
<td>$4 \times 10^{-3}$ lb.</td>
</tr>
<tr>
<td>Weight of Straw</td>
<td>$2 \times 10^{-3}$ lb.</td>
</tr>
<tr>
<td>Bending Strength of Straw (K)</td>
<td>$2 \times 10^{-3}$ lb./in.</td>
</tr>
<tr>
<td>Free Period of Oscillation (T)</td>
<td>0.55 sec.</td>
</tr>
</tbody>
</table>

3. Mathematical Determination of Grain Impulse Force

The first mathematical solution was obtained by considering a mechanical system as shown below in which an applied force causes displacement of a mass having a spring and a dashpot to oppose this motion.

![Mechanical System Diagram](image)

The equation describing this mechanical system is

$$m\ddot{x} = F - kx - cx$$

Similarly, when an impulse force is applied to the head of a grain plant, the system can be represented by the following second order linear differential equation

$$m\ddot{x} + c\dot{x} + kx = f\delta(t)$$

where
- $m = \text{mass of grain plant (head plus } \frac{1}{3} \text{ of stem)}$
- $c = \text{viscous damping coefficient of air}$
- $k = \text{spring constant of plant stem}$
f = impulse force

t = time

x = displacement of grain head

\dot{x} = velocity of micro-switch lever arm

\ddot{x} = acceleration of switch

\begin{align*}
\dot{m}\ddot{x} + c\dot{x} + kx &= f\delta(t) \\
\text{when } t=0, \ x=0, \ \dot{x}=0
\end{align*}

Using the Laplace Transform the equation becomes

\begin{align*}
(ms^2 + cs + k)\tilde{x} &= f \quad \text{since the Laplace Transform of the } \delta \text{ function is unity} \\
\tilde{m} \left[ \left( \frac{c^2}{m} + \frac{cs}{m} + \frac{k}{m^2} \right) + \frac{\sqrt{4km - c^2}}{2m} \right] \tilde{x} &= f
\end{align*}

\begin{align*}
\tilde{m} \left[ \left( \frac{s + \frac{c}{2m}}{2m} \right)^2 + \frac{\sqrt{4km - c^2}}{2m} \right]^2 \tilde{x} &= f
\end{align*}

We assume that \( c^2 < \sqrt{4km} \)

\begin{align*}
\text{Let } & \quad a = \frac{c}{2m} \quad \text{and} \quad b = \frac{\sqrt{4km - c^2}}{2m} \\
\tilde{m} \left[ \left( \frac{s + a}{b^2} \right)^2 + \frac{b^2}{b^2} \right] \tilde{x} &= f \\
\tilde{x} &= \frac{f/m}{(s + a)^2 + b^2} \\
x(t) &= \frac{f}{bm} e^{-at} \sin bt \\
f &= \frac{bm x(t)}{e^{-at} \sin bt}
\end{align*}
The value of force \( F = \frac{\text{impulse force}}{\Delta t} \),

Where \( \Delta t = t_1 - t_0 = \text{time of contact with the grain plant} \)

It was assumed that in the mathematical calculations the equivalent weight which should be used would be equal to the weight of the head plus one-half the weight of the stem or straw. Thus from table C1

\[
W = 4 \times 10^{-3} + \frac{2 \times 10^{-3}}{2} = 5 \times 10^{-3} \text{lb}
\]

\[
K = 2 \times 10^{-3} \text{ lb/inch}
\]

\[
T = 0.55 \text{ sec.}
\]

\( C \) for air \((60 - 70^\circ F) = 0.018 \text{ centipoise} \)

\[
1 \text{ centipoise} = \frac{1 \text{ gm}. \text{sec.}}{\text{cm.}} \times \frac{1}{100} \times \frac{2.54 \text{ cm.}}{1 \text{ inch}} \times \frac{12 \text{ inch}}{1 \text{ ft.}} \times \frac{1 \text{ lb.}}{453.6 \text{ gm.}}
\]

\[
= 6.72 \times 10^{-4} \text{ lb. sec./ft.}
\]

\[
C = 0.018 \times 6.72 \times 10^{-4} = 1.21 \times 10^{-5} \text{ lb. sec./ft.}
\]

