Evaluation of header height control mechanisms

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EVALUATION OF HEADER HEIGHT CONTROL MECHANISMS

by

Kenneth Allen Woodruff

A Thesis Submitted to the
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Kenneth A. Woodruff was born in Lee County, Iowa, on March 25, 1945. At age seven, he and his family moved to a farm near Keosauqua, Iowa. He is the oldest of seven children born to Eston and Florence Tweedy Woodruff.

Kenneth graduated from Van Buren Community High School, in 1963; with honors from Keokuk Community College, in 1965, with the degree Associate in Arts; and from Iowa State University, in 1968, with the degree Bachelor of Science in Agricultural Engineering.

The great influence of agriculture on his life has instilled in him a sincere love and respect for farming as a way of life.
INTRODUCTION

Soybeans, the Cinderella crop, became the "number two crop" of the American farmer in the 1960's. The acres harvested and the yield in bushels per acre in 1950, 1960, and 1969 were 13,807,000, 21.7; 23,655,000, 23.5; and 40,875,000, 27.3 respectively.

The soybean is the major export farm commodity with more than one billion dollars' worth of soybeans being sold overseas for cash during 1967, 1968, and 1969. This crop is the major source of foreign exchange for the United States.

A similar increase in soybean production is reflected in the figures for Iowa: 1,930,000, 2,599,000, and 5,283,000 acres in 1950, 1960, and 1969, respectively. During this same period the average yield increased thirty percent.

The value of soybeans as a food source for protein and oil as well as the industrial uses has contributed to the phenomenal increase in demand for this crop. These factors will cause the soybean to become the "number one crop" in the foreseeable future in both acreage and cash value.

Along with the increased soybean acreage and yield, came increased interest in soybean harvesting machines. The self-propelled combine, developed during World War II, has become the primary harvesting machine. Tests conducted in Ohio (21) in the late 1950's indicate that losses during combine harvesting of soybeans frequently exceed 10 percent of the total yield. Of these total losses, over 80 percent (and in later studies as high as 93 percent) were gathering losses or losses incurred during
the "attack of the combine on the crop". In earlier tests, beans remaining in pods attached to the stubble, or stubble loss, averaged 17 percent of the gathering losses.

The magnitude of stubble loss is influenced by several factors. It is mainly dependent on the height of cut by the cutter bar of the combine and the distribution of beans along the stem of the soybean plant. Lamp et al. (21) plotted the distribution of beans versus height above the ground for several varieties, Figure 1. The stubble loss that could be expected from a certain cutting height could be determined by evaluating the data based on row spacing, variety, plant population, planting date, and type of cultivation, etc.

The cutting height is determined, within the limits of the machine design and surface roughness, by the combine operator. He determines the position of the combine header. He also determines the operating speed which influences his first determination. Because the reaction time of the operator and the height control mechanism remains the same as the operating speed increases, the header must be operated higher off the ground to clear the ground peaks that it would have lifted over at a slower speed.

The Ohio tests cited earlier showed that stubble loss increased 65 percent when the operating speed changed from 2.5 to 5.0 miles per hour, while all gathering losses rose only 40 percent. This increased stubble loss with higher operating speed may be influenced by greater slippage against the knife section-guard cutting mechanism, but more importantly by the necessity of operating the combine header at a greater cutting
Fig. 1. Plot of distribution of soybeans versus height above ground for several varieties from Lamp et al. (Iowa State University data added)

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height to reduce the chances of running the cutter bar into the ground. To reduce stubble loss, the farmer now has two alternatives at the time of harvest: 1) reduce forward velocity of the combine, or, 2) install an automatic control mechanism. But reducing speed increases the length of the harvest season (thus increasing shatter loss) and also reduces the productivity of the combine. To increase the production of the combine, it is desired to increase the operating speed, while at the same time reducing stubble loss. This research was conducted to determine the value of the commercial header height control for combines in reduction of average cutting height, and to design an automatic header height control superior in performance to the controls commercially available.
Other Machine Controls

Automatic height controls are or have been applied to grain combines, nut harvesters, cane cutters, and cotton strippers. As automatic header height control systems are developed, they will be applied to moldboard plows, cultivators, spraying equipment, etc.

In his elevational control mechanism for an implement carrier, Bowie (7) used a pair of mechanically unseated, spring-loaded ball hydraulic valves to control the height of the gathering mechanism of a nut harvester. When the sensing skid raised due to a contour change of the soil, it mechanically unseated the first spring-loaded ball. This allowed the oil flow from the pump to be directed to the lift cylinder of the gathering mechanism. As the sensing skid passed over a dip in the soil, it moved away from the first ball valve but mechanically unseated the second spring-loaded ball which was connected to the same cylinder port. This allowed fluid to return from the single-acting cylinder to the tank, lowering the gathering mechanism.

