A COMPOUND HELICAL CUTTERBAR-
DESIGN AND FIELD TESTING

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CHAPTER I

INTRODUCTION AND OBJECTIVES

Introduction

Harvesting of forage and cereal crops often begins with the cutting operation. Since cutting is only one in a long series of operations, it is expedient that this procedure be completed in as quick and efficient a manner as possible to help reduce harvest costs and losses.

In forage crops there are two major cutting objectives. Firstly, the speed at which the cutting operation occurs is important if losses due to weather are to be minimized. Secondly, the closeness and cleanliness of the cut are important from the standpoint of yield per acre.

For cereal crops there are again two major cutting objectives. As in the case of forage crops, the first objective is speed. The second is again yield, but rather than being associated with closeness of cut, it is related to seed loss. If the plant is subjected to large amounts of agitation during the cutting process, seed loss is increased due to shattering.

One point must be kept in mind with respect to all the objectives mentioned above. This is the power consumed in order to achieve any particular objective. If power usage increases to such an extent that it economically masks the advantage attained, the solution is no longer appropriate.

The cutting mechanism presently used on most agricultural machines is the reciprocating cutterbar or, as it is sometimes known, the sickle bar. Often used in conjunction with this cutter, especially in cereal crops, is a reel. The reel has three main functions: 1) to move the crop into the cutting area and align it for improved cutting, 2) to hold the crop during cutting, and 3) to prevent chopping of the crop by moving it away from the cutter into an appropriate collection device.

The basic design of the reciprocating cutter is far from ideal. There is the inherent disadvantage associated with any reciprocating action, that is, speed. Conventional pitman drives are limited to 1000 rpm, while dynamically balanced systems may operate at up to 1200 rpm (40). If forward travel per stroke is limited to a maximum of four inches as recommended by Kepner (39), this would allow a ground speed of nine mph. Generally, however, only three in. per stroke is recommended to avoid a ragged and uneven stubble. This limits ground speed to only 6.8 mph and results in low capacities.

There is a great waste of energy in a reciprocating system. A large quantity of energy is consumed in the constant acceleration and decceleration of the knife; this energy is wasted as it is not used directly in the cutting operation. Associated with the reciprocating cutterbar are large amounts of inherent friction. Not only does this consume and thus waste energy, but it also increases wear, thereby increasing operating costs.

Another disadvantage of the reciprocating cutterbar system is seed loss in cereal crops. The reciprocating motion of the knife induces a shaking action in the crop which can increase seed loss and reduce yield. The reel also increases seed loss. As each slat of the reel comes in contact with the crop it actually hits the stalks unless reel speed and ground speed are perfectly matched. This striking action causes shattering of the seed heads and a reduction in the crop yield. In some seed crops it has been shown that cutterbar losses account for 65 to 80 percent of the total seed loss in a combine (55, 61).

A second cutting unit, sometimes used in the harvesting of forage crops, is the flail type mower. There are, however, two main disadvantages associated with this unit. Firstly, the crop is chopped up to such an extent that the finer pieces are lost during the collection operation, resulting in a 5 to 10 percent reduction in yield (40). Secondly, if the ground surface is fairly rough, the flailing action can cut the high spots off the ground. This soil is then mixed with the forage, contaminating it as a feed as well as making it more susceptible to spoilage during storage.

Power consumption in the flail type mower is considerably higher than in the conventional mower as the stems are cut more than once. Unless the forage is to be chopped, any energy expended in this second cutting is wasted. In addition, the flail type mower has an added disadvantage in that it can be used only for forage crops, thus requiring a farmer to invest in two cutting units.

It was with these disadvantages of present cutting methods in mind that Bledsoe (5) in 1969 developed and laboratory-tested a rotary sickle having a compound helical knife configuration. This unit was claimed to be capable not only of cutting the stems but also of trajecting them out of the cutting area, thus eliminating the need for a reel.

This cutter proved very successful in the laboratory, thus it was decided that the next logical step in the testing and development of the new cutting device should be field testing. It is with this idea that the objectives for this research and thesis were developed.

Research Objectives

1. Modify the original design and fabrication procedure developed by Bledsoe to achieve the following:

   A. a design that allows easy replacement of the various components of the cutting unit, and

   B. a method of manufacture that can be used in mass production of the components.

2. Determine a method to correct the loss of edge on the cutting surfaces brought about through usage.

3. Observe and evaluate the unit in the field to determine the optimum combination of design and operating parameters in several representative forage and cereal crops, with consideration being given to power requirement, speed of operation, trajection of the severed stalks, and quality of cut.

4. Compare the new cutting unit to a reciprocating cutterbar to determine whether it has significant advantages over the present system to warrant its practical use.

CHAPTER II

REVIEW OF LITERATURE

Many types of cutters used for the harvesting of agricultural crops have been developed and reported in the literature over the last 80 years, with their inventors claiming numerous advantages over conventional mowing machines. This review, however, is not intended to be a complete survey of all the inventions.

For the purpose of clarification the review has been divided into four sections. These are: 1) sickle bar improvements, 2) continuous cutting loops, 3) vertical axis cutters, and 4) horizontal axis cutters.

Sickle Bar Improvements

In 1954 Elfes (18) stated that the only two ways to increase output with a single knife reciprocating mower were to increase cutterbar length, or to increase knife speed. The latter case would allow ground speeds to be increased while maintaining the forward travel at three in. or less per stroke of the knife, thus avoiding a ragged and uneven stubble. Elfes concluded that the first solution was not feasible due to structural problems, and thus developed a new type of drive in order to increase operating speeds. The drive consisted of a two-throw crankshaft driven by a V belt. One throw of the crank drove the knife while the second drove a counterweight in a direction geometrically similar but opposite in sense to that of the knife. Field testing of the new drive system proved successful as unbalanced forces were negligible for speeds of up to 1350 rpm. This higher speed then allowed higher ground speeds and an increase in acres mowed per hour as compared to a conventional mower limited to 1000 rpm.

In 1962 Harbage and Morr (27) used Elfes' first solution of increasing cutterbar length to increase capacity. They contended that counterbalancing was not the answer since seven or eight mph was the maximum speed that an operator could stay on a tractor and maintain control for most field conditions.

The authors selected 10 ft. as their design length. They found the knife head had to be redesigned to take the increased loads but that the pitman and ball used on seven foot mowers were satisfactory for the 10 foot model. In addition, the cutterbar had to be strengthened to take the additional drag forces. Field tests showed the unit to have a 45 percent increase in capacity over the conventional seven foot mower for the same ground speed.

In the last five years, several other patents have been granted which claim increased operating speeds or increased life by introducing some type of counterbalancing device on the drive mechanism (9, 26, 59, 33). The only differences existing among the patents is the orientation and size of the balancing masses used and in their connection to the drive system.

Several patents have recently been introduced which are intended to improve quality of cut by altering the knife, ledger, or guards. The patent by Pool (54) has knife sections which are beveled on the top back corners. As these slide under the guards they hold the knife down, increasing cutting effectiveness.

Three patents employ knife sections in which one cutting surface faces up while the other faces down (58, 71, 6). This balances cutting forces on each section, thereby preventing the lifting of the knives off the ledgers during shearing. Used in conjunction with these knife sections in two of the patents are guards placed alternately on the top and the bottom of the knife (58, 71). This helps to hold the knife in proper cutting alignment and increases cutting effectiveness.

Cullimore (16) suggests guards in which the lip has a spring action. The lip then forces down on the knife producing good knife-to-ledger contact, increasing cutting effectiveness. This invention then eliminates the need for hold-down clips.

Two other inventors have modified the guards so that the serrated, or cutting, edge is an integral part of the guard eliminating the need for ledger attachment (14, 35). In Jerman's (35) case the guard is serrated at the top and bottom of the knife passage. He claims this eliminates clogging and uneven cutting while reducing wear on the moving parts of the sickle.

In a more novel approach, McNair (44) has completely reversed the order of the parts in a reciprocating cutterbar. He has suggested making the bottom cutter move while the top cutter becomes the stationary surface. In essence, this means holding the knife still and reciprocating the ledgers. The advantages claimed by the patentee are twofold: 1) improved performance and 2) easily replaceable upper teeth.

A method used to reduce vibration and increase dynamic balance during cutting is the employment of two knives acting in opposite directions. Buchholz (8) divided the cutting length into two sections, one moving in the opposite direction to the other. Hinks (31) also used two knives, however one was mounted on top of the other giving a scissor-like action.

Beusink (4) employed an oscillating series of knives linked to an eccentric drive such that they moved in symmetrically opposite directions for vibration-free operation. The device consists of a series of knife pairs which are pivoted at their bases. A drive bar is pivotally connected to the knives about one-third of the way along their length. As the bar is reciprocated, the knives oscillate. Claimed advantages, in addition to reduced vibration, are higher operating speeds and reduced friction due to the pivotal rather than sliding nature of the cutter's operation.

In a novel drive means, Cousino (15) uses an impact to provide the reciprocating action to two knives, one mounted above the other. A cam-like device rotates and strikes the end of a knife section causing it to move the length of its stroke. A spring then returns the knife and it is ready to be struck again. This occurs for each of the knives simultaneously, only in opposite directions. The inventor claims a balanced operation with speeds of up to 3000 movements per minute being attainable. This then increases mowing capacity considerably over conventional mowers, which operate at only 2000 strokes per minute.

Continuous Cutting Loops

There are four patents claimed in the last five years which utilize blades fastened to a revolving belt as the cutting mechanism (32, 42, 25, 43). In all but one design (32), the belts rotate about a vertical axis and have self-sharpening teeth imbedded which extend horizontally outward. The size, constructional material, and spacing of the teeth are generally the only variations among the cutters. A view of one of these units is shown in Figure 1a.

In one of Hofer's (32) designs, Figure 1b, the teeth are not self-sharpening but are replaceable. In another model, the teeth extend in both directions, front and rear, allowing the belt to be turned over to provide a new set of cutting edges. These teeth, however, are not replaceable.

The second class of continuous cutting loops may be called chain cutters. These are very similar to the belt cutters previously described except that a chain rather than a belt is used to move the knives. In Quick's (56) patent, the chain is divided into two sections. Each half of the cutterbar has teeth moving to the outside. This action is claimed to have the advantages of: 1) balancing of the cutting action and forces, and 2) reducing header seed loss. This latter advantage is a result of the bases of the cut stalks being pushed to the outside, leaving the heads pointing inward. This alignment of the cut stalks supposedly leads to gentler feeding of the material.

The third class of continuous cutting loops might be entitled cable cutters. A unit patented by Henzman (29), and shown in Figure 1c, employs a cable rather than a belt rotating about a vertical axis. The cutting produced by the cable is then a combined impact and sawing action. Cable cross sections can be varied to provide several cutting surfaces. Three possible cross sections are shown in Figure 1c.

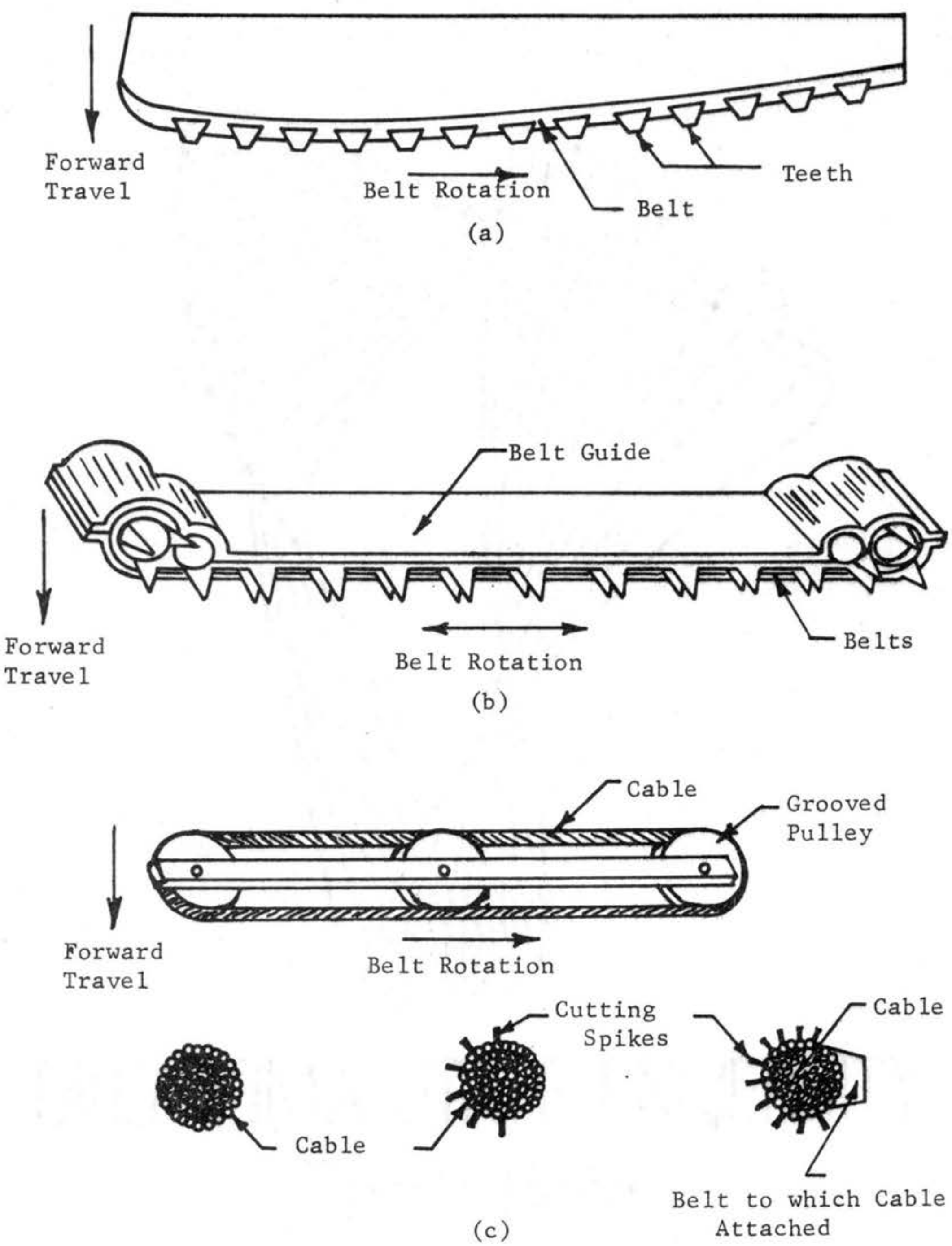


Figure 1. Continuous Cutting Loops: (a) Vertical Driven Belt, (b) Horizontal Driven Belt, and (c) Cable Cutter

Vertical Axis Cutters

Included in this general group of mowing machines is the rotary type commonly used for lawns or in agricultural purposes for the cutting of weeds and small brush. These, however, are not used for the harvest of agricultural crops since the crop is cut many times, reducing it almost to a pulp. Two machines of this type have been patented recently by König (38) and van der Lely (69).

In recent years however, there has been developed a series of cutters using a rotary action about a vertical axis in which the crop is not chopped up. These units, then, are suitable for the harvesting of forage and cereal crops. This type of cutting unit can be classified in two groups. One group has the drive train above the cutting surfaces while the other has the drive train below.