\[
a = \frac{c}{2m} = \frac{1.21 \times 10^{-5} \text{ lb. sec.}}{2 \text{ ft.}} \times \frac{32.2 \text{ ft.}}{5 \times 10^{-3} \text{ lb. sec.}^2} = 0.039 \text{ sec}^{-1}
\]

\[
b = \sqrt{\frac{4km - c^2}{2m}}
\]

but \( 4km \gg c^2 \)

\[
b \approx \sqrt{\frac{4km}{2m}} = \sqrt{\frac{km}{m}} = \sqrt{k}
\]

\[
\approx \sqrt{\frac{2 \times 10^{-3} \text{ lb./in}}{5 \times 10^{-3} \text{ lb.}} \times \frac{32.2 \text{ ft.}}{\text{sec}^2} \times \frac{12 \text{ in}}{\text{ft}}} \approx 12.5 \text{ sec}^{-1}
\]
b can also be determined by using the value of the free period of oscillation of a grain plant which was obtained experimentally.

\[ T = \frac{2\pi}{b} \]

\[ b = \frac{2\pi}{T} = \frac{2\pi}{0.55} \]

\[ = 11.4 \text{ sec}^{-1} \]

Assume that \( x = vt = 0.5 \text{ ft.} \). This is an average value of grain head movement obtained when the lever arm of the micro switch strikes the grain plant at a point located one inch below the top of the head.

At a velocity of 5 mph. \( v = 7.33 \text{ ft./sec.} \)

\[ \Delta t = \frac{x}{v} = \frac{0.5 \text{ ft.}}{7.33 \text{ ft./sec.}} = 0.0682 \text{ sec.} \]

\[ F = \frac{bx}{at e^{-at \sin bt}} \]

\[ = \frac{12.5 \text{ sec}^{-1}}{0.0682 \text{ sec.}} \times \frac{5 \times 10^{-3} \text{ lb}}{32.2 \text{ ft./sec}^2} \times \frac{0.5 \text{ ft.}}{e^{-0.039}(0.0682) \sin(12.5)(0.0682)} \]

\[ = 31.3 \times 10^{-3} \text{ lb} \]

\[ = \frac{18.9 \times 10^{-3} \text{ lb}}{(2.2)(1) \sin 48.8^\circ} \]

\[ = 0.0189 \text{ lb} \text{ or } 0.30 \text{ ounces} \]

At a velocity of 3 mph. \( v = 4.4 \text{ ft./sec.} \)

\[ \Delta t = \frac{0.5}{4.4} = 0.1136 \text{ sec.} \]

\[ F = \frac{bx}{\Delta t e^{-at \sin bt}} = \frac{12.5 \text{ sec}^{-1}}{0.1136 \text{ sec.}} \times \frac{5 \times 10^{-3} \text{ lb}}{32.2 \text{ ft./sec}^2} \times \frac{0.5}{e^{-0.039}(0.1136) \sin(12.5)(0.1136)} \]
\[
\frac{31.3 \times 10^{-3} \text{lb}}{(3.66)(1) \sin 81.4^\circ}
\]

\[= 8.68 \times 10^{-3} \text{ lb}
\]

\[= .00868 \text{ lb. or } 0.11 \text{ ounces}
\]

The second mathematical solution was obtained by considering the free period of vibration of the grain plant. The period \( T = \frac{2\pi}{n} \) where \( n \) = frequency of vibration in cycles per second.

The differential equation of motion is

\[\ddot{x} + n^2 x = 0\]

or \( m\ddot{x} + mn^2 x = 0\)

and if \( F \) is the external force for the forced motion

\[m\ddot{x} + mn^2 x = F\]

If \( v \) is the velocity of the object striking the grain head, then \( F \) is the force from contact \((t = 0)\) to release \((t = t_1)\) We have

\[x = vt, \quad \dot{x} = v, \quad \ddot{x} = 0\]

This means that the grain head remains in contact with the moving object (micro switch lever) after the initial impact or contact.

\[\therefore \quad mn^2 vt = F\]

The total impulse from just after impact to release is:

\[
\int_0^{t_1} Fdt = \int_0^{t_1} mn^2 vdt
\]

\[= \frac{1}{2} mn^2 vt_1^2 = \frac{1}{2} m \left(\frac{2\pi}{T}\right)^2 vt_1^2 = \frac{2\pi^2}{T^2} \frac{mv(t)}{T^2}
\]

There is also an impulse at impact as a result of the change from rest to velocity, \( v \).