A mechanism to control the height of a hydraulically-driven rotary sugar cane cutter was described by Suggs and Abrams (33). The system consisted of a hydraulic cylinder which was connected to the same pressure line as the hydraulic motor driving the sugar cane cutter, Figure 2. The system utilized the phenomenon, of increased pressure in the hydraulic circuit as the cutting height decreased, to control the cutting height. A compression spring provided position feedback. Therefore, a control
position (height of cut) existed for each value of pressure. Steady-state regulation for an optimum selection of the design parameters was approximately equal to 1/4 inch for an 8 inch change in ridge height. Response speed for the same set of parameters was calculated to be approximately 0.1 second for 98 percent correction to a step input.

Sanderson (28) described a hydraulic height sensing unit that was used with a cotton stripper mounted on a tractor with a closed center hydraulic system, Figure 3. A ground-engaging shoe controlled a restrictor valve, Figure 4, to maintain the correct machine height.
Fig. 3. Diagram of the hydraulic height sensing system for a cotton stripper described by Sanderson.

Fig. 4. Section view of the restrictor valve used in the hydraulic circuit above.
In his study of soybean harvesting losses at Iowa State, in 1948, Everett (14) tested an automatic hydraulic cutter bar control which he fitted on an Allis-Chalmers, Model 60, pull-type combine. This system consisted of a pump, a reservoir with oil supply, a gate valve, and suitable mechanical linkages from the "flapper-plate" sensor, to actuate the valve, Figure 5. The pump flow bypassed the header lift cylinder until the valve began to close. Closing of the valve caused the pressure to rise in the header lift cylinder and the header was lifted until the "flapper-plate" opened the valve allowing the header to lower.

Everett's study also included gage wheel cutter bar control which he found superior to the automatic hydraulic cutter bar control by 3.5 to 4.5 percent, as measured in "cutter bar loss".

An automatic header height control was developed by Kaminski and Zoerb (20) in 1963. This control was designed to provide automatic height-of-cut adjustment in grain crops such as oats and wheat. The system consisted of two micro-switches, two relays and a solenoid-operated, 3-position, hydraulic directional control valve, Figure 6. The lever-actuated micro-switches are mounted on a combine or windrower header ahead of the cutter bar. With the normally-open switch above the grain, and the normally-closed switch below the top of the standing grain, the header height position was controlled.

Annat and Metcalfe (3), in 1963, proposed a system to provide a floating header. In this system with a skid plate on the bottom of the header, the header drags along on the soil surface with part of the load
Fig. 5. Schematic diagram of Everett's automatic hydraulic cutter bar control

Fig. 6. Schematic diagram of Kaminski and Zoerb's electric automatic header height control system for cereal crops
of the header being carried by the machine's hydraulic system through the float valve, Figure 7. The pressure remained essentially constant in this system and the amount of load carried was determined by the position of the adjustable stop. The large spool was mechanically actuated at the left end to provide manual control. The small spool served as a safety valve, blocking the flow to the tank when the pump pressure was lost thus preventing the header from lowering.

Sallee (27), in his 1963 patent, showed a metering valve used in conjunction with the existing combine header lift system. When fluid flow from the pump was directed to the top left port of the metering valve, Figure 8, the poppet valve opened and unseated the ball below it. The right plunger formed the metering valve which maintained proper flow to, or from, the header lift cylinder. Flow could return to the tank from the cylinder only if pressure was available to unseat the poppet and ball, thus providing a safety check valve.

Shonkwiler (30), in his second patent, disclosed the design of sensor fingers that sensed ahead of the cutter bar. The sensors were best adapted to the automatic header height control disclosed in his United States patent 3,137,984, (allowed January 7, 1964), and now manufactured and sold by Kelly Farm Equipment, Mishawaka, Indiana. These sensors were designed to provide a crop lifting function in addition to the sensing function. The sensors rotated a shaft mounted under the cutter bar which tensioned a cable connected to the metering valve.

In his 1965 patent, Mack (22) claimed ease of changing broken guards due to the novel mounting of the feeler bar. His feeler was similar to the Noble feeler bar and others, but it is mounted farther rearward.
Fig. 7. Section view of the float valve used in Annat and Metcalfe's floating header system

Fig. 8. Section view of the metering valve for Sallee's header height control system
Mack's major contribution, however, was the 3-position, spring-centered, hydraulic directional control valve which incorporated into one block the following: a tandem center to dump pump flow in the spool center position, a one-way check valve, and a relief valve. Provision was also provided for manual control of the header.

Another type of header height control was proposed by the J. E. Love Company\(^1\). Control was accomplished by connecting a pressure-sensitive electronic switch to the hydraulic line between a solenoid-operated directional control valve and the header lift cylinder. The header was allowed to slide along on the ground with the pressure changes in the system providing the switching signals. The solenoid valve directed the flow to control the header. This system (in somewhat altered form) was tried at Iowa State University in 1969. The author's experience with this system revealed it was less than satisfactory. The friction force developed between the header bottom and the soil caused actuation in the system directionally opposite to that which was desired.