If consideration is first given to those driven from above, it can be noted that 13 patents have been granted on such units in the past five years. Generally each of the mowers utilizes only four rotary assemblies for the entire cutting length. Each of these rotary assemblies usually consists of a drum, a knife and a skid shoe as illustrated in Figure 2a by an enlarged view of Glunk's (21) rotor. Two other drum type cutters as patented by Zweegers (72) and van der Lely (68) are shown in Figures 2b and 2c respectively. Glunk (22) and Zweegers (73, 74) later followed their original patents with improved knife design allowing for increased safety. The knives were also made more readily accessible, making blade replacement easier. In 1971, Glunk (23) again modified his original unit by adding a deflection shield. This was done to form a single windrow instead of the two previously formed,

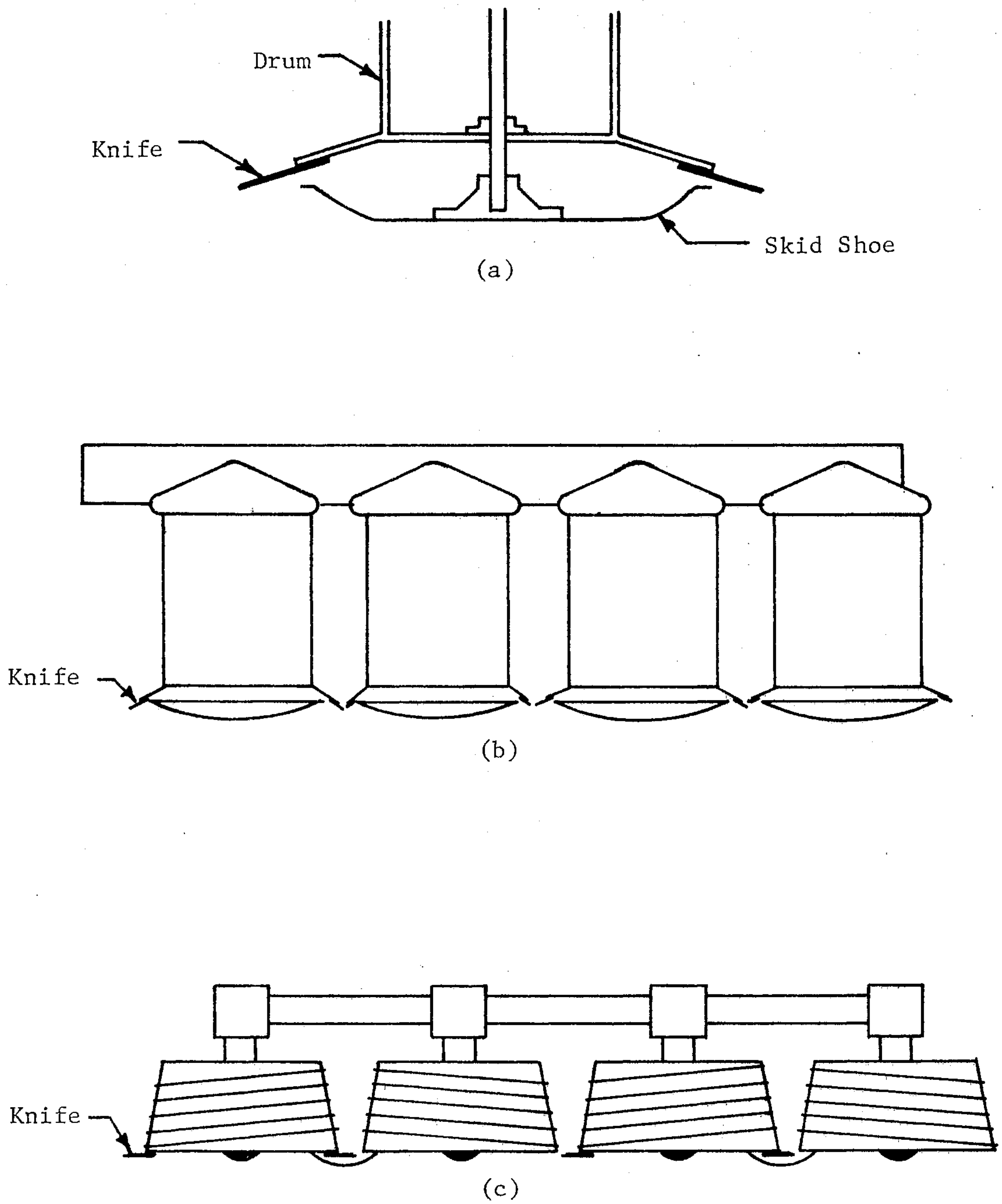


Figure 2. Vertical Axis Cutters - Top Drive. Patented by (a) Glunk, (b) Zweegers, and (c) van der Lely

making collection of the cut material easier.

In 1969, Gorham (24) patented a rotary cutter having overlapping disks which were self-sharpening. In addition, each disk had a different peripheral speed with the inventor claiming minimum vibration as a result. Clogging was not found to be a problem as it was for some of the earlier drum types.

The drum type rotary cutter has been suggested for use in conjunction with conditioners. Scarnato (60), who patented such a unit, claimed the drums threw the cut material into the conditioner, thus improving the feeding mechanism and eliminating the need for a reel. In addition it was claimed that the drums tended to spread the crop before it entered the conditioner, allowing for a more uniform conditioning.

In 1972, Peacock (53) patented a mower-conditioner in which the conditioning rollers rotated about a vertical axis behind the knives. That is, each pair of cutters had a separate pair of rollers. The advantage claimed here is that only short rollers are needed, thus reducing production costs.

Previous to this, Gaertner (20) had patented a similar unit for row forages only. The difference between the two units lay in the fact that Gaertner's had the knives mounted directly on the bottom of the rollers. The plants were then actually held and crimped while cutting occurred. In 1970, Schertz (61) developed and field-tested a similar unit intended for use on soybeans. Instead of the rollers being hard for crimping of the cut material, they were padded so as to gently grab the plants and transfer them and their seeds to a gathering mechanism.

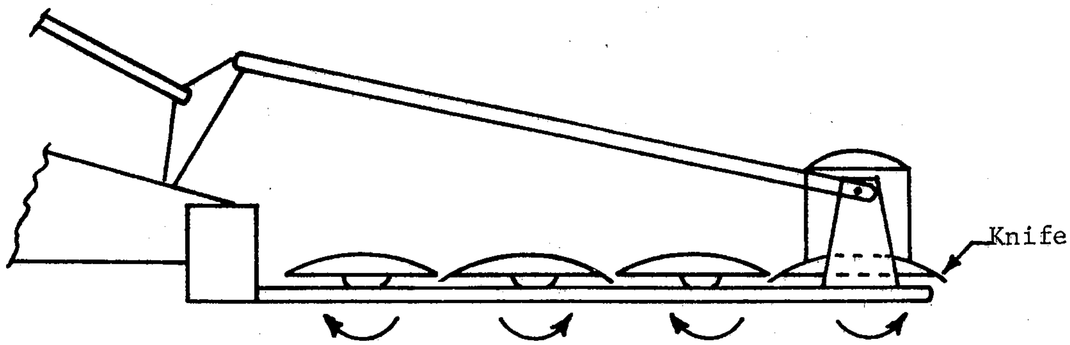
The second class of vertical axis cutters are those driven from below. Two types, as patented by Heesters (28) and Kline (41), are shown in Figures 3a and 3b respectively. Here again, only four rotors per cutterbar are used. Generally, the patentees claim a gentle cutting action and closeness of cut with Heesters even claiming his machine to prevent seed loss by virtue of the ease of the cutting operation.

Eder (17) has a slightly different unit in that the disks are helical in shape and overlap as is shown in Figure 3c. The shape is intended to lift the crop after a single cutting and convey it over the cutters and into a swath. A commercially available unit called TAARUP (66) is presently in production following this basic design.

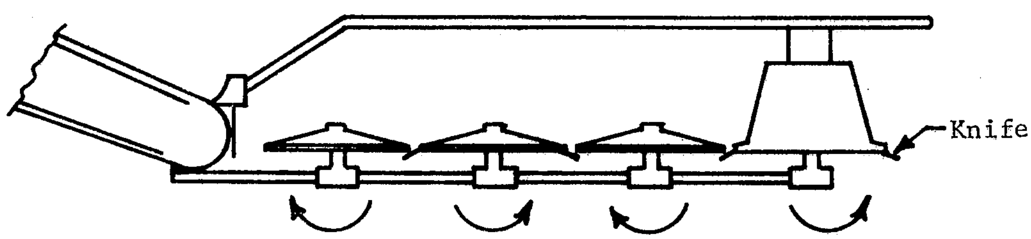
The operating speeds of all the vertical axis rotary cutters vary from 1500 to 3000 rpm (30). It is with these speeds that such units claim their greatest advantage, for ground speeds of up to 16 mph are then possible. If width of the units is considered, this translates into a capacity of approximately 10 acres per hour. It should be remembered here that most of the units are very narrow, with six feet being the largest. Dākon, however, manufactures a mower with a cutting width of eight feet ten inches (67).

Horizontal Axis Cutters

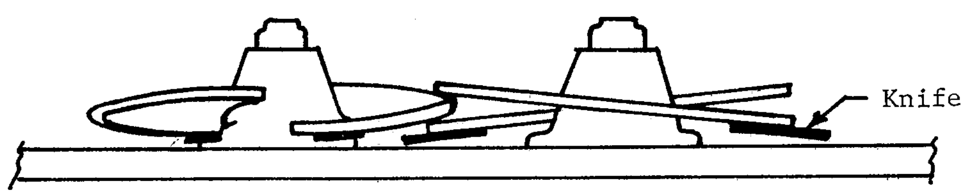
Included in this group are the flail mowers used for agricultural purposes and the reel type lawn mowers. Neither of these will be mentioned further except to say that there have been numerous new flail mowers and modifications to existing units patented in the last five years. This review, however, is confined to horizontal axis cutters having their cutting surfaces attached to the drive shaft in a fixed manner such that the action of their cutting edge is helical in



(a)



(b)



(c)

Figure 3. Vertical Axis Cutters - Bottom Drive. Patented by (a) Heesters, (b) Kline, and (c) Eder

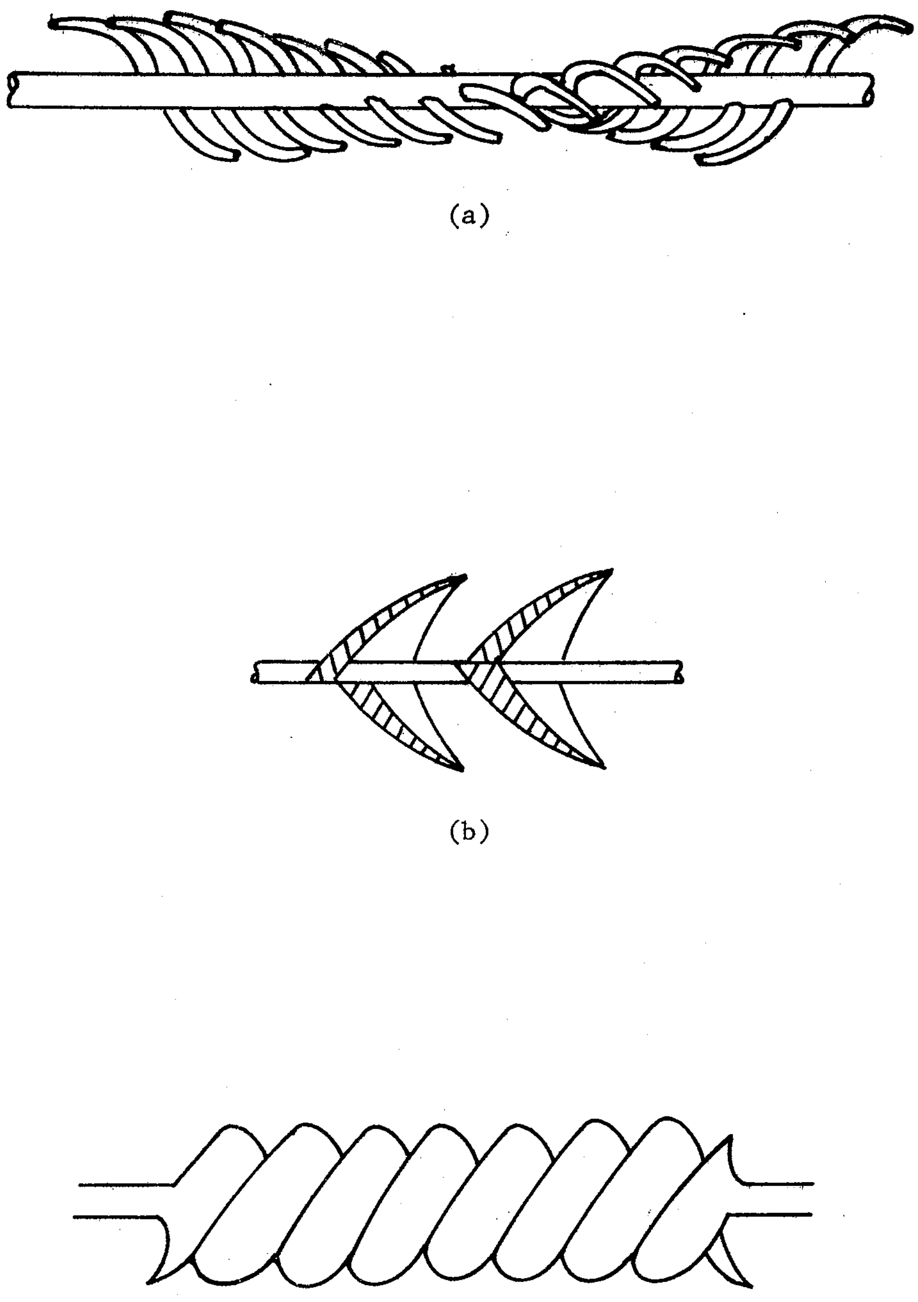
nature. Cutters of this type may be divided into two groups: 1) curved blades attached to a shaft, and 2) disks attached to a shaft.

Considering the blade type first, it may be noted that this is not a new idea. Beekman (1,2) received patents on two such devices, one of which is shown in Figure 4a, in 1893. In his patent claims he refers to a helical cutting edge lying in the surface of a cone. The cutter consisted of a series of spiral fingers which projected to form hooks. When rotating, these hooks fed the grain uncut by one series of knives into the next.

In 1927, Newton (47) patented a device very similar to Beekman's in that the blades were wrapped in a helical manner about the axis of rotation. A view of the cutter is shown in Figure 4b.

In 1936, Waller (70) patented a cutter "having a plurality of helically disposed cutting blades provided with cutting faces disposed forwardly in the direction of rotation." The rotating member's outer edge worked against a stationary blade to produce the cutting action. This unit thus relied on double rather than single element impact cutting. A view of the cutter is shown in Figure 4c.

The rotary horizontal axis cutter using disks, attached at an angle to the shaft, as the cutting elements is not a new idea either. In 1942, Newton (48) received a patent for a mower in which a series of elliptical-shaped disks were mounted on a shaft at an angle to the axis of rotation. As shown by Figure 5a, a series of V-shaped stationary cutting surfaces were mounted below the disks. As the cutter rotated, the crop was separated into bunches which were then sheared between the disks and V-shaped sections. The cutting thus actually took place first in one lateral direction and then in the other.