This is a change of momentum which is \( mv \).
Total impulse = \( mv + 2\pi^2 \frac{mv}{T} \)

\[ = mv \left[ 1 + 2\pi^2 \left( \frac{t_1}{T} \right)^2 \right] \]

The required force \( F = \frac{\text{Total Impulse}}{\Delta t} \)

\[ = \frac{mv}{\Delta t} \left[ 1 + 2\pi^2 \left( \frac{t_1}{T} \right)^2 \right] \]

Where \( \Delta t = t_1 - t_0 \) = time of contact with the grain plant

Using the same values for the variables

\( W = 5 \times 10^{-3} \text{lb.} \quad T = 0.55 \text{ sec.} \)

At a velocity of 5 mph, \( v = 7.33 \text{ ft./sec.} \)

\( \Delta t = \frac{x}{v} = \frac{0.5 \text{ ft.}}{7.33 \text{ ft./sec.}} = 0.0682 \text{ sec.} \)

\[
F = \frac{5 \times 10^{-3} \text{ lb. sec.}^2}{32.2 \text{ ft.}} \times 7.33 \text{ ft. sec.} \times \frac{1}{0.0682 \text{ sec.}} \left[ 1 + 2\pi^2 \left( \frac{0.0682}{0.55} \right)^2 \right]
\]

\[ = 16.7 \times 10^{-3} (1 + 0.245) \text{ lb} \]

\[ = 20.8 \times 10^{-3} \text{ lb} \]

\[ = .0208 \text{ lb. or 0.33 ounces} \]

At a velocity of 3 mph, \( v = 4.4 \text{ ft./sec.} \)

\( \Delta t = \frac{x}{v} = \frac{0.5 \text{ ft.}}{4.4 \text{ ft./sec.}} = 0.1136 \text{ sec.} \)

\[
F = \frac{5 \times 10^{-3} \text{ lb. sec.}^2}{32.2 \text{ ft.}} \times 4.4 \text{ ft. sec.} \times \frac{1}{0.1136 \text{ sec.}} \left[ 1 + 2\pi^2 \left( \frac{0.1136}{0.55} \right)^2 \right]
\]

\[ = 6.02 \times 10^{-3} (1 + 0.84) \text{ lb} \]

\[ = 11.1 \times 10^{-3} \text{ lb} \]

\[ = .0111 \text{ lb. or 0.18 ounces} \]
The lever-actuated micro switches used in the control system were purchased with lever arms 2\(\frac{1}{2}\) inches long. The maximum operating force required to actuate this switch was found by experiment to be 2.0 ounces, applied at the end of the lever. With a 10-inch lever arm on the switch, the maximum operating force required was reduced from 2.0 ounces to 0.5 ounces.

The results of these calculations showed that a speed of 5 mph, two grain plants striking the end of a 10-inch lever arm provided sufficient force to actuate the micro switch.
1. **General**

There was a two-fold purpose for mounting the sensing unit ahead of the cutter bar. First, the sensing unit had to be placed where it would be controlled by the height of the uncut grain plants. Secondly, because the hydraulic section of the control system has a relatively slow response time compared to the electrical system. It was necessary in grain fields with rapidly changing grain heights, to have the sensing unit mounted at some distance ahead of the cutter bar to provide sufficient time for the hydraulic cylinder to make the required cutter-bar movement.

A mechanical linkage used for mounting the sensing unit (see Figure 13), had to maintain the proper micro-switch height as the cutter-bar position changed and thus provide the desired stubble height in a variable height crop. The design of this linkage depended upon the construction and the type of machine that the sensing unit was to be mounted on.

2. **Design and Construction of the Mechanical Linkage**

The field tests were conducted with a Cockshutt No. 414 pull-type swather, hence the sensor mounting was designed for this particular machine. The preliminary step in the design of the mechanical linkage was to draw a scale diagram of the side view of the swather. From this diagram it was possible to study the movement of the swather platform as the cutter bar was raised and lowered. It was observed that the slope of the platform on this swather remained relatively horizontal as the cutter-bar position changed, since the wheels of the swather were located behind the platform. This change in platform slope had to be considered since it
affected the operation of the mechanical linkage.