An approach to the operation of a single-acting header lift cylinder for header height control was illustrated by Allen (2). Through a counterbalance valve, a 3-position, open-center directional control valve was used to control the header lift cylinder. Flow directed to one port of the counterbalance valve unseated a spring-loaded poppet and the lift cylinder extended. Pilot pressure opened an orifice allowing

retraction of the cylinder. A feeler connected to the spool of the
directional control valve and mounted on the header provided the feedback
and the signal.

Eimer (13) and Nastenko (24) discussed a control mechanism to main-
tain cutting height on trailed combine-harvesters developed by the
Ukrainian Scientific Research Institute for Mechanization in Agriculture.
The displacements of a shoe skid were transmitted via a spring-loaded
lever system to the spool of a 2-way hydraulic directional control valve.
The valve controlled a double-acting hydraulic cylinder that was mounted
between the hitch and frame of a Russian KKKh-3 maize harvester. Nastenko
stated that tests in the Khersonii Harvester Factory showed positive
results.

Woodin invented and holds the patent on the automatic header control
manufactured by Noble Manufacturing Company, Sac City, Iowa\(^1\). The design
of this control included a steel feeler bar pivoted below the cutter bar
with paddles extending rearward to sense the ground contour. As the
feeler bar pivoted, Figures 9, 10, a lever attached to it struck contacts
that were connected to a solenoid-operated directional control valve.
When the lever made contact, the appropriate solenoid was energized to
raise or lower the header. The manufacturers claimed a savings of 3 or 4
bushels of soybeans per acre.

Header height controls available (fall of 1970) from most combine
manufacturers are similar to either the Noble or the Allis-Chalmers

\(^1\)Neuhring, Robert, Sac City, Iowa. Noble header height control.
Fig. 9. Case, Model 960, with Noble header height control feeler bar

Fig. 10. Lever striking contact (A) of Noble header height control
which is discussed in a later chapter.

A method for dynamic analysis of the header height control was presented by Rehkugler (26). Among the assumptions made regarding the system behavior for this analysis were:

1. The combine is restricted to travel in a straight line at constant velocity on level ground. (Planar motion)
2. Tire behavior can be represented by an appropriate spring constant and viscous damping coefficient.
4. Ground disturbances could be represented by sinusoidal inputs of various frequencies and amplitudes.

He developed a general mathematical description of a combine equipped with an automatic header height control of the trailing-finger type with hydraulic actuation of the header position. Based on these description equations, he showed the construction of an analog computer solution to determine the error expected in following the ground contour precisely at the height specified by the control.
OBJECTIVES AND PROCEDURE

The overall objective was to investigate the merits of an automatic header height control on a combine during soybean harvest.

The procedure was as follows:

1. Design and build a header height control using a fluidic system.
2. Evaluate the performance of the header height control.
3. Perform statistical comparisons to demonstrate the advantages of automatic header height control over the manually actuated hydraulic control.
4. Enumerate the sources of loss due to cutting "too high".
DESIGN OF THE FLUIDIC SYSTEM

The National Fluid Power Association defines fluidics as "the technology where sensing, control, information processing, and/or actuation functions are performed solely through utilizing fluid dynamic phenomena".

This technology offers many possibilities in Agricultural Engineering. Howard et al. (18) illustrated one possibility in a fluidic-hydraulic control system for automatically maintaining a full load on a hydrostatic drive tractor engine. The fluidic-hydraulic control system adjusted the hydrostatic transmission drive ratio to achieve maximum work output under variable loading conditions. Laboratory tests showed that the system has considerable potential for practical use. Other possible uses of fluidics in agriculture are as follows:

1. Fluidics could provide the sensing circuit for a hydraulic leveling system on a hillside combine.
2. Fluidics could provide monitoring and counting functions on planting machines.
3. Fluidics could be used for bin and hauling vehicle content level sensing.

In the research discussed in this thesis, fluidics technology was applied to the problem of automatically controlling the height of the cutter bar of a combine. Fluidics was chosen because it has had limited application in Agricultural Engineering and because it has the following inherent advantages over other methods of control:

1. Fluidic devices are rugged and insensitive to vibration.
2. Response characteristics do not change due to wear.
3. With non-contact sensing, forces required to trigger a sensing circuit are nil.

4. With the recommended filtration, moisture and dust in the atmosphere cause no problems.

5. In many cases, installation is simplified.

The following are disadvantages of fluidics:

1. An air compressor is required to supply the fluid on most agricultural machinery.

2. Fluidic tubing may not be as convenient to use as electrical wiring.

3. Fluidic components are more expensive than their electronic or mechanical counterparts.

Design of the Fluidic Circuit

The specifications set down for the fluidic circuit are as follows:

1. The circuit should be capable of receiving and processing several signals simultaneously, since a series of sensing devices is necessary to sense the ground across the width of the combine header.