(a)

(b)

(c)

Figure 4. Horizontal Axis Cutters - Blade Type. Patented by (a) Beekman, (b) Newton, and (c) Waller

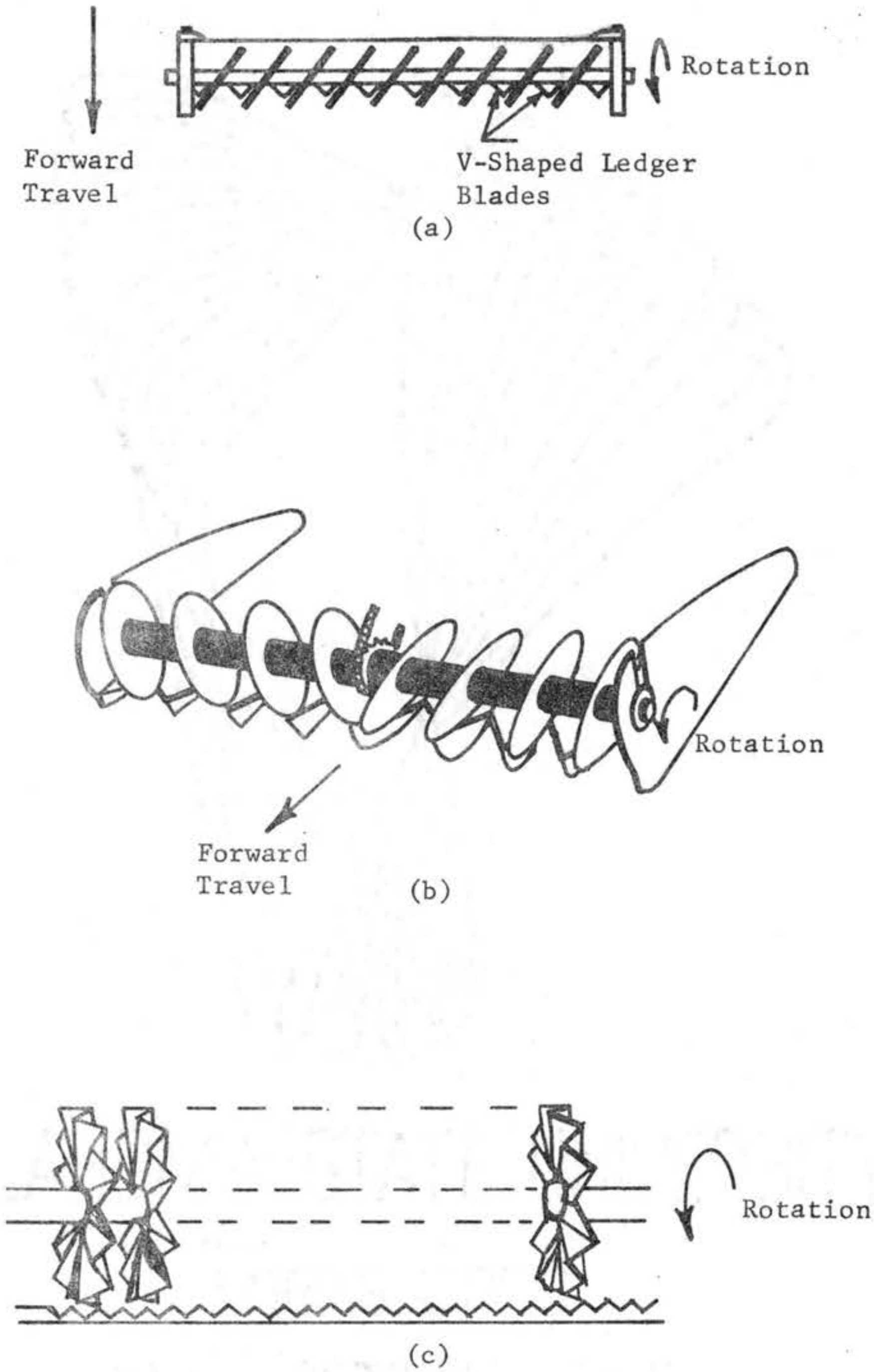


Figure 5. Horizontal Axis Cutters - Disk Type with Rotation Downward at Front. Patented by (a) Newton, (b) Brauer, and (c) Benson

Five other inventors patented cutters similar to Newton's (7, 37, 57, 3, 62). In each case but that of Remonte (57), a series of V-shaped stationary cutters were used below the rotating member. Remonte, on the other hand, used a straight edge as the opposing surface. Cutting then took place by two element shear brought about by the downward rotation of the front of the rotating member against the stationary knife. Apart from Brauer's (7) and Benson's (3) cutters, depicted in Figures 5b and 5c respectively, all the rotating elements of these units were essentially indiscernible in appearance from that of Newton's design and hence are not shown.

In 1958, Chambliss (12) received a patent on a cutter which again had members mounted on a horizontally rotating shaft at an angle to the axis of rotation. This unit had several unique aspects in comparison to the previously mentioned patents. Firstly, the cutters were not disks but were square plates mounted at an angle to the shaft. Each plate edge was serrated and the plates themselves were mounted loosely on the shaft allowing them to yield when striking a hard object, thus preventing serious damage. The serrated edges on the plates helped to straighten up a leaning crop, making it more easily cut by the following plate edge. The serrations were also able to cut any horizontally-disposed vegetation, thus making the machine capable of cutting crops leaning at any angle.

The second main difference between Chambliss's cutter and previous designs was the direction of rotation, with Chambliss's cutter rotating upward at the front. The third difference was that the unit was used without a stationary cutterbar and relied on impact or single element cutting in its operation. A front view of Chambliss's cutter is shown in Figure 6a, while a top view is shown in Figure 6b.

Miller (46, 45) developed and tested another rotary cutter generally following earlier patents in that a series of disks were mounted at an angle to a horizontal shaft. Thus, as with earlier cutters, the edges of the disks traced a helical path during rotation. However, the differences between earlier patents and Miller's design were twofold: 1) upward rotation of the leading edge of the cutter, and 2) use of curved guards and ledgers as the opposing cutting edge. Impact cutting was not used by the author, as he stated that it would tend to chop and shred rather than mow.

In a series of field tests at rotary speeds of 6750, 5650, 3600, and 3380 rpm, Miller found the unit effective in cutting, with the only problem coming in the feeding of the stalks into the cutting area. Finer crops also produced some problems in that they bent and passed between the cutters and ledgers and were not sheared. Miller found the cut stalks to fall to the rear of the cutterbar with clogging or wrapping up of the cut materials around the rotor to be absent. Thus, the unit was generally judged satisfactory in accomplishing the main objective of increasing capacity while cutting satisfactorily. The cutter was considered capable of ground speeds of two or three times conventional mowing speeds.

In 1970, the latest patent concerning a rotary cutter was granted to Cassady (10). This device used a square rather than a circular shaft and had the added difference that only portions of disks were mounted on it. A side view of a cutting disk appears as a "figure 8" as shown by Figure 6c. Blades then were attached to the disks on the top and bottom of the "8", rather than using the disk edges as the

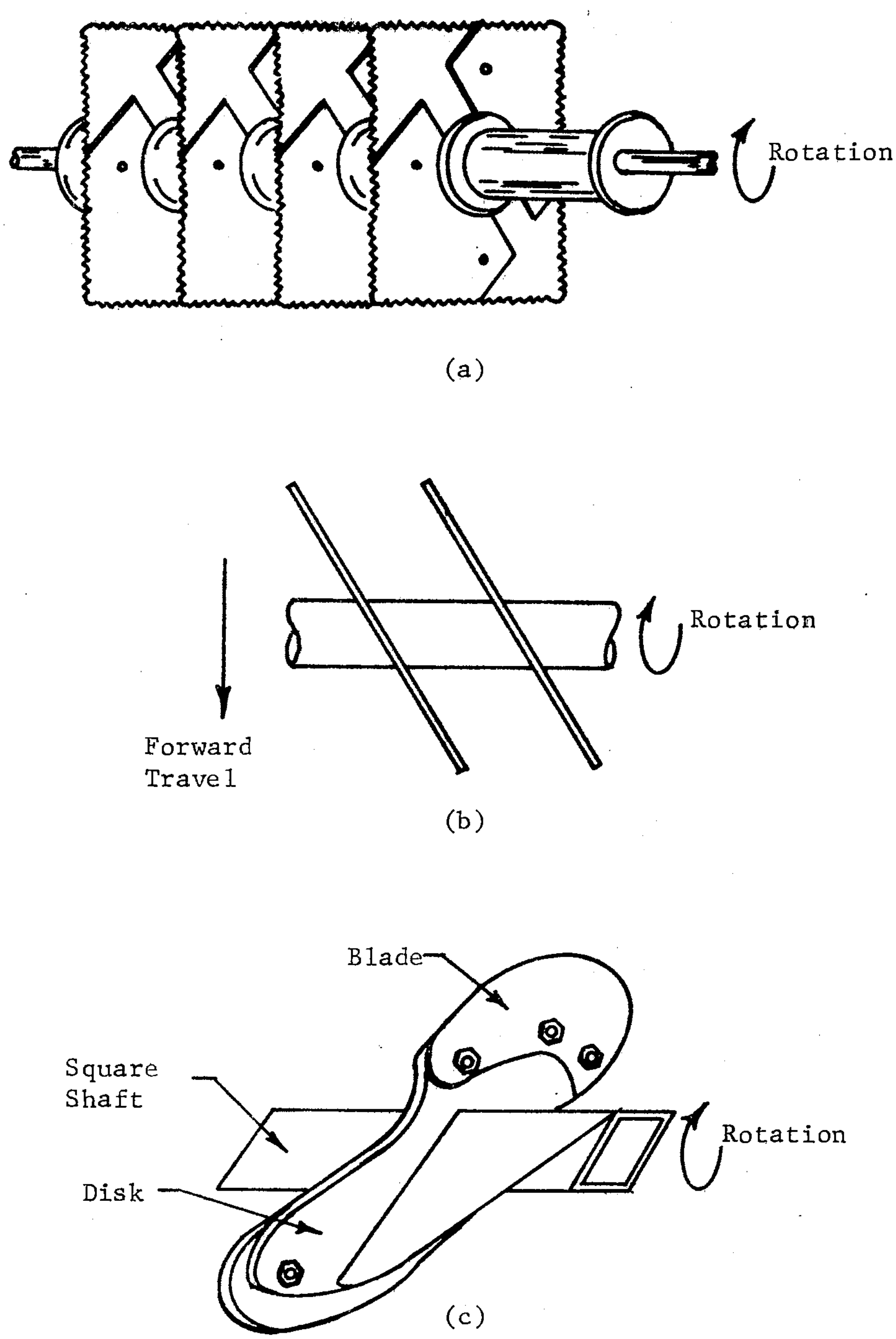


Figure 6. Horizontal Axis Cutters - Disk Type with Rotation Upward at Front. Patented by Chambliss, (a) Front View and (b) Top View; and by (c) Cassady

cutting surfaces. No stationary cutting surface was employed in conjunction with the ten inch diameter rotor as the unit relied on impact cutting for its mode of operation. Rotary speeds of 3600 to 4000 rpm were recommended for the cutter with the severed stems then being trajected up and over the rotor, preventing chopping up of the severed stalks.

One other rotary cutting unit developed along the same lines, that is a horizontally rotating shaft upon which sections of disks are mounted, was built and tested by Bledsoe (5). Details of this study will not be dealt with in this review, as they will be brought out in further chapters of this thesis.

CHAPTER III

DESIGN AND CONSTRUCTION OF THE CUTTING UNITS

Helical Cutters

The basic design of the cutters, particularly in relation to the cutting surfaces, followed Bledsoe's (5) design criteria established through his extensive laboratory testing. With this in mind then, it is best to look at Bledsoe's cutter before entering into the discussion of any modifications that were made for the field model.

Bledsoe classified his cutter as a "modified elliptical disk design" as only portions of elliptical disks were used. The basic cutter diameter of <u>three and one-half inches</u> chosen by Bledsoe was a compromise between adequate peripheral speeds needed to meet the criteria of impact cutting and space limitations. Each half of a cutting unit appeared V-shaped in a top view with an identical sector placed diametrically opposite the first cutter on the rotor shaft with the "V" pointing in the opposite direction. This orientation then provides a basic static balance to the cutter assembly. Bledsoe actually built and tested only one-half of the V-shaped sector, as a cutter is symmetrical about its axial centerline. Eliminating half of the cutter was thought not to decrease the accuracy of the results but rather reduced fabrication procedures and problems.

Each half of the V-shaped sector consisted of a sector of an elliptical disk placed at an angle to the rotor shaft, such that its periphery lay in the surface of a right circular cylinder with an axis identical to that of the rotor shaft. Top and side views of the base disk mounted on the shaft are shown in Figure 7. These disk edges then approximated cylindrical helicies with a helix angle equal to the angle between the plane of the disk and the plane of rotation. The left side of the V-shaped sector formed a right-hand cylindrical helix and would deflect stems to the left, while the right side of the sector formed a left-hand cylindrical helix and would deflect stems to the right.

At the periphery of each disk sector, a ledge was extended transverse to the disk face. This ledge, shown shaded in Figure 8, had a bevel angle of 30 degrees measured parallel to the rotor axis at every point along its edge. The actual cutting blades were fastened on this ledge using small machine screws.

Originally, Bledsoe constructed four such rotary cutters having four different knife angles. These angles were 26, 36, 46, and 56 degrees. Through the laboratory testing, the 46 degree rotor was found to have the best configuration in providing for the optimum combination of the power requirements and most favorable trajection of the severed stems. In addition, each rotor was tested using both dull and sharp blades, with the latter proving to be better.

Thus from Bledsoe's design, there are four dimensions or criteria to be adhered to in the construction of a field model: 1) a cutter diameter of three and one-half inches, 2) a knife angle of 46 degrees, 3) a knife bevel angle of 30 degrees, and 4) sharp blades.

Since ease of production and ease of cutter replacement were

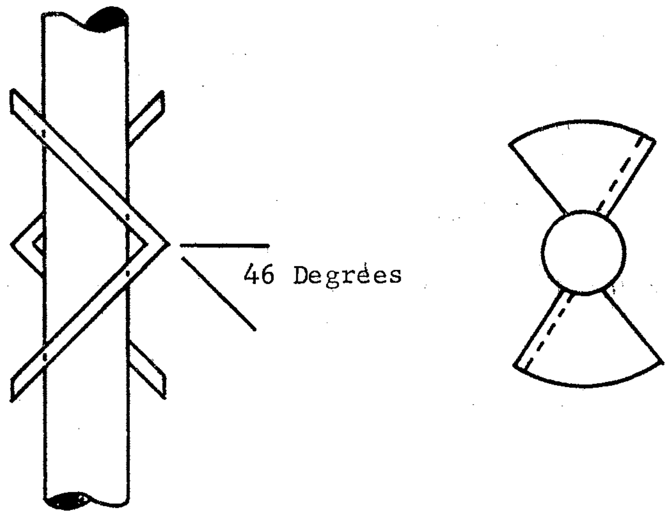


Figure 7. Top and Side Views of the Base Disks as Mounted on the Shaft

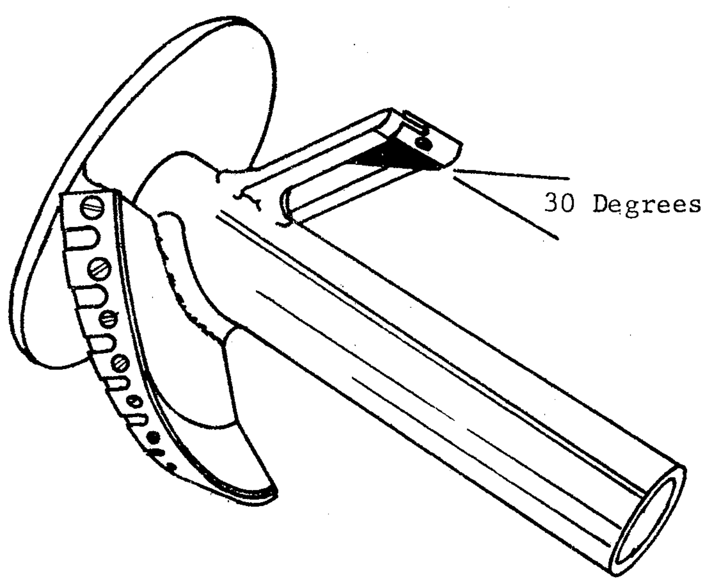


Figure 8. Drawing of One-Half of a Cutter Showing the Ledge Attached to the Base Disk and the 30 Degree Bevel Angle

essential elements for a field unit it was decided that casting would lend itself well as a solution. In addition, the use of integral blades in the casting would eliminate the problems of blade attachment and perhaps lend the cutters to some degree of self-sharpening during cutting.

To help visualize and facilitate design of the cutter, several models were constructed using modeling clay, and one was fabricated using a section of one inch shaft and sectors cut from one-quarter inch plate. Various cutter configurations and attachment means were considered until the final shape was decided upon.

The next step in the cutter design and construction was to enlist the aid of a professional patternmaker at a commercial foundry to make the balsa wood master pattern. Using the author's clay models, the master pattern was constructed and finally completed after many revisions and several sample castings. For economic reasons, sand casting was used; however, the rough casting formed was a problem. In addition, no sharp edges could be poured, as was desired for the cutting edge, since such an edge would fail to run during the casting. Also, if such an edge happened to pour, it would cool very rapidly due to its thin cross section, making it very brittle when compared to the rest of the cutter. This would lead to easy breakage or shattering of the edge upon impact with any hard object.

To correct for these problems, one-eighth inch of machine stock was added to the inside and outside radii of the cutters. In addition, the cutter edge was poured blunt to facilitate casting and eliminate breakage during cleaning of the rough casting at the foundry.