It was decided to use a moveable lever arm which pivoted about a support arm bolted to the swather platform, directly below the cutter bar. The lower end of the lever arm was made to move along the ground. Lengthening the support arm increased the magnification of the upper micro-switch movement as the cutter-bar height was changed.

A trial and error method of graphical solution was employed in the design of the linkage. The upper end of the lever arm was required to move about 3 to 4 times the distance (vertical height) that the cutter bar moved. After a suitable design was reached, the parts were constructed and the unit was assembled. The movable lever arm had a series of holes drilled in it, so that the location of the pivot point could be changed to allow the desired relative movements.

The operation of the linkage was checked by measuring the micro-switch height and cutter-bar height for various positions of the swather platform. The final checks and adjustments of the linkage were made during the field tests.

3. Location of the Sensor Unit

Good control by the system can be obtained only if the sensor unit is mounted in the proper location. The proper location is difficult to determine because of the variety of changes in grain height which may be encountered by the system. In crops with rapidly changing grain heights the sensor unit should be placed further ahead of the cutter bar. This allows the hydraulic system sufficient time to perform the required cutter-bar movement so that the grain is cut at the desired height. On the other hand, in a grain field with a relatively uniform height of crop, the sensor unit should be placed closer to the cutter bar.
A mathematical approach to determine the proper location of the sensor unit is given. An equation was derived to permit the designer to calculate the optimum sensor unit location for a given grain slope. Two nomograms are also provided. One is useful for graphically determining the size of the lag in the system when operating in various grain slopes and at different velocities. The term lag refers to the distance that the upper micro switch is below the top of the grain. The other nomogram can be used to determine where the sensor unit should be mounted when the system lag is known.

A diagram showing system lag is shown below. The micro switch has moved a distance \(x\) during a time of \(t\) seconds. There is a large grain slope, \(M\) in percent resulting in a lag = \(L\) of the control system after moving a distance \(x\). The micro switches should be mounted at a distance \(D\) ahead of the cutter bar in order to reduce the lag to zero.

\[L = y \tan \theta \cdot \frac{M}{100}\]

\[x = vt\]

It was necessary to introduce a swather factor relating micro-switch movement to hydraulic cylinder movement.

**Swather Factor** \[K = \frac{\text{Change in Micro Switch Height (Inches)}}{\text{Cylinder Movement (Inches)}}\]

It was assumed that a standard hydraulic cylinder was employed in the control system.

*A.S.A.E. Standard Cylinder With 8 in. Stroke*
A standard hydraulic cylinder moves at a rate of 5 inches/sec.

Micro Switch Movement in time t sec. = 5Kt inches

Change in micro switch height y = 5Kt inches

\[
\tan \theta = \frac{y}{x} = \frac{5Kt}{vt} = \frac{5K}{v}
\]

\[
L = \frac{5K}{v}
\]

\[
D = \frac{vL}{5K}
\]

But \( L = Mx - y \)

\[
= Mvt - 5Kt
\]

\[
= (Mv - 5K)t
\]

\[
D = \frac{vt(Mv - 5K)}{5K}
\]

D = distance sensor unit should be ahead of cutter bar in inches

M = grain slope in %

v = velocity in inch/sec.

t = time in seconds

The lag is given by the expression

\[
L = Mx - y
\]

\[
= Mvt - 5Kt
\]

With most conventional swathers or combines it can be assumed that the cutter bar will be moved from the minimum operating height to the maximum operating height during a time of 1 second. If we assume that \( t = 1 \) sec. the expression for lag becomes:

\[
L = Mv - 5K
\]

A nomogram for this equation is shown in Figure D1 (Page D6).
The nomogram is used by first selecting a grain slope $M$ on the extreme right hand scale. A line is drawn from this point through the velocity $v$ and the value $vM$ is obtained. The value of $vM$ obtained on the lag scale is then transferred to the adjacent linear scale. A second line is then drawn from this point to the required value of $K$. The value of the lag can then be obtained from the middle scale.

The expression relating the distance that the sensing unit should be mounted ahead of the cutter bar to reduce the lag to zero is $D = \frac{vL}{3K}$.

A nomogram for this expression is shown in Figure D2, (Page D7). This nomogram is used by selecting the value of the lag on the extreme left-hand scale. A line is drawn from this point to the swather factor $K$. A second line, from the first intersection point is drawn through the velocity $v$ and extended to intersect the extreme right-hand scale. This scale gives the required value $D$. 