2. The circuit should give priority to a "raise" signal, since the header has to clear the peaks in the soil.

3. Provision should be made for manual operation of the header for transporting and operating in crops not requiring use of the automatic header height control.

4. The fluidic control circuit should interface with the hydraulic circuit of the combine to provide the gain necessary to lift the header.

5. The fluidic circuit should perform the functions of "raise", "lower", or "hold" signalling the hydraulic valves within 175 msec (milli-seconds).

The design of the fluidic circuit to provide the logic and the hydraulic circuit to control the combine header height was idealized as shown in Figure 11. The first deviations from this design began with
securing primary components of the proposed control circuit, Figure 11, in early June, 1970. (For explanation of the fluidic symbols see Appendix A.)

One of the early obstacles encountered was procurement of the fluidic-to-hydraulic interface device. The device as designed in the circuit should be a 4-way, 3-position, spring-centered, tandem-center, hydraulic directional control valve.

Because a valve of this design with fluidic operators could not be located, the circuit was revised, Figure 12, to include two 4-way, 3-position, spring-centered, closed-center directional control valves with fluidic operators.

The valve specifications as stated by the manufacturers, Norcon (Norris) Limited, Burgess Hill, Sussex, England, for their series 218F, 1/4-inch directional control valve are:

1. Minimum signal pressure-fluidic operator--6 iwg
2. Minimum working pressure--100 psi
3. Maximum working pressure--5,000 psi
4. Nominal rated flow--4.5 gpm
5. Pressure drop across 2 ports at nominal rated flow--50 psi
6. Minimum permissible differential pressure between pressure and tank ports--100 psi
7. Response time--100 msec

These specifications appeared to be compatible with the proposed circuit.

The response time of the fluidic operated directional control valves was given in the specifications. The time was calculated for travel of the pressure signal along the length of the fluidic tube. (See Appendix B
Fig. 11. Diagram of the idealized control circuit including both fluidic and hydraulic components.

Fig. 12. Diagram of the control circuit revised to include two hydraulic directional control valves.
for response time calculations.) Also the response time of the fluidic circuit components when supplied 10 psi air was given by the manufacturers. This total time was 149 msec. The 175 msec set down in the specifications then allowed time for the hydraulic circuit to respond when the machine was operating at 4 mph or less.

A Gast, Model 1550, oil-less air compressor was selected to supply air to operate the fluidics and power the valve operators. The estimated flow required for the fluidic circuit and sensors was 10 scfm (standard cubic feet per minute). The compressor was driven at 1700 rpm to provide 14.5 cfm.

One of the areas of much needed improvement in automatic header height controls was in sensing the header position relative to the ground. All of the commercial controls at the present time use a "feeler bar", or series of fingers mounted below and behind the cutter bar, Figures 13, 14, 15, 16. These commercial designs eliminated the conflict between the unharvested crop and the sensing device, but they also provided sensing approximately 6 to 8 inches behind the cutter bar. Therefore any abrupt changes in soil surface were sensed too late to avoid running the header into the ground, Figure 17. The desirability of having a series of sensors placed ahead of the cutter bar becomes evident to the combine operator.

A mechanical feeler was designed for the system, Figure 12, with the following desirable features:

1. Sensing 12 inches ahead of the cutter bar. This distance allows time for the system to react, according to specifications, at operating speeds up to 4 mph.
Fig. 13. Massey-Ferguson, Model 410, with mechanical linkage actuated header height control and feeler bar

Fig. 14. Case, Model 960, with cable actuated header height control and feeler bar
Fig. 15. International Harvester, Model 815, with mechanical linkage actuated header height control valve and feeler bar

Fig. 16. Oliver, Model 535, with electric actuated header height control and feeler bar
2. Utilization of the non-contact interruptible jet sensor. The non-contact sensor eliminates the possibility of wear changing the sensing response.

3. Combination with a crop lifter to provide pick-up of lodged stalks.

4. Low force required for signal input eliminating the need for adjustable "height of cut".

5. Will signal "raise" even for step inputs of greater amplitude than motion of sensor.

This feeler was too sensitive because of its one inch dead zone. This narrow dead zone caused unnecessary response to small input signals. A new feeler was designed with features similar to the first, but had in addition, provision for adjusting the sensing range, Figure 18. The position of the lower link is sensed by two interruptible jet sensors, one supplying the "raise" signal and the other supplying the "lower"
Development of the Fluidic System

The development of the fluidic system will, for ease of understanding, be presented in chronological order. In mid-July, 1970, the fluidic-operated directional control valves were installed in the hydraulic system of the Allis-Chalmers Gleaner, Model K, self-propelled combine used in this study. When the hydraulic valves were manually actuated, the system functioned as expected.