The choice of metal from which the casting was to be poured was made upon the advice of metallurgists and salesmen at the foundry. An 8640 alloy steel was used. This is a nickel-chromium-molybdenum steel which is very hard and tough, yet not brittle. Such a steel would lend itself to holding a sharp edge upon machining, but would not fracture easily upon striking a hard object.

Following receipt of the castings from the foundry, it was necessary for the cutters to undergo a series of machining operations. In three of the operations, specially-constructed jigs were employed. This was found necessary to ensure uniformity among the cutters, as well as to hold the rather oddly-shaped units during the machining processes.

The first operation was the machining of 0.5 in. radius on the base of the cutter. This was done to ensure a close and repeatable fit between the cutter and the ground one inch drive shaft. Initially, this operation was omitted and the rough casting was bolted directly to the shaft. It soon became evident, however, that this could not continue if any accuracy in the cutter diameter was to be maintained. This then led to machining in a specially-constructed jig. To cut the 0.5 in. radius, a one inch endmill was placed in the chuck of the lathe. The jig was then fastened to the lathe carriage and moved into the rotating endmill.

Following this operation, the five-sixteenths inch bolt hole, used for the attachment of the cutter to the shaft, was drilled. This was accomplished using the same jig described above, except that it was inverted during the drilling process. On the bottom side of this jig, a five-sixteenths inch hole had been drilled, which was then used as a guide for the drill bit during the drilling operation. This procedure thus ensured proper alignment of the cutters on the shaft such that a pair would be diametrically opposite.

The next step in the cutter manufacture employed a thirteen-sixteenths endmill having an integral five-sixteenths inch pilot, a drill press, and a jig. The jig consisted of a one inch diameter shaft having a five-sixteenths inch dowel pin three-quarters of an inch long, extending perpendicularly from the shaft. The cutter was set down over the dowel pin onto the shaft. The dowel then held the cutter in proper alignment such that the facing would be perpendicular to the bolt axis. By setting a stop on the drill press each cutter's depth was kept constant. This facing operation was done to allow the lock nut to sit on a smooth flat surface perpendicular to the bolt axis. This helped to ensure a proper locking action of the nut and prevented loosening of the cutters during operation.

The final step in the machining process was the turning of a cutter pair to the correct diameter. This was performed in a lathe by mounting the pair on a one inch shaft and turning their diameter to 3.5 in. $\pm$ 0.02 in. Some hand file work was then required to remove small pieces of metal that had "turned over" in the lathe work.

Following this, the cutters were each paired according to weight. The final weights of the cutters varied from 254 to 288 gm, with the average being 269 gm. This pairing by weight ensured static balance and tended to increase dynamic balance.

Each cutter pair was mounted on the drive shaft using a section of cold rolled five-sixteenths inch round bar stock threaded on both ends. A "Flexnut" locknut was used on each end of the stud bolt to ensure that the cutter pairs were locked together and would not vibrate loose during usage. The use of a rod threaded on both ends was employed to add to the static balance, as a normal bolt with a head on one end and a nut on the other is not balanced. Figure 9 shows the top, bottom, and side views of a cutter, while Figure 10 shows the top, front, and side views of the cutter unit or pair as mounted on the one inch shaft.

No dynamic balancing of the cutters was done; however three pairs were checked as to their state of imbalance. The technique employed by the commercial balancing company was one in which a figure of merit is used to determine balance. For perfect balance, a figure of merit of 2.0 is required at 2400 rpm, while one of 0.7 is required at 3600 rpm. The three cutters tested had figures of merit of 1.6, 1.2, and 1.4. Thus these cutters could be considered dynamically balanced up to about 2800 rpm. However, this was judged to be close enough to the 3600 rpm requirement, considering the shaft size and bearing spacing, not to require dynamic balancing of each individual pair of cutters.

Since one of the thesis objectives was "to determine a method to correct for the loss of edge brought about through usage" some comment on this is in order before the discussion of the cutters is complete.

As already mentioned it was intended that the use of casting as a production technique in combination with the shape of the cutting edge might lead to some degree of self-sharpening. This, however, would correct only for moderate amounts of wear and not for nicks in the knife edges resulting from contact with a hard object. To correct such large dull spots, some mechanical means of sharpening must be provided.

One solution could be to mount a piece of beveled shim stock

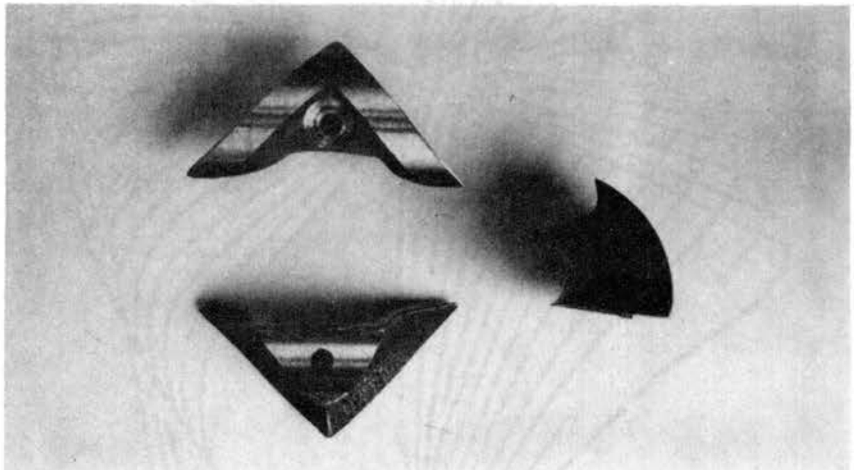


Figure 9. Top, Bottom, and Side Views of a Cutter

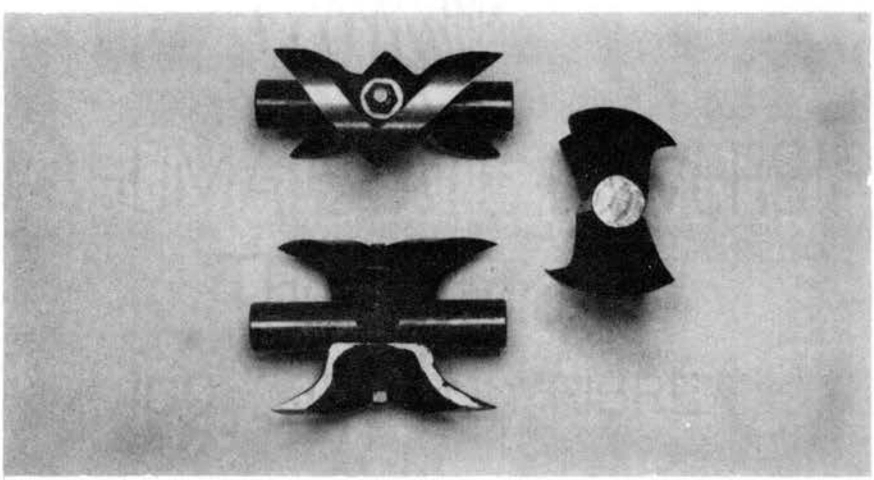


Figure 10. Top, Front, and Side Views of a Pair of Cutters Mounted on the One Inch Shaft

between the cutter and the mounting shaft. This would displace the cutters outwardly by a given amount. The cutting pair could then be mounted in the lathe and turned to the required 3.5 $\pm$ 0.002 in. diameter, giving a sharp new cutting edge.

A similar method could employ the use of welding to build up the inside of the cutter rather than using shim stock. This surface would then be machined smooth as in the initial cutter manufacture, followed by the turning of the cutter to the required diameter.

A final solution might be simply to replace a damaged cutter with a new unit. This would be feasible only when the costs of a new unit would be less than or equal to the costs for the resharpening processes previously mentioned.

Guard-Ledger

As in the case of the cutter, the guard-ledger assembly followed Bledsoe's basic design. The design had only two basic criteria to meet, those were the five degree ledger blade angle with a slope opposite to that of the knife, and the 45 degree bevel angle on the ledger. Casting was again chosen as a means of manufacture for several reasons. First, as for the cutters, was the ease of manufacture and ease of part replacement. Second, the use of casting eliminated the need for ledger attachment, as the guard and ledger were cast in a single unit. In addition, it was hoped that the ledger might be self-sharpening as it is on the some of the conventional guards now in production.

Again, design of this element of the cutterbar started with modeling clay, followed by the making of the balsa wood master pattern by a commercial patternmaker. Several changes and sample castings were again required to establish the final guard shape.

Since sand casting was to be used, again for economic reasons, additional machine stock of about one-eighth inch thickness was added to the surfaces to be machined. As in the case of the cutter, the ledger edges were cast blunt to reduce the risk of damage during the rough cleaning by the foundry and to increase the pouring quality of the mold.

Following receipt of the rough castings, a series of machining operations was performed on each in two specially-constructed jigs. The first operation involved the milling of the surfaces labeled A and B in Figure 11. This was accomplished using a three inch diameter endmill in a vertical head milling machine. Making the cut a one-pass process for both surfaces ensured a right angle between them, allowing for a better fit on the cutterbar frame. In addition, the corner of the endmill had a slight radius, thus reducing stress concentrations at the junction of the two surfaces. This junction or radius is labeled R in Figure 11.

The second operation in the process was the drilling of the bolt and dowel pin holes used to fasten and align the guard on the cutterbar. To rely on one or two bolts alone to line up the guards and cutters under the close tolerances desired was deemed impossible, hence the employment of the dowel pins. This drilling was performed while the guard was held in a jig. The jig utilized three drill bushings to guide the drill press bits, with the bolt hole being three-eighths in. in diameter, while the dowel pin holes were only one-quarter in.

The next operation was the counter-sinking of the bolt hole on the

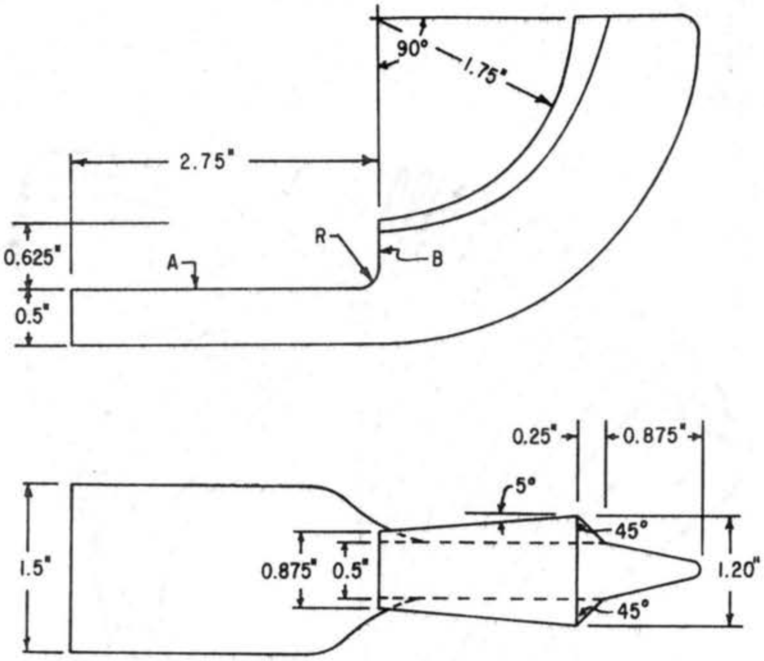


Figure 11. Dimensioned Drawing of the Guard-Ledger Assembly

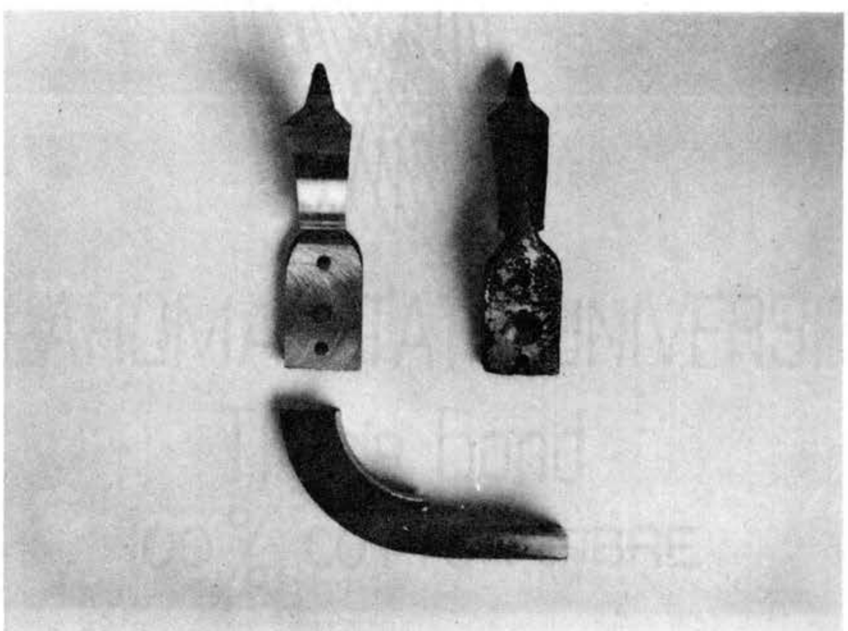


Figure 12. Top, Bottom, and Side Views of the Completed Guard-Ledger

bottom side of the guard using an 82 degree countersink in a drill press. This was done to accommodate the socket head, flat cap screw that was to be used to hold the guard in place. A flat headed screw was employed in order to eliminate any protrusions from the bottom of the cutterbar, thus reducing cutting height in the field.

The final machining was a lathe operation performed using another jig. During this operation the diameter of the ledger was turned to 3.488 $\pm$ 0.002 in. Following the lathe operation some hand filing was required to remove some small burrs from the ledger edges. The final guard-ledger assembly is shown in top, bottom, and side views in Figure 12.

Cutterbar

A total cutting length of seven feet was decided upon as it would fit well into the running gear and framework available and would be equal in length to a conventional mower.

It was immediately obvious that a single unsupported length of shaft would be impossible both from the aspect of the dynamics associated with an unsupported shaft and also from the close tolerance in clearance that was desired between the cutters and ledgers. It was therefore decided that the shaft should be divided into more than one section. This would allow for any bend in the supporting frame, reducing chances of the cutters hitting the ledgers and causing damage. Also by reducing unsupported shaft length, the problem of critical speeds would be reduced. Calculations showed a bearing spacing of 25 in. as the maximum necessary to eliminate the problem of critical shaft speed.

The general support for the cutter and bearing mounts was made from two pieces of five-eighths in. cold rolled steel bar stock. These were bolted together at the bottom to form a right angle of dimensions three and one-half in. by three and one-half in. Initially, a piece of three and one-half in. angle iron three-quarters in. thick was to be used for the basic frame. It was found, however, that even after milling of the angle to the required five-eighths in. thickness, the bow in the angle was far too excessive for the tolerances in cutter-ledger clearance required.

The bearing mounts, which can be seen in Figure 13, were constructed of five-eighths in. cold rolled steel. Each of the eight mounts required three, three-eighths in. bolts and two, one-quarter in. dowel pins to properly position and hold them in place. The holes for the bolts and dowel pins in both the bearing mounts and the angle section were located and drilled using three jigs each containing properly sized drill bushings. The bearings were press fit in place; "Loctite" bearing mount was used as an additional security measure to hold them in place. To ensure proper depth of seating of the bearing, a groove was machined around the outer edge of the bearing mounting hole, into which fit the snap ring extending from the outer race of the bearing. The bearings used were NICE 7616DLG single row radial ball bearings having a radial capacity of 330 lb. and a limiting thrust capacity of 375 lb. (11).

A left and a right hand bearing mount were constructed so as to absorb any thrust loads. Each shaft section was held horizontally in place by a one-eighth in. diameter roll pin which was pressed into the shaft and rested against the inner race of the bearing. In addition,

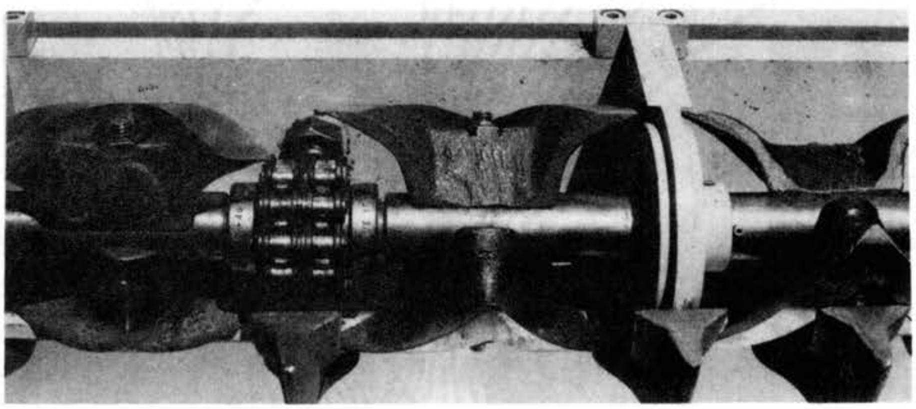


Figure 13. View of a Bearing Mount and Chain Coupling as Mounted on the Cutterbar

the inner race had two set screws which were tightened on the shaft and helped hold the shaft in position.

The bearing mounts were so located on the angle frame that not more than three cutters, or 15 in., was between them. This then met the 25 in. maximum bearing spacing mentioned earlier. To allow for two pair of cutters to revolve as closely as possible to each other at the bearing mounts, a one-quarter in. by three-sixteenths in. groove was cut around the bearing mount at a diameter of three and one-quarter in. The cutter tip then revolved within this groove.

The couplings used to join the four shaft sections together were made up of pairs of ten tooth sprockets and a length of size 40 double strand roller chain. Total length of the coupling, shown in Figure 13, was two and one-sixteenth in. while diameter was two and one-eighth in. This size was small enough to allow mounting between cutters but not interfere with the cutting action, while still allowing for adequate power transmission.

As each cutter had a width of four and one-half in., it was decided that a guard spacing of five in. would allow adequate clearance beteeen cutters, and yet give proper overlapping of the cutters and ledgers. Although five in. spacing of the guards was all that was necessary for proper cutter operation it was decided to make provision for the attachment of a middle guard. This would enable increased protection of the cutters from large objects and also reduce the possibility of human limbs entering the cutting area.

The holes for the dowel pins and bolts used for the guard attachment were drilled using a jig containing a three-eighth in. and two 0.246 in. drill bushings. These three holes were drilled at 2.5 in.

spacings along the entire length of the cutterbar. The dowel pins were then pressed into the angle rather than into the guards.

In the locations where the guards and bearing mounts coincided, the same three-eighths in. bolt was used to hold the bottom of the bearing mount and the guard. Final clearance between the cutters and ledgers varied from 0.007 in. to 0.020 in. over the length of the cutterbar, with the variation being due to construction inaccuracies.

Helical Cutterbar Frame

The basic frame and running gear was a Hesston PT-10 windrower. This provided the wheels, hitch mechanism including a tongue capable of swinging from road to field position, and a lift assembly suitable for powering from a standard hydraulic cylinder. On this frame was mounted a sub-frame to which the previously described helical cutterbar was attached.

The sub-frame consisted of a four by four by five-eighths in. angle iron to which were welded three, one-quarter in. side plates. These plates in conjunction with the original side plates from the PT-10, acted as crop dividers at each end of the cutterbar. The third side plate divided off an area in which the drive assembly and instruments could be isolated and thus protected from damage.

The helical cutterbar was bolted to the four by four in. angle of the frame using eight, one-half in. diameter bolts. To ensure that the cutterbar was not bent or twisted in this process, shims of appropriate thicknesses were placed between the two angle sections at each bolt location.

As a final frame component, two height-adjustable skid shoes were mounted on the bottom of the angle iron at each end. This allowed for adjustment of cutting height while still enabling the cutterbar to "float" on the ground and follow general surface contours.

Power Train

Since the cutter shaft was mounted within 3 in. of the ground surface, it was impossible to attach the drive motor directly to the end of the rotor shaft. To solve the problem, the use of a jack shaft was employed as shown in Figure 14. Four, one and one-half in. wide size H gearbelts were used as the power transfer mechanism. The jack-shaft allowed a vertical displacement of 8.3 in. giving adequate clearance for the drive motor. Power was transferred to the jackshaft from the motor by a size 50 chain coupling. This coupling consisted of two, sixteen tooth sprockets and an appropriate length of size 50 double strand roller chain.

The power for the cutter was supplied by a hydraulic motor, shown in Figure 14, which in turn was driven by either a John Deere 2520 tractor, having 61 pto hp (36), or a Massey Ferguson 135 tractor having 35 pto hp (51), through a gearbox and hydraulic pump. The use of a hydraulic drive system or hydrostatic transmission was chosen for two basic reasons. Firstly was the ease with which cutter rotary speeds could be changed from 0 to 3900 rpm, independently of ground speed and tractor engine rpm. Secondly was the ease of power measurement as only pressure drop across the motor and flow though it need be known in order to calculare output horsepower.

The hydraulic pump and motor were both series 18 Sundstrand models. Each was the axial piston type and had a variable swash plate angle,

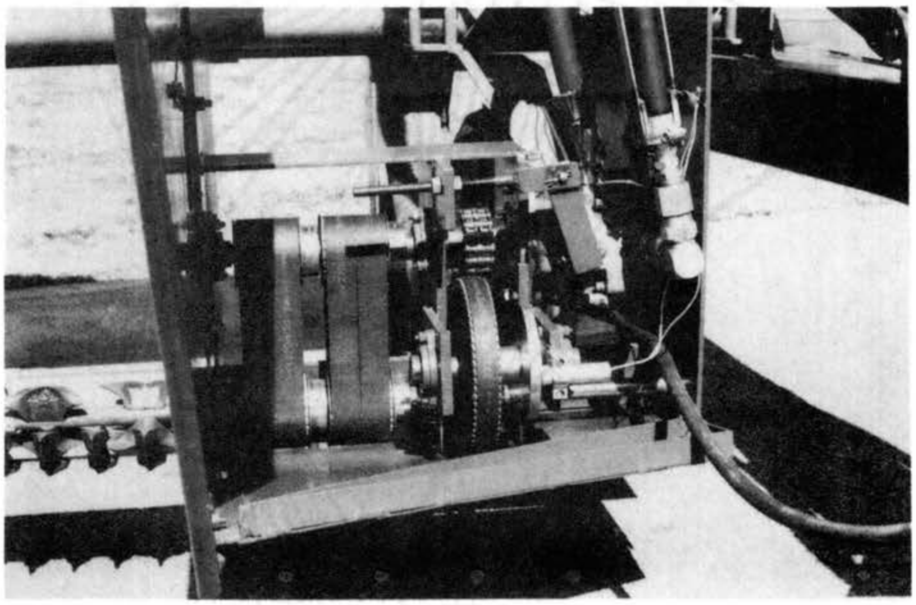


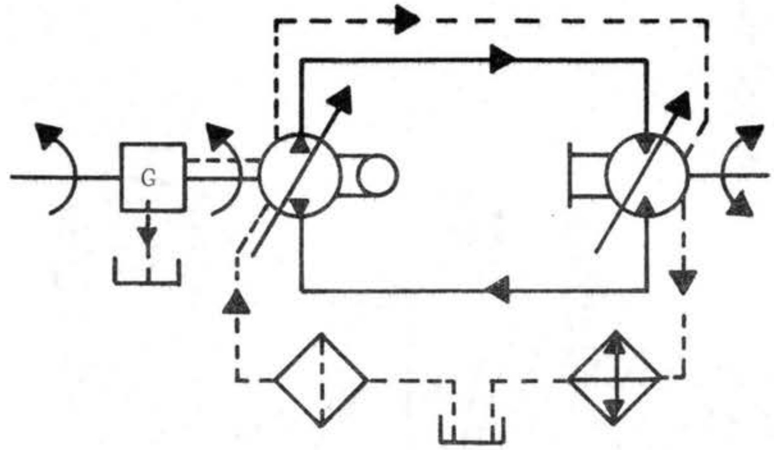
Figure 14. Drive Assembly Showing the Jack Shaft, Drive Belts and Motor

This allowed for displacements of from 0 to 2.3 in.^{3}/rev for a variation in swash plate angle of 0 to 18 degrees. The pump and motor were capable of speeds up to 3900 rpm and of pressures up to 5000 psi. The control moments on each of the units were a maximum of 125 inlb per 1000 psi and were stroke reducing in nature (65).

Used in conjunction with the pump and motor in the hydraulic circuit were a five gallon reservoir constructed from sheet metal, a 10 micron replaceable cartridge filter produced by the Lenz Corporation, and a heat exchanger manufactured by the Hayden Company. A schematic drawing of these hydraulic components and the associated plumbing required for the hydraulic system is shown in Figure 15, while a photograph of the entire drive train is shown in Figure 16.

Since the units were variable displacement, a means of control was necessary. For the motor this control was fairly simple, as is shown in Figure 17a. A control arm was pinned to the swash plate shaft. Attached by a pin to the end of this arm was a threaded one-half in. diameter rod having a clevis on the pinned end. The threaded rod passed through a hole in a plate. Two nuts, one on each side of the plate, allowed the motor swash plate to be set at any desired angle.

For the pump, the problem was not quite as straightforward. The hydraulic pump had a small internal gear charge pump. In order to start or stop the main pump, the swash plate had to be in neutral and a charge pressure greater than 150 psi had to exist. This ensured proper seating of the piston shoes in the swash plate and prevented possible damage to the assembly. The problem was to provide some means whereby the pump could be started with a zero degree swash plate angle, and then be stroked to the desired angle from the tractor seat.



G is the 4:1 Speed Increaser

Figure 15. Schematic Drawing of the Hydraulic Circuit

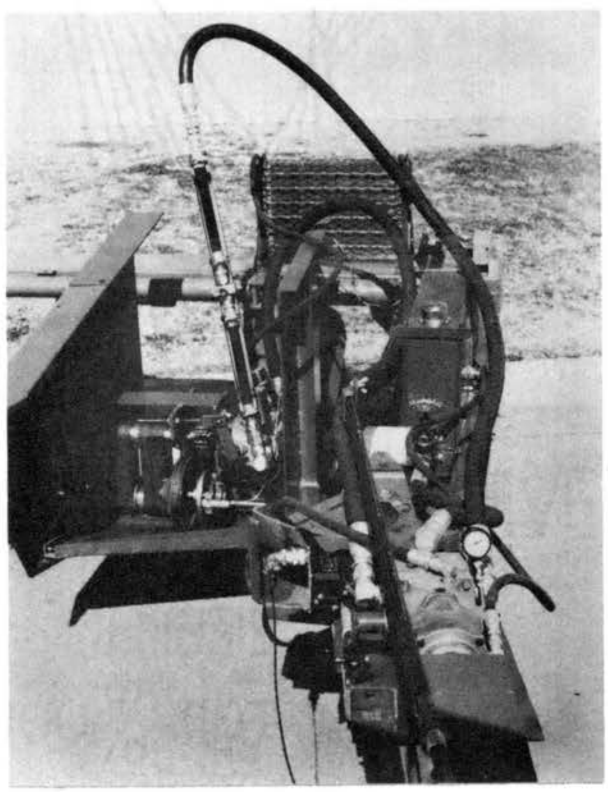
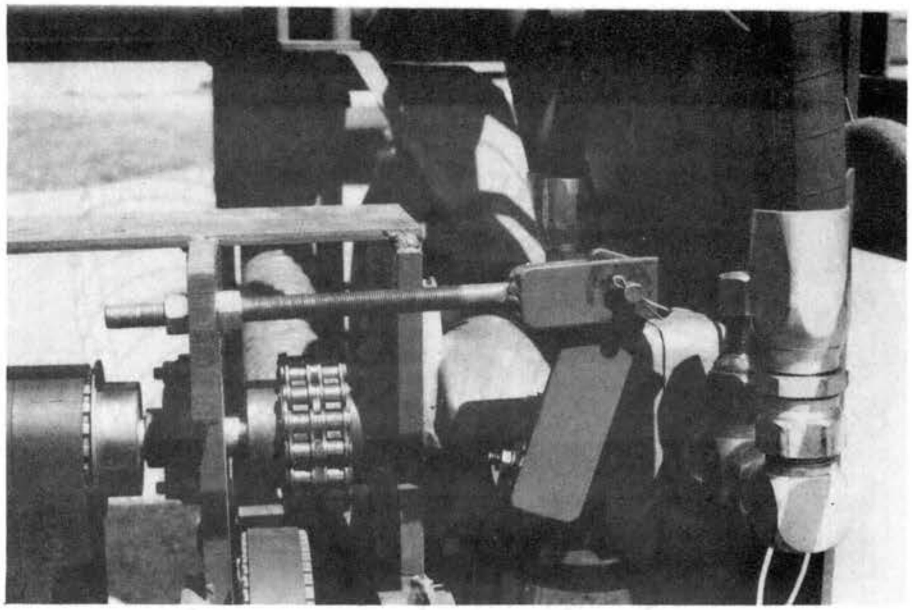


Figure 16. The Helical Cutterbar's Entire Drive Train

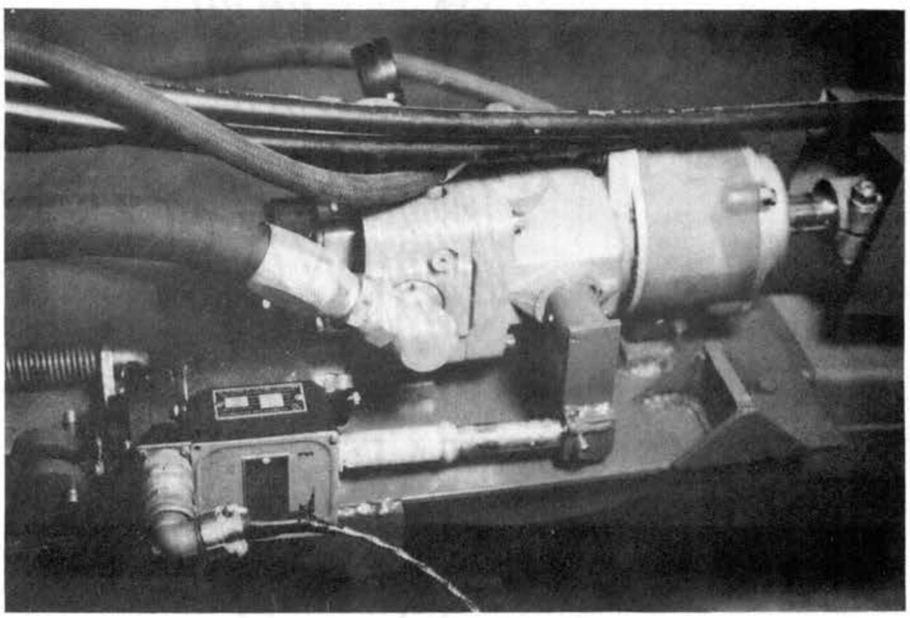
The control unit finally used was an airplane flap actuator, as shown in Figure 17b. This unit had a capacity of 850 lb. in compression and 1750 lb. in tension, which were more than adequate for that required. The actuator was powered by a 24 volt dc motor but had the advantage of integral micro switches to limit its stroke. Since the unit required 24 volts, it was necessary to mount an extra 12 volt battery on the tractor in series with the existing 12 volt battery. The circuit was then activated by a switch from the tractor seat. By setting the micro switches, the pump could be stroked to a preset value, at which point one micro switch would shut the dc motor off. To move the pump to neutral, the switch was flipped in the opposite direction, reversing the dc motor. To ensure that the extra battery was kept charged, a switching circuit was added. This allowed switching of the two batteries from a series to a parallel configuration such that the second battery was charged from the tractor alternator.

Since motor speeds near the top of the rated motor rpm were required, it was necessary to drive the pump at a speed greater than the 540 rpm available. This was due to the fact that even at full pump displacement, motor displacement would have to be held at 0.36 in.^{3}/rev to allow motor speeds of 3600 rpm. This, of course, became almost impractical. In addition, at 540 rmp only 5.4 gpm would be pumped at full stroke and if system pressure was operated at the maximum of 5000 psi, this would allow for only 15 hp. It was felt that this might be inadequate for the cutter.