The air compressor with drive, filter and pressure relief valve was installed, Figure 20. Also, installation of the fluidic circuit was completed along with a supply pressure gage and fluidic selectors for manual operation of the system, Figure 21.

The fluidic logic circuit was designed for input signals from as many as seven feelers plus the inputs from the manual fluidic selectors. The signals from the interruptible jet sensors provided the input signals for the first stage of the fluidic circuit, the OR/NOR gates, Figure 12.

The outputs from the OR/NOR gates provided the control signals for the second stage of the circuit. In the "raise" side of the circuit, the $O_1$ outputs controlled the second stage Inhibited OR gate whose $O_1$ output was connected to the fluidic operator of the "raise" directional control valve. In the "lower" side of the circuit, the first stage $O_1$ outputs control the OR/NOR gate whose $O_2$ output was connected to the fluidic operator of the "lower" directional control valve. The circuit was in the "hold" mode when it was receiving neither a "raise" signal nor a "lower" signal.
Fig. 18. Final design of mechanical feeler incorporating two interruptible jet sensors

Fig. 19. Final design of mechanical feeler with rear cover removed showing mounting of interruptible jet sensors (B)
Fig. 20. Compressor (C), 0.3 micron filter (D), and valves (E) installed on the right side of the Allis-Chalmers Gleaner, Model K, combine

Fig. 21. Operators control console consisting of fluidic circuit, supply pressure gauge, and manual selectors installed on combine
In early August, 1970, initial trials indicated that one of the valve spools was not shifting. Investigation revealed that the tank port served as drain for the nozzle in the fluidic operator. Blocking the drain effectively blocked the nozzles at each end of the spool and the spool was hydraulically balanced, Figure 22. The circuit was then revised to include a check valve, Figure 23.

The response to the fluidic signal was checked and found to be somewhat slower than expected. The feeler was installed on the header, Figure 24, to determine the effect of slow response on the system performance. As was expected, performance was unsatisfactory. The delay in response to the sensors signals was so great that the header was still raising as the system was signalled to "hold". The header would then continue to raise through the "hold" signal. It would then lower, in response to the "lower" signal, clear through the "hold" signal range until it had sufficient time to respond to the raise signal.

In an effort to compensate for the, as yet, unexplained slow response, a flow divider was added to the hydraulic circuit to slow the raise rate of the header and give the circuit time to respond, Figure 23. This action decreased the dead zone that would be required for stability of the system.

Further efforts to reduce the response time included removal of the spool centering springs, application of a signal to the second operator on the "lower" valve to move the spool out of the "lower" position, and addition of a mechanical stop at the end of the spool to assure return of the spool to the closed center position and not beyond, Figure 25. These
Fig. 22. Fluidic-operated hydraulic directional control valve with operator (F), nozzle (G) and pin (H) removed

Fig. 23. Schematic diagram of the control circuit showing the addition of a flow divider and a check valve
Fig. 24. Final design of feeler mounted on cutter bar

Fig. 25. Fluidic-operated directional control valve with operators (F), spool (J), and mechanical stop (K) removed
modifications yielded no notable change in system response.

When the directional control valves were ordered, the system pressure was specified at 2000 psi because the relief valve was set at this pressure. The system pressure was actually at 1200 psi maximum because helper springs necessary for operation of the Allis-Chalmers automatic header height control were not removed. The possibility that the reduced pressure might slow response of the valves became evident. Small compression springs were installed in the valves to assure rapid return of the actuation pins that blocked the nozzles of the fluidic operators. This modification may have reduced the response time but not to the extent that the system would perform differently from the operation observed after addition of the flow divider.

At this point in the development, the fluidic circuit was suspected of causing the slow response. Visual indicators installed in the signal lines to the fluidic operators on the valves showed the rapid response of the fluidic circuit.

Consultation with industrial representatives indicated that the 3 psi signal being received by the fluidic operators in the valves was quite adequate but the flow rate was not high enough due to the large fluidic capacitance of the bellows in the fluidic operators. In an effort to provide a greater flow rate, two Corning Digital Amplifiers were added to the circuit, Figure 26. These devices have about twice the OR/NOR or Inhibited OR output flow at a given supply pressure. With the response

\[ \text{Nutt, H., Corning Fluidic Products, Corning, New York. Capacitance of the fluidic operators. Private communication. 1970.} \]
time just noticeably reduced, the automatic header height control did not warrant field evaluation.

The development of the system was terminated at this point (October 10, 1970) because the harvesting tests had to be conducted. To continue the development, it was determined that at least one of two things would have to be done to make the system operable. Either, a fluidic circuit would have to be designed to produce much greater output flow than that produced by the circuit presented here, or a major redesign of the valves would have to take place to reduce their fluidic capacitance. A possibility might be replacing the bellows with a rolling diaphragm.