To solve the problem some type of input gearing was necessary. The solution was a 4:1 speed increaser produced by the Cessna Corporation of Hutchinson, Kansas. The unit was a sun and planetary gear



(a)



(b)

Figure 17. Devices Used to Vary Swash Plate Angle: (a) the Unit Used on the Motor, and (b) the Linear Actuator Mounted on the Pump

arrangement with the pto shaft driving the planets. This in turn drove the sun gear which was in essence the pump input shaft. Lubrication for the gearbox was provided by the venting of some of the pump case oil through a hole in the mounting flange. From the speed increaser, the oil then flowed to the reservoir, allowing for constant cooling of the unit. An overall view of the compound helical cutter with all the components in place is shown in Figure 18.

Reciprocating Cutter

The basic unit used for this cutting assembly was a Hesston PT-10 windrower. The reel and conditioner rolls were removed such that power input to the unit would be for cutting only. In addition, the cutting width was shortened to equal the length of the rotary unit, for comparison purposes. This was accomplished by placing a one-quarter in. end plate in the same position as in the rotary unit and then making suitable changes in the PT-10's shield structure. As the unit had previously been used in conjunction with a reel and crimper there was a curved deflection plate leading back and upward from the knife. This was cut down in width and height to reduce any clogging problems that might have been encountered due to its presence.

To ensure that the unit was in top shape to provide a fair control or comparison unit, the cutterbar was completely overhauled. A new set of top serrated sections were mounted on the knife and the hold-down clips were adjusted to their proper setting. The knife was checked and adjusted for register with the unit being slightly overstroked, as the stroke was three and one-sixteenth in., while guard spacing was only three in. The ledgers were integral with the guards and were

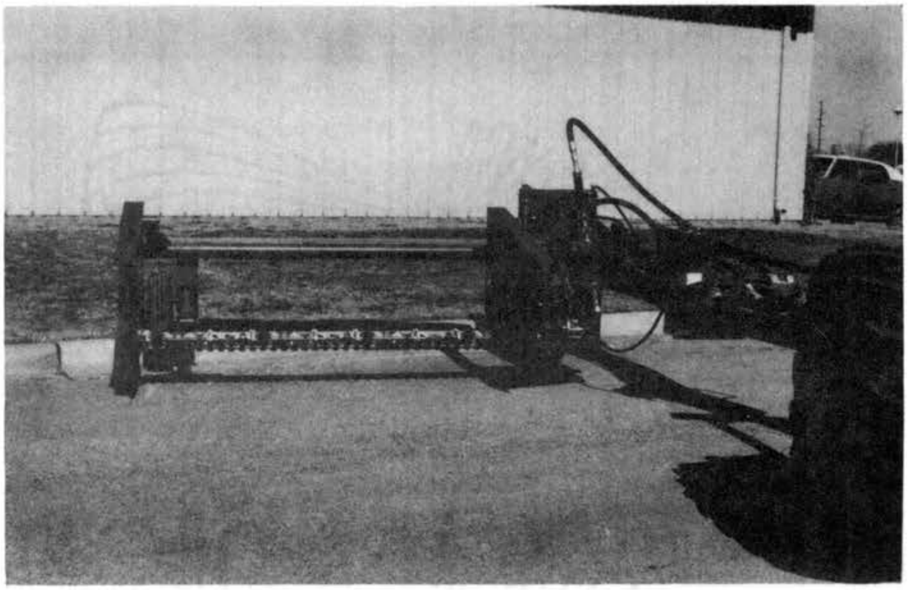


Figure 18. Overall View of the Compound Helical Cutter

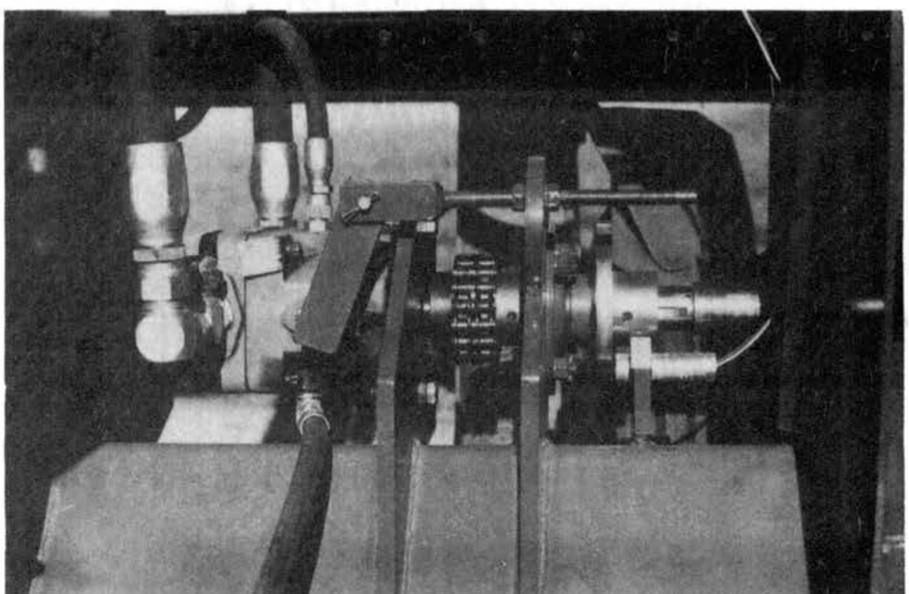


Figure 19. Drive System Used on the Reciprocating Cutter

intended to be self-sharpening. A visual observation showed them to be in reasonable cutting condition, thus they were not replaced. All of the guards however, were aligned vertically and horizontally to eliminate added friction on the knife which would result in increased power consumption.

The same hydraulic system was used to power this unit as well as the rotary cutter; however, appropriate modifications had to be made to accommodate mounting of the various system components. A view of the drive system is shown in Figure 19. The hydraulic motor was connected directly to the eccentric pitman drive shaft by the use of a size 50 chain coupling. The drive shaft had been modified in length and bearing arrangement to accommodate such a change.

CHAPTER IV

THEORETICAL COMPARISON OF THE TWO CUTTING UNITS

Reciprocating Cutterbar Kinematic Analysis

A knowledge of any reciprocating cutterbar's design and operating speeds is necessary in order to construct its individual cutting diagrams.

The reciprocating cutterbar used in this study was a Hesston PT-10 windrower. The unit was overstroked, as it has a guard spacing of only three in., while it had a stroke of three and one-sixteenth in. A scale drawing of a knife section and ledger is shown in Figure 20. The knife had an operating speed of 800 cycles per minute when driven from the tractor pto at the recommended 540 rpm (52).

Ground speed is one other operating variable which must be known before a cutting diagram may be drawn. Since the Hesston operator's manual did not recommend any speeds, the Agricultural Engineer's Yearbook (49) was consulted. It lists the average speed of a mower as ranging from five to seven mph, while that for a mower-conditioner is said to vary from four to six mph. It was concluded that a range of from four to seven mph would then cover all possibilities and hence was used.

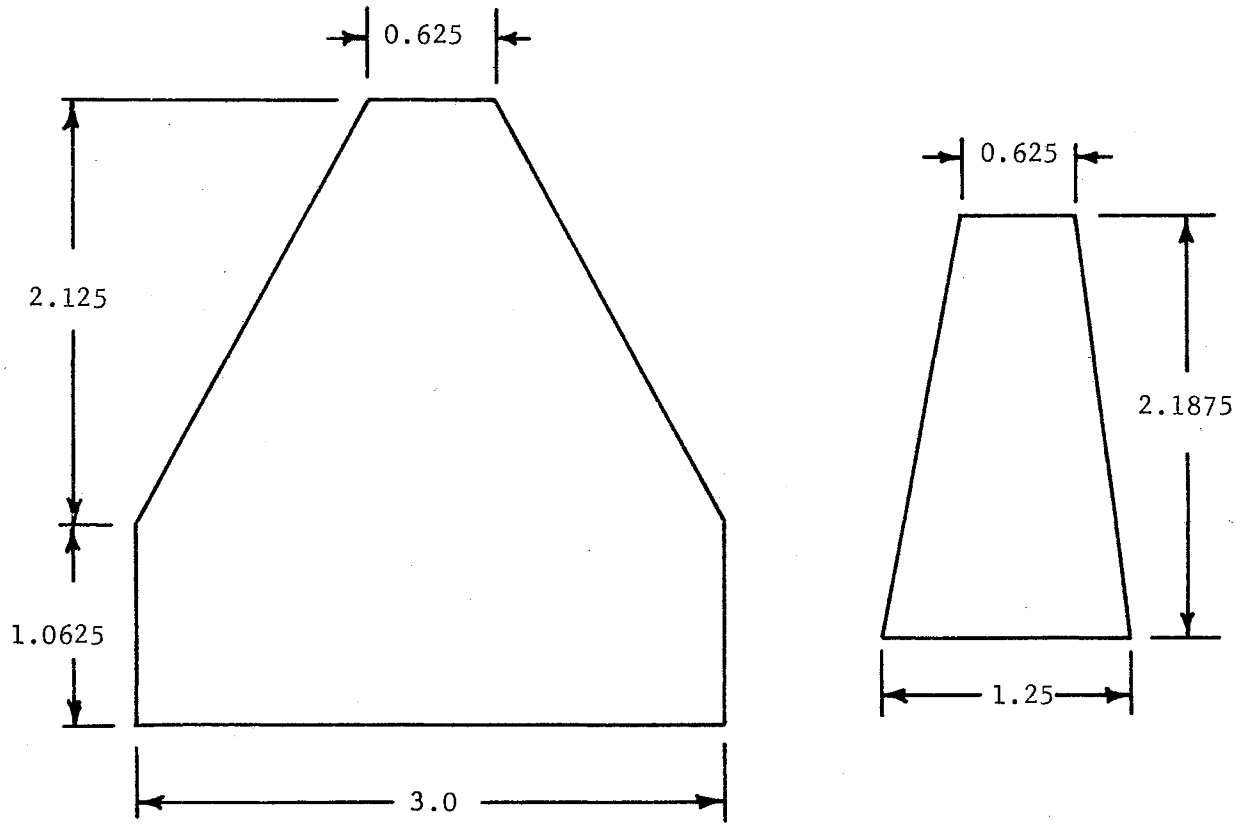


Figure 20. Scale Drawing of the Reciprocating Unit's Knife and Ledger Sections

Table I lists the forward travel per stroke of the cutterbar for ground speeds of four, five, six, and seven mph.

TABLE I

FORWARD TRAVEL PER STROKE FOR THE RECIPROCATING CUTTERBAR

Ground Speed (mph)	Forward Travel (in.)
4	2.64
5	3.30
6	3.96
7	4.62

Kepner (39) recommends no more than four in. of forward travel per stroke of the knife. If this criterion is used, Table I shows the PT-10's top speed to be only six mph. However, for comparison purposes, this limitation was ignored, and all four cutting diagrams were drawn, as shown in Figure 21.

From each of these diagrams, the maximum side stalk deflection shown by line AB, and the maximum rear stalk deflection shown by line CD, were determined. These results are tabulated in Table II.

Table II gives an indication of the theoretical uneveness of the stubble left by the mower at each speed, for the variation in stubble height is approximately equal to the maximum stalk deflection. Actual

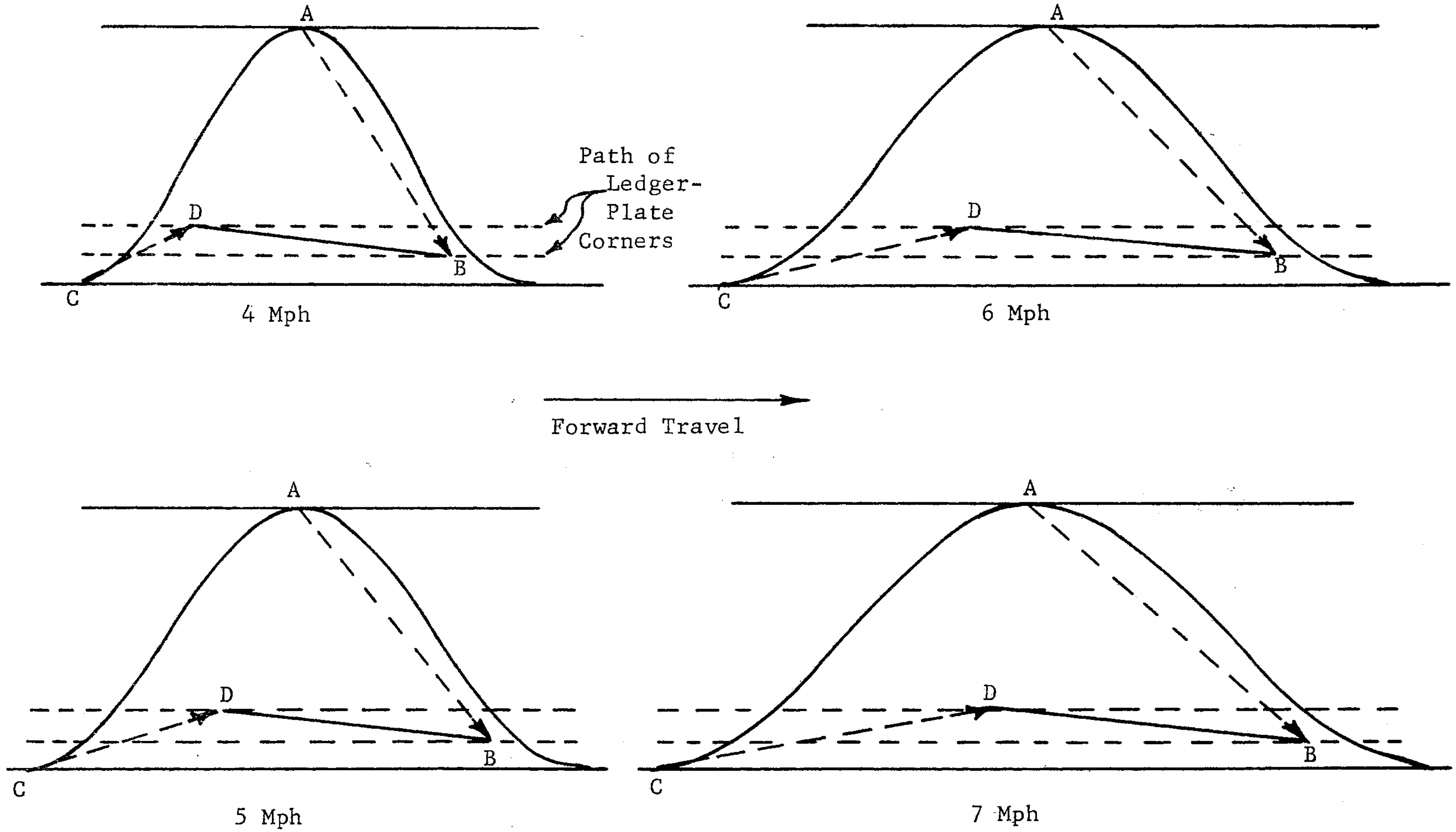


Figure 21. Cutting Diagrams for the Reciprocating Cutterbar for 4, 5, 6, and 7 Mph. Line AB Represents Maximum Side Stalk Deflection; Line CD Represents Maximum Rear Stalk Deflection; Line BD Represents the Cutting Line

side stalk deflection may be less than that listed in Table II. This is due to the slipping of the stalks along the sickle section edge brought about by the forward motion of the cutterbar rather than their being held in place and pushed to the ledger as indicated by line AB in the cutting diagrams.

TABLE II

STALK DEFLECTIONS FOR THE RECIPROCATING CUTTERBAR

Ground Speed (mph)	Rear Stalks (in.)	Side Stalks (in.)
4	1.59	3.25
5	2.41	3.53
6	3.28	3.78
7	4.12	4.19

Referring now to Principles of Farm Machinery (40), it is found that the maximum deflection of the rear stalks should not exceed 2.4 in. for best performance when cutting within two or three in. of the ground. Using this as a criterion it becomes obvious from Table II that a five mph ground speed is maximum for the Hesston PT-10 windrower.

Rotary Cutterbar Kinematic Analysis

A theoretical determination of uneveness of stubble height left by the helical cutterbar is not as straightforward as it is for the reciprocating unit. The very action of the knife tends to produce an uneven stubble as it rotates, and in addition stalk deflection caused by the second cutting element of the pair increases stubble length.

If the path traced by a point on the knife edge of a cutter is observed it would be noted that it resembles an inverted prolate cycloid. The shape of the cycloid depends on both the angular velocity of the rotor and the rate of forward travel of the rotor axis. This path can then be used in determining uneveness of stubble height as well as zones of double cutting. The latter term is used to describe areas where a second cut is made on the stubble, resulting in reduced height.

The simplest and most reliable way of producing these traces for various combinations of rotor angular velocity and linear velocity is through the use of an analog computer and an x-y plotter. The governing equations and accompanying circuit diagram used by the author in conjunction with the analog are given in Appendix A.

A review of pertinent literature was undertaken to determine what combinations of ground and rotary speeds should be investigated with the analog computer. Feller (19) found that single element impact cutting occurred for a range of knife speeds of 9.57 to 31.8 ft/sec in alfalfa and sudan grass. Input energy imparted to the stems increased as knife velocity increased for the alfalfa but not for the sudan, whereas cutting energy was found to be unaffected by knife speed.

Chancellor (13) used impact cutting to sever timothy stems. He found that for the range tested, 136 to 273 ft/sec, speed had little effect on the deflection obtained in the cut stem; however, a speed of 150 ft/sec was recommended as a minimum for consistently reliable results. It should be noted here that Chancellor did not measure energy consumed in the cutting, but rather based his findings on the deflection or energy transmitted to the stems.

Bledsoe (5) found that rotor speed and hence knife speed did not have a significant effect on input energy required to cut a stem but that it did have a significant effect on cutting torque. For the range tested, 1800 to 3600 rpm, rotary speed produced a quadratic effect with respect to the torque values measured, with the best rotor speed occurring in the range of 3100 to 3600 rpm.

The helical cutters studied in this research had a diameter of 3.5 in. If this is considered in conjunction with Feller's minimum knife speed of 9.57 ft/sec, a rotor speed of approximately 650 rpm would be possible. However, Bledsoe showed decreased rpm to produce increased torque values. Thus a compromise of 1200 rpm might be considered practical. A maximum rotor speed of 3600 rpm, as used by Bledsoe, would also seem feasible for a field unit. It should be noted here that even at 3600 rpm, rotor peripheral speed or knife speed, is only 55 ft/sec or about one-third of that recommended by Chancellor.

Since the lowest ground speed listed by the Agricultural Engineer's Yearbook for a conventional mower was four mph, the rotary unit should be capable of speeds no less than this, and hence this value was used for the theoretical studies. In the laboratory tests of the compound helical cutter, Bledsoe found optimum operating conditions to be 3118 rpm and a feed rate of 4.38 in./rev. This implies a ground speed of 12.9 mph. Ground speeds ranging from 4 to 14 mph would then seem suitable for the theoretical studies.

These operating conditions and ranges were then used in conjunction with the analog computer to produce the inverted prolate cycloid traced out by a point on the cutting edge of a knife. Figures 22 through 25 show these paths for four ground speeds from 4 to 14 mph and for each of four rotary speeds from 1200 to 3600 rpm. The zones of double cutting are shown cross-hatched in the figures while zones of triple or more cutting are shown shaded.

If the four figures are compared it can be noted that for a given rotary speed, as ground speed increases, uneveness of the stubble increases while the zone of double cutting decreases. The same results are found for a given ground speed, as rotary speed decreases.

In the determination of which combination of ground speed and rotary speed is best, consideration must be given to two criteria: minimum power consumption and maximum yield. Considering power consumption firstly, it can be noted that if there is any double cutting, power is wasted. Thus the first criterion would demand no double cutting. Secondly, to increase yield, the crop must be cut as closely as possible to the ground such that the maximum possible amount of crop is harvested. Although double cutting does reduce stubble height and hence would appear to increase yield, it does not, for generally the small sections cut off would be lost in the gathering processes. If these two criteria are now considered in relation to the harvesting of agricultural crops the following may be noted.

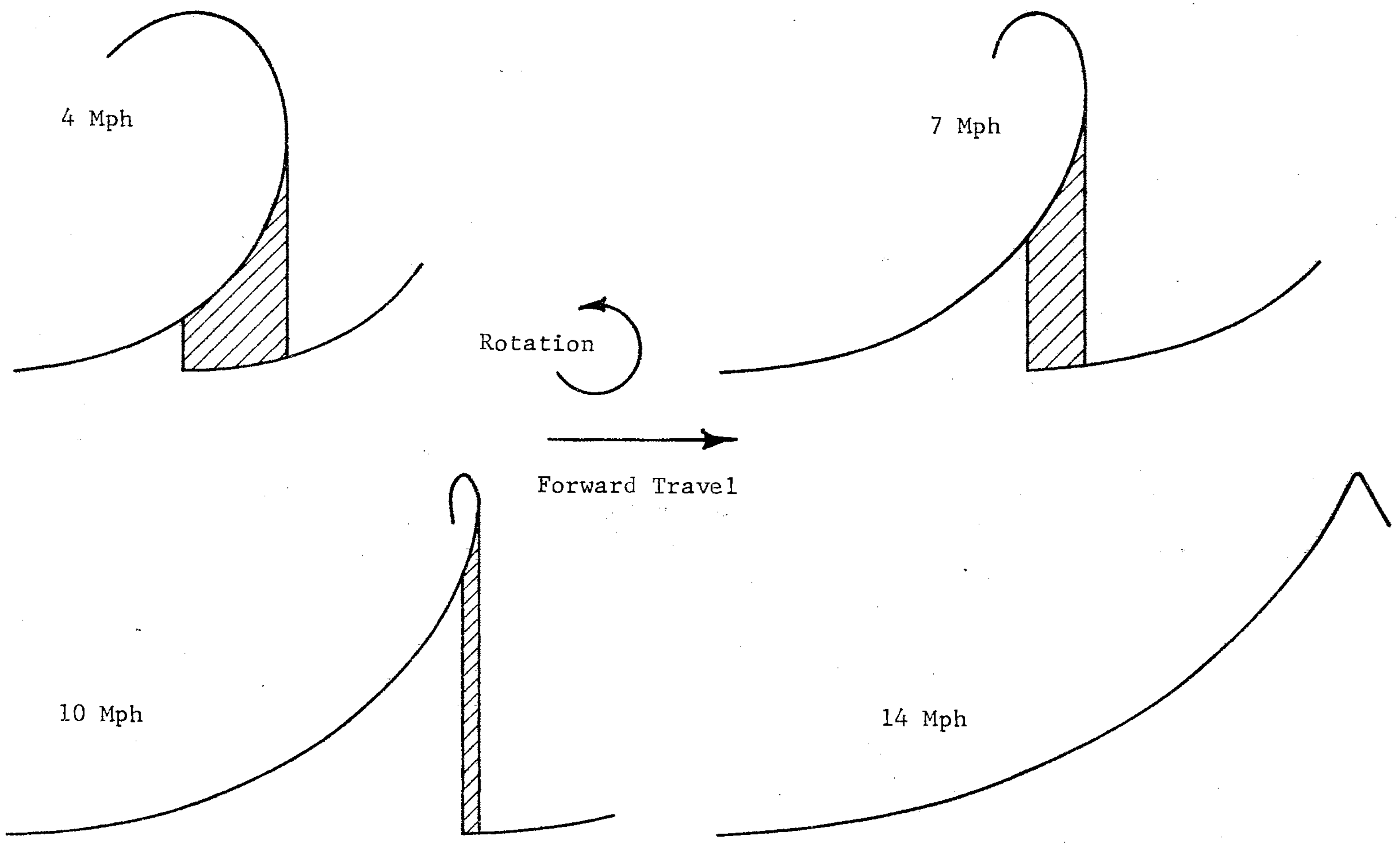


Figure 22. Path Followed by a Point Located on the Cutting Edge of the Rotor Turning at 1200 Rpm. Cross-Hatched Portions Show Areas of Double Cutting

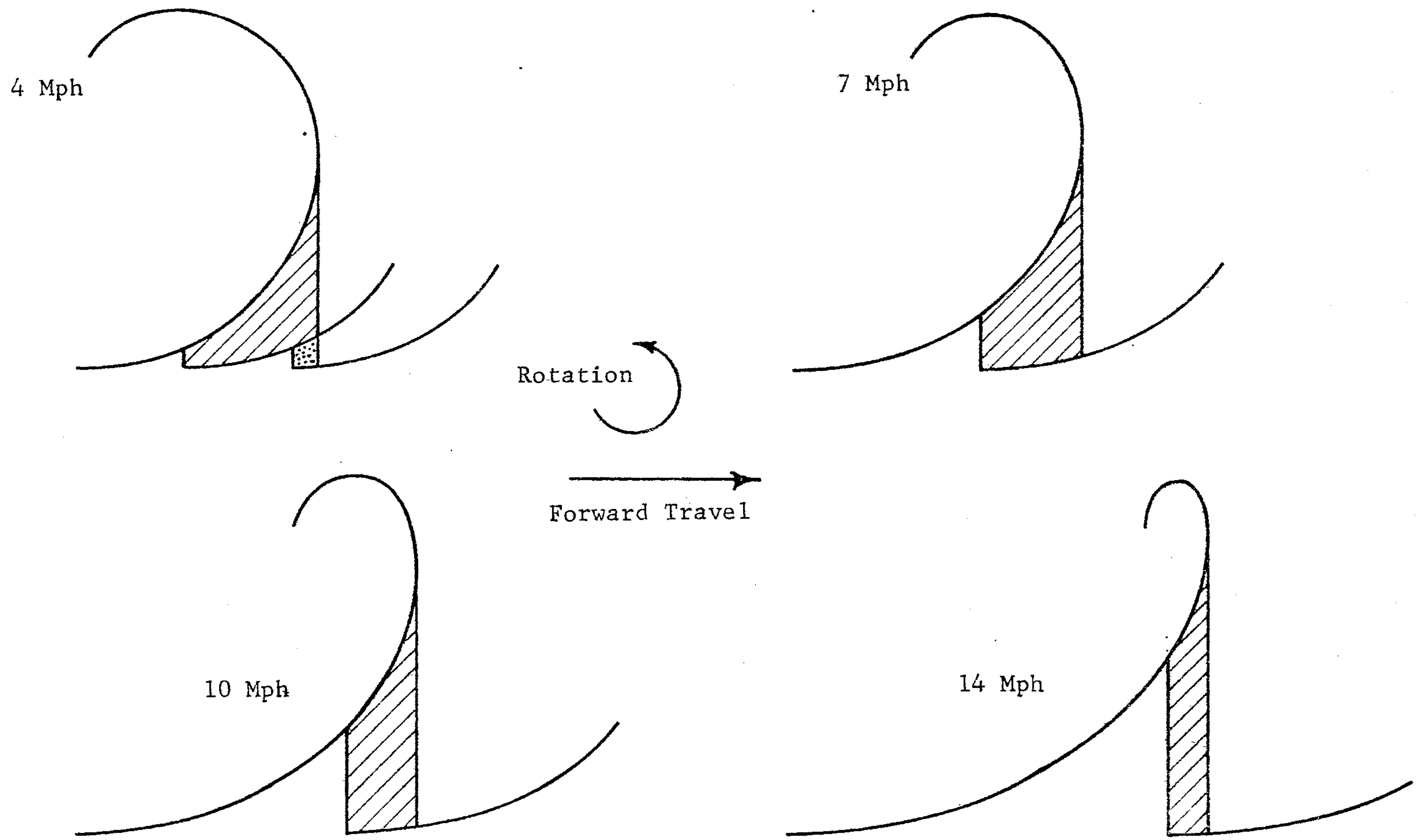


Figure 23. Path Followed by a Point Located on the Cutting Edge of the Rotor Turning at 2000 Rpm. Cross-Hatched Portions Show Areas of Double Cutting

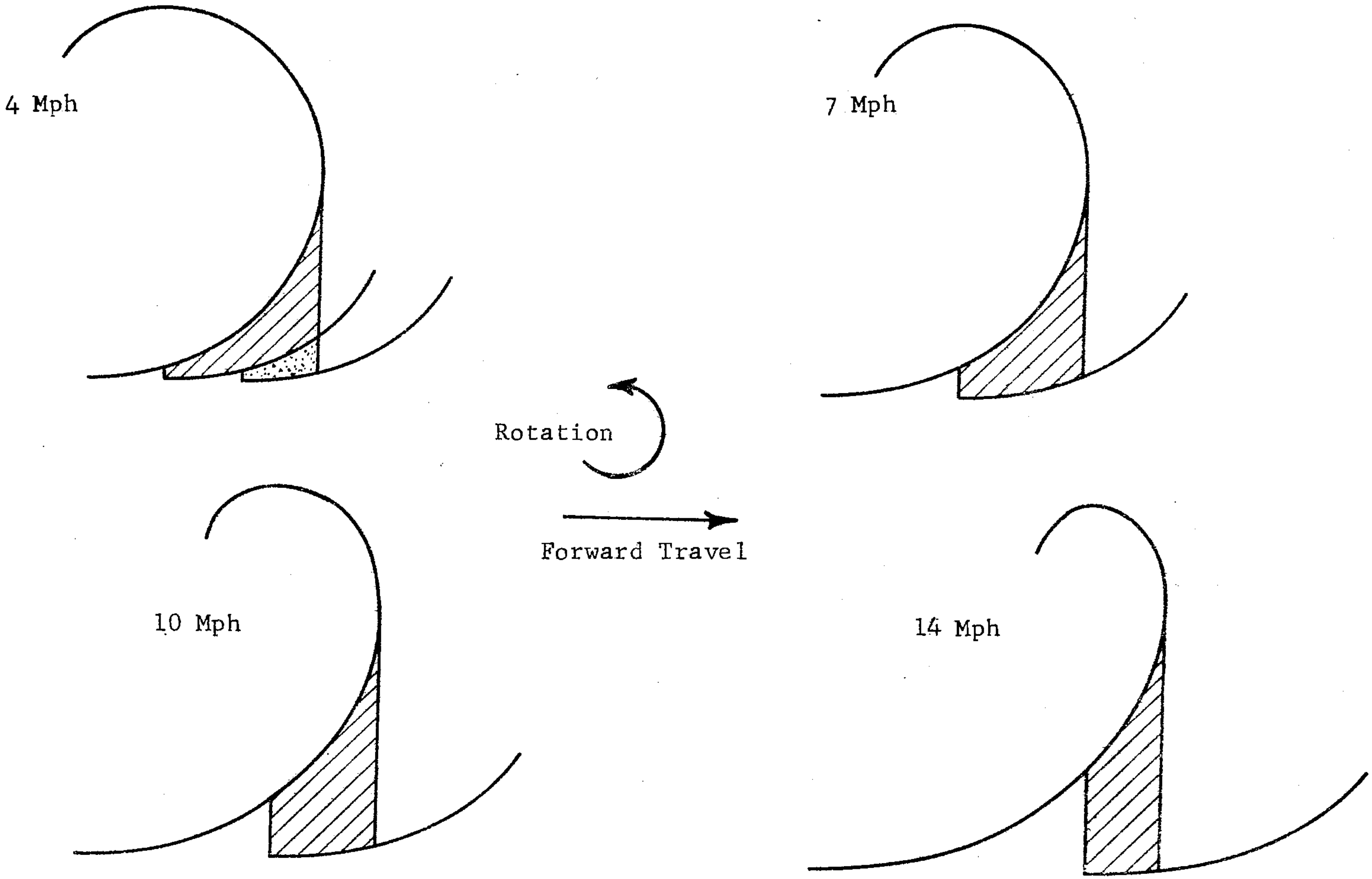


Figure 24. Path Followed by a Point Located on the Cutting Edge of the Rotor Turning at 2800 Rpm. Cross-Hatched Portions Show Areas of Double Cutting