Whichever course might be followed, the development time could easily extend six months or more. The field test program was revised to include only the commercial equipment available and on hand for the 1970 harvest season.

The final hydraulic circuit configuration, shown in Figure 27, included the Allis-Chalmers automatic header height control which was functionally unaltered for the field studies which follow.
Fig. 26. Diagram of the control circuit showing the addition of two Digital Amplifiers

Fig. 27. Diagram of the final hydraulic circuit configuration allowing operation of either the fluidic system or the Allis-Chalmers header height control
COMPARATIVE TEST OF MANUAL AND AUTOMATIC CONTROLS

This comparison was originally intended to include (1) manual control, i.e. manual operation of the directional control valve in the combine hydraulic header-lift circuit; (2) commercial automatic control, i.e. the Allis-Chalmers "Genie" automatic header height control which is available commercially; and (3) the fluidic control, i.e. the automatic header height control with the incorporated fluidic logic circuit discussed earlier. For reasons discussed in the preceding chapter, the automatic header height control with the fluidic system was deleted from the comparative tests.

To achieve manual control, the operator was instructed to maintain a cutting height which he felt would enable the machine to harvest the most soybeans without running the header into the ground. This involved continuous operator observation of the position of the cutter bar relative to the crop and soil surface. If the cutter bar appeared to be cutting too low, which might cause soil to be taken into the header with the crop, the operator lifted the control lever which actuated the control valve to lift the header. If the cutter bar appeared to be cutting too high, which increased stubble and cutter bar loss, he lowered the control lever which actuated the control valve to lower the header. The working hydraulic circuit is shown in Figure 27.

To achieve automatic control, the operator simply lowered the control lever into the "detent" position thus providing continuous flow to the automatic control circuit, Figure 27. The only other requirement specified for the operator was the adjustment of cutting height, made at the
metering valve, to allow for changes in soil strength. The changes in soil strength determine how much the feeler bar paddles "dig in". Again, the instructions were to maintain a cutting height which would enable the machine to harvest the most soybeans. The operator then had to decide between cutting too low, taking soil in with the crop and cutting too high, increasing stubble loss.

Design of the Test

Randomized complete-block design was chosen for the comparative tests. The plot layout is given in Appendix C. The treatments, consisting of manual and automatic control in combination with four forward speeds, were coded according to the code given in Appendix C. These treatments were then assigned to plots within the blocks using a table of random permutations.

The same operator drove the combine throughout the test. The test was conducted within a four hour period on October 16, 1970, at the Iowa State University Agricultural Engineering and Agronomy Research Center, Ames, Iowa. The soybeans were planted in 30-inch rows with conventional weed control used uniformly throughout the plots. At the beginning of the harvest, the sky was clear with wind at approximately 15 mph. The Amsoy variety soybeans tested 13 percent moisture content with the Delmhorst Instrument Company moisture indicator. The operating speeds were set according to the speedometer provided on the machine and the reel index was maintained at 1.25 through the entire test. The combine was the Allis-Chalmers Gleaner, Model K, equipped with a 10 ft. header.
The variable measured in this test was stubble height or cutting height. A 12-inch diameter frame was placed in a plot across a row, Figure 29. An average height of the stubble within the frame was recorded for five frame placings in each plot. These five stubble heights were then averaged to give one data point for each plot.

Observations

During the harvest of the plots, several observations were made regarding operation of the machine:

1. While operating the machine with manual control, the operator had little or no time to attend to other machine functions.
2. In general, the corrections made with the manual control were larger than necessary.
3. The operator noted mental fatigue from using manual control at the high speeds.
4. A sensing system that would allow backing the machine without raising the header is needed.
5. The operator suggested that he was able to concentrate and maintain an average cutting height considerably lower on the short plot rows, than would be expected if he were to operate a whole day in the field.
6. Soil was taken into the header 5 times during the experiment with manual control and at no time did the header dig into the soil with the automatic control.

Close scrutiny of the stubble left in the plot provided additional observations regarding what actually happened during the cutting process. Lamp et al. (21) have defined "stubble loss" as the soybeans left in the pods attached to the stubble, Figure 30, and "stalk loss" as the soybeans left in the pods attached to that portion of the stem that had been cut twice by the cutter bar, and pods cut by the cutter bar, Figure 31.
It was observed that these are not the only losses that can occur due to a high cutting height. Whole pods can be cut from the stem without being shattered, Figure 32. Also pods can be caused to shatter without actually cutting the pod, Figure 33. These soybeans have also sometimes been counted as "shatter loss". Whole pods have also been knocked off the stem by yet another mechanism; i.e., slippage of the stem between the knife section and the ledger. This same phenomenon can cause soybeans to shatter. Lodged loss can also be attributed to cutting "too high" as long as the lodged portion of the soybean plant is still attached to the stem, Figure 34.

Results of the Test

The analysis of variance for 8 treatments arranged in a randomized complete-block design is given in Table 1. (The original data appear in Appendix C.) The F-test indicates that both the effect of controls and the effect of speeds were significant at the one percent level.

The table of means, Table 2, shows the average cutting height that was measured for both the automatic and manual controls. The greatest difference in average cutting height occurred at the highest speed of 5 mph. This might represent a stubble loss as high as 6 percent more for the manual control than the automatic control.
Fig. 28. Crop condition in plots before harvest looking down row

Fig. 29. Twelve-inch frame and steel tape used for measuring stubble height
Table 1. Analysis of variance of cutting height of soybeans

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blocks</td>
<td>7</td>
<td>18.15</td>
<td>2.59</td>
<td>2.19</td>
</tr>
<tr>
<td>Controls, C</td>
<td>1</td>
<td>19.91</td>
<td>19.91</td>
<td>16.87**</td>
</tr>
<tr>
<td>Speeds, S</td>
<td>3</td>
<td>21.92</td>
<td>7.31</td>
<td>6.19**</td>
</tr>
<tr>
<td>C x S</td>
<td>3</td>
<td>6.04</td>
<td>2.01</td>
<td>1.70</td>
</tr>
<tr>
<td>Error</td>
<td>49</td>
<td>58.18</td>
<td>1.18</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>63</td>
<td>124.20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

** Means significant at the 1% level.

Table 2. Means of cutting height in inches

<table>
<thead>
<tr>
<th>Speeds of operation in miles per hour</th>
<th>Overall control means</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 3 4 5</td>
<td></td>
</tr>
<tr>
<td>Manual control</td>
<td>4.6 5.2 4.8 6.8 5.4</td>
</tr>
<tr>
<td>Automatic control</td>
<td>3.7 4.2 4.4 4.7 4.2</td>
</tr>
<tr>
<td>Overall speed means</td>
<td>4.2 4.7 4.6 5.8 5.8</td>
</tr>
</tbody>
</table>
Fig. 30. Stubble loss from cutting soybean plants too high

Fig. 31. Shatter loss from cutting soybean pod
Fig. 32. Whole soybean pods lost by cutting at point of attachment

Fig. 33. Shatter loss from cutting at tip of soybean pod
Fig. 34. Lodged branch missed by cutting soybean plant too high
An automatic header height control was designed and developed using a fluidic circuit to perform the logic and fluidic sensors to pick up the signals from the mechanical feelers. The development was terminated when it was discovered the system response was too slow for field evaluation, and it was determined that the fluidic circuit or the fluidic operated control valves would have to be extensively redesigned.

Comparative field tests were conducted with an Allis-Chalmers Gleaner, Model K, self-propelled combine. The header height was controlled both manually and automatically with the Allis-Chalmers "Genie" header height control. The comparative tests were conducted at four operating speeds with one driver. The average cutting height was measured for each type control and the data were analyzed statistically.

Several types of soybean losses not previously enumerated by researchers were illustrated. Each of these losses could be avoided if the plants were cut low enough.
CONCLUSIONS

1. Automatic height control of the combine header with a fluidic system is (with appropriate development) feasible.

2. The average cutting height of a combine equipped with automatic header height control was 2 inches lower than the same machine operated manually by the same operator at 5 mph.

3. Lowering the cutting height of a header from 6.8 inches to 4.7 inches reduces the stubble loss of soybeans from 6 percent to 11 percent depending on variety, cultural practices, etc.
RECOMMENDATIONS FOR FURTHER RESEARCH

The author recommends the following as desirable further research:

1. Investigation of use of the engine exhaust as a possible power supply for the fluidic circuit.
2. Analyze and redesign the fluidic-to-hydraulic interface valves used in this study.
3. Conducting research on the use of hydraulic oil as the fluid for the fluidic system.
4. Application of the hillside combine header to the level-land combine to provide lateral header control.
5. Determination of the effect of reel speed on cutting height.
6. Application of fluidics to other control problems as mentioned in a previous chapter.
LIST OF REFERENCES


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The author is especially grateful to his dear wife, Lynn, for her indulgence and encouragement throughout the program.
APPENDIX A: EXPLANATION OF FLUIDIC SYMBOLS
Fig. 35. Explanation of typical fluidic device symbol

Fig. 36. Symbols of fluidic devices with corresponding truth tables
APPENDIX B: CALCULATION OF RESPONSE TIME

The total response time of the fluidic circuit is the sum of 1) the time required for the shock wave signal to travel the length of the tube, 2) the charge-up time for the tubing, 3) the response time of the directional control valve, and 4) the response time of the series of fluidic devices.

Transport time of a shock wave traveling at sonic velocity can be estimated as follows for air at room temperature:

\[ c = \sqrt{\frac{k}{\gamma} R T} \]

where
- \( c \) = velocity of sound \( \ldots \text{ft/sec} \)
- \( k \) = ratio of specific heats \( \ldots 1.4 \)
- \( g \) = acceleration of gravity \( \ldots 32.2 \text{ ft/sec}^2 \)
- \( R \) = gas constant \( \ldots 53 \text{ ft-lb/lb-}^\circ R \)
- \( T \) = temperature \( \ldots 530^\circ R \)

At room temperature, sonic velocity is 1100 ft/sec or approximately 1 msec per foot.

A finite amount of time is also required to charge-up the fluidic lines because of the compressibility of the fluid (air). This time is proportional to the volume of fluid under compression and inversely proportional to the quiescent flow:

\[ t = \frac{a}{Q_0} \]

where
- \( t \) = time \( \ldots \text{sec} \)
- \( a \) = tube cross-sectional area \( \ldots 0.023 \text{ in}^2 \)
Then

\[ l = \text{length of tube} \ldots .20 \text{ ft} \]

\[ Q_0 = \text{quiescent flow} \ldots .0.12 \text{ scfm} \]

Then

\[ t = \frac{(0.023 \text{ in}^2)(20 \text{ ft})(60 \text{ sec/min})}{(0.12 \text{ ft}^3/\text{min})(144 \text{ in}^2/\text{ft}^2)} \]

\[ t = 0.016 \text{ sec or } 15 \text{ msec} \]

The response times listed by the respective manufacturers were 100 msec for the directional control valve and 5 msec maximum for each of the fluidic devices. Each signal switches three fluidic devices in series requiring a total of 20 msec.

The total response time is given as follows:

\[ T = \frac{1}{c} + t + V + nF \]

where

\[ T = \text{total response time} \ldots .\text{sec} \]

\[ l = \text{length of tube} \ldots .20 \text{ ft} \]

\[ c = \text{velocity of sound} \ldots .1100 \text{ ft/sec} \]

\[ t = \text{charge-up time of the lines} \ldots .0.016 \text{ sec} \]

\[ V = \text{response time of the directional control valves} \ldots .0.100 \text{ sec} \]

\[ n = \text{number of fluidic devices in a series} \ldots .3 \]

\[ F = \text{response time of individual device} \ldots .0.005 \text{ sec} \]

Then

\[ T = \frac{20}{1100} + 0.016 + 0.100 + (3)(0.005) \]

\[ T = 0.149 \text{ sec or } 149 \text{ msec} \]

If the machine is operating at 4 mph, it will travel 0.87 ft in 0.149 sec.
APPENDIX C: COMPARATIVE TEST DATA

Table 3. Data recorded for header height control comparative test\textsuperscript{a}

<table>
<thead>
<tr>
<th>Control</th>
<th>Speed (mph)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual</td>
<td>2</td>
<td>4.1</td>
<td>4.8</td>
<td>3.9</td>
<td>5.8</td>
<td>4.6</td>
<td>4.9</td>
<td>4.4</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6.1</td>
<td>8.8</td>
<td>4.3</td>
<td>3.9</td>
<td>4.4</td>
<td>5.3</td>
<td>4.6</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4.8</td>
<td>4.9</td>
<td>5.4</td>
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<td>5.9</td>
<td>3.8</td>
<td>4.2</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6.2</td>
<td>13.0</td>
<td>4.5</td>
<td>6.7</td>
<td>5.7</td>
<td>5.6</td>
<td>6.3</td>
<td>6.4</td>
</tr>
<tr>
<td>Automatic</td>
<td>2</td>
<td>3.3</td>
<td>3.4</td>
<td>3.8</td>
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<td>3.8</td>
<td>3.9</td>
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<td>5.4</td>
<td>4.3</td>
<td>4.5</td>
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<td>4.2</td>
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<tr>
<td></td>
<td>5</td>
<td>3.9</td>
<td>4.9</td>
<td>4.4</td>
<td>4.9</td>
<td>4.7</td>
<td>4.2</td>
<td>5.1</td>
<td>5.6</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Each datum is an average of five measurements.
Fig. 37. Plot lay-out for randomized complete-block design experiment

<table>
<thead>
<tr>
<th>PLOT NUMBER</th>
<th>TREATMENT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MPH, MANUAL CONTROL</td>
</tr>
<tr>
<td>2</td>
<td>MPH, MANUAL CONTROL</td>
</tr>
<tr>
<td>3</td>
<td>MPH, AUTOMATIC CONTROL</td>
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<td>6</td>
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</tr>
<tr>
<td>7</td>
<td>MPH, MANUAL CONTROL</td>
</tr>
<tr>
<td>8</td>
<td>MPH, AUTOMATIC CONTROL</td>
</tr>
</tbody>
</table>
Fig. 38. Means of cutting height versus operating speed, data from Table 2