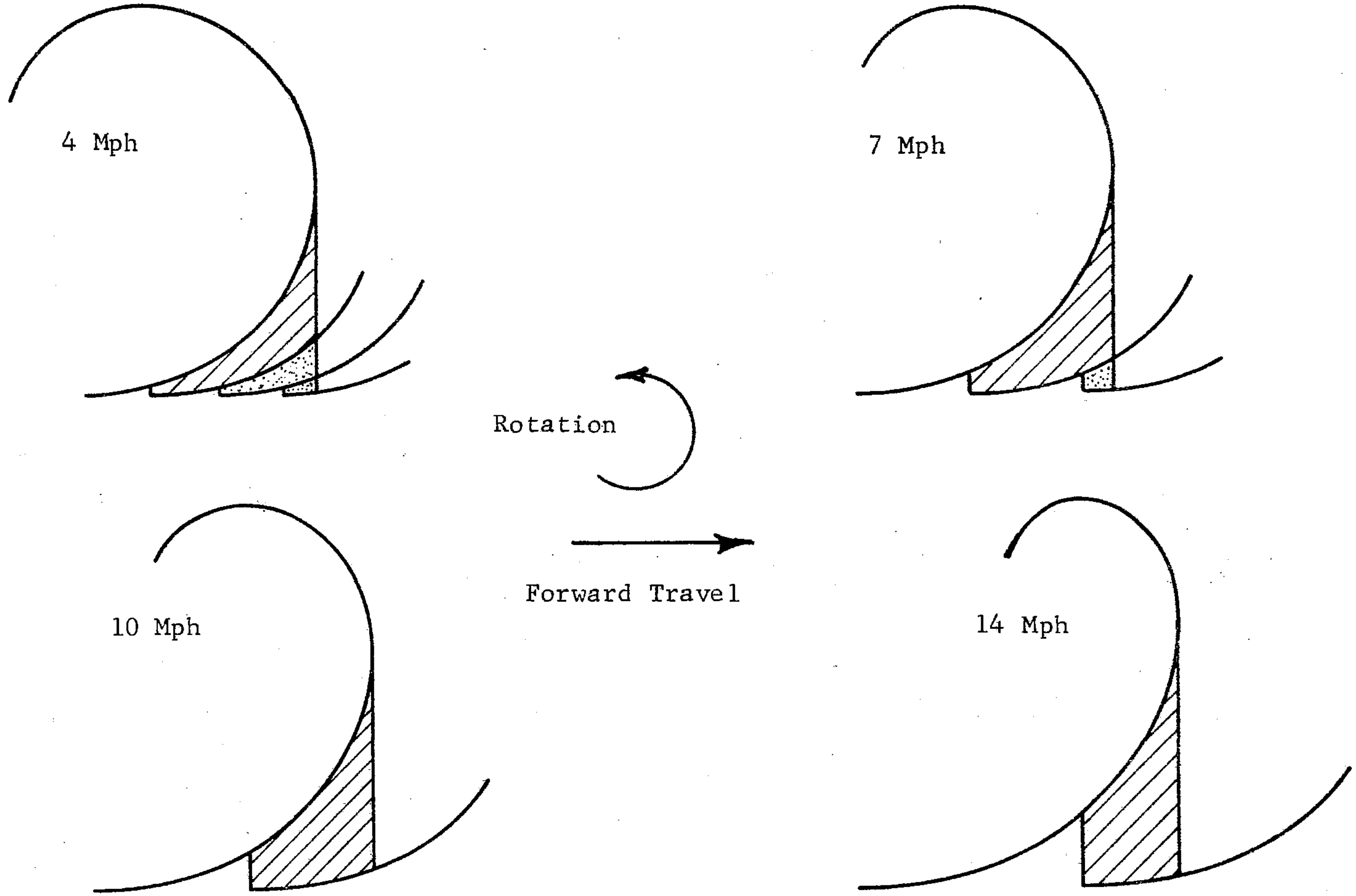


Figure 25. Path Followed by a Point Located on the Cutting Edge of the Rotor Turning at 3600 Rpm. Cross-Hatched Portions Show Areas of Double Cutting

In cereal crops, yield related to stubble length is relatively unimportant, thus minimum power is the remaining criterion to be met, Thus for cereal crops a combination of rotary speed and ground speed producing no double cutting would be ideal. In forage crops, however, both criteria must be met. This becomes impossible so a compromise based on the economics of the situation must be established, that is how much power may be sacrificed to get an increased yield or vice versa.

Tied in with all of the previous discussion is the effect of input power as it varies with ground speed, rotary speed, and the unit's overall capacity. The solution as to which combination of speeds is "best" then becomes a complex economic problem and will not be dealt with in this thesis.

In addition to the combination of ground and rotary speeds, the other factor producing stubble uneveness is stalk deflection or interference of one cutter to the feeding of uncut stalks into the second member of the pair. Figure 26 is a side view of a cutting unit at zero degrees of rotation, that is the position at which the tip of the cutter is just even with the cutterbar's leading edge. Figure 26a shows the position of a stalk at absolute maximum horizontal stalk deflection, while Figure 26b illustrates the position of minimum possible stalk deflection for a zero degree cutter orientation. It can be noted that this minimum deflection is a result of the stalk contacting the central one inch diameter mounting shaft. In this position the stalks have their most vertical orientation and hence least deflection.

Not only is maximum stalk deflection at each point throughout

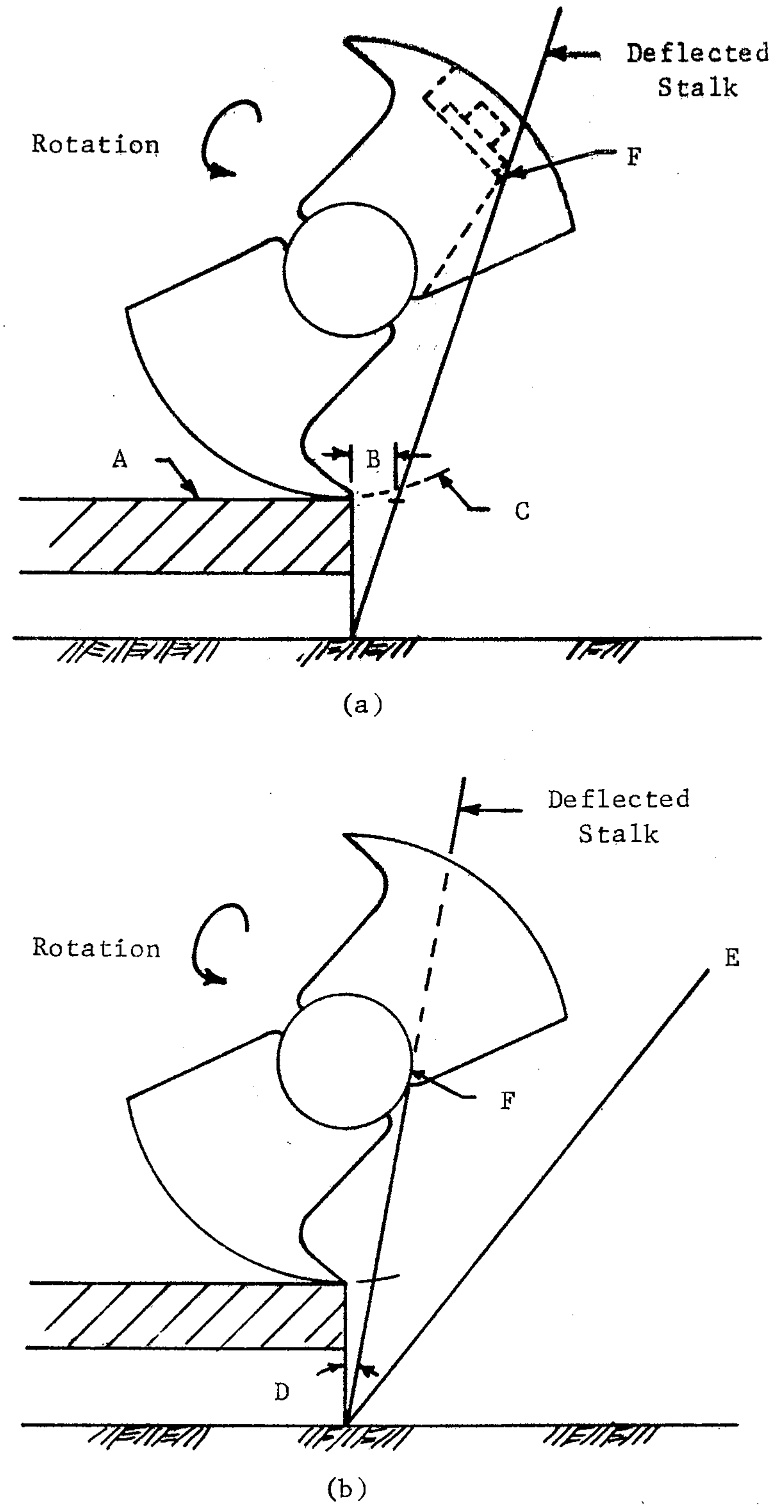


Figure 26. Side View of a Cutting Unit at Zero Degrees of Rotation Showing (a) Maximum Stalk Deflection, and (b) Minimum Possible Stalk Deflection

the cutter's rotation of interest, but also is the total area of deflection produced by the second cutter. To calculate these values for the compound helical cutterbar, photographs at four degree intervals of cutter rotation were made of a top view of a single cutter. From each of these photographs the maximum stalk deflection for each four degrees of cutter rotation was measured. Similarly, the total area of stalk deflection or interference was measured using a compensating polar planimeter. Four representative top views of the cutter, at 4, 28, 52, and 72 degrees, are shown in Figure 27. The shaded portions indicate the areas of stalk deflection.

The values that were measured from the photographs could not be compared directly, however. This was because the contact point, that is the point at which the deflected stalk touched the cutter as shown by the F in Figure 26, varied in height from photograph to photograph due to the rotation of the cutter. Since this height varied, the same measured maximum stalk deflection could produce different angles of deflection, or in essence different actual deflections. The same can be said for the areas of stalk deflection. As graphs of maximum stalk deflection and area of stalk deflection versus cutter rotation were desired, a constant height had to be established.

A convenient height, and the one chosen, would be at one and one-eighth in. above the ground, that is at the top of the cutterbar, designated by the A in Figure 26a. The corresponding deflection then becomes the distance B shown in Figure 26a. By the use of similar triangles and a knowledge of the height of the contact point for each photograph, the maximum deflection and the area of deflection at the cutterbar were calculated for each four degrees of cutter rotation.

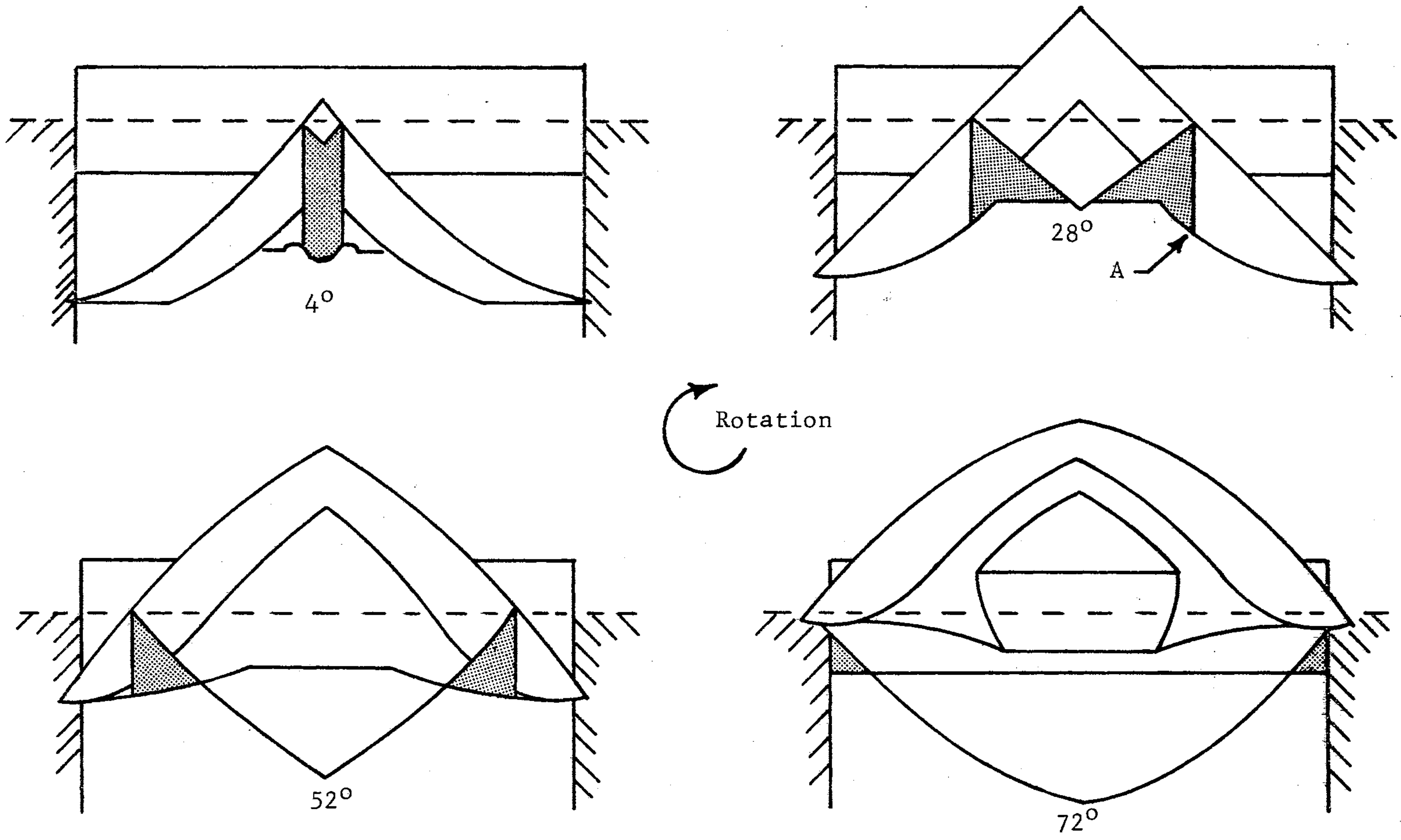


Figure 27. Top View of a Cutter Showing Horizontal Stalk Deflection and Area of Deflection for Four Angular Positions of the Rotor. Shaded Portion is the Area of Deflection; Slashed Portion is the Guard; Dashed Line is the Leading Edge of the Cutterbar

The results are listed in Table III along with the height of contact and the measured values of stalk deflection and area of deflection. Figures 28 and 29 are graphical representations of this data.

The peak in the curve shown in Figure 29 from 24 to 44 degrees is due to the back part of the V section of the cutter causing the maximum deflection. This point is labeled A in Figure 27. From 52 to 68 degrees the curves are flat. This is due to the rotor shaft producing the deflection while the blade is still emerging from behind the cutterbar. At 68 degrees, the knife edge no longer is emerging from the cutterbar but rather is moving forward from it. This results in a rapid decrease in each of the curves with their values falling to zero when a vertical line touching the knife edge and the rotor shaft coincide at the ledger. At this point there is no more interference. Other irregularities in the curves can be seen in Figures 28 and 29, and are due only to small variations on the backs of the cutters, hence needing no further description.

The difference between maximum and minimum horizontal stalk deflection shown in Figure 26 is only 0.16 in. If this deflection is considered in relation to the uneveness of stubble height, it would produce only a 0.03 in. variation. In fact, even at the maximum deflection of 0.36 in., stubble length would be increased by only 0.06 in. These figures, however, are based on a knife moving horizontal to the ground surface, when in actuality the knife path is curved as shown by the C in Figure 26a. This path tends to increase the effect of the deflection and results in an actual maximum increase in stubble height of 0.12 in. In essence, however, this increase tends to even out the stubble, for the stalks would be slightly longer at the beginning of

TABLE III

MAXIMUM DEFLECTIONS AND AREAS OF DEFLECTION IN THE HELICAL CUTTERBAR

Rotor angle (degrees)	Height of contact (inches)	Deflection at contact point (inches)	Deflection at cutter-bar (inches)	Area at contact point (sq inches)	Area at cutterbar (sq inches)
0	3.91	1.25	0.36	0.00	0.00
4	3.75	1.08	0.32	0.50	0.15
8	3.81	1.01	0.30	0.67	0.20
12	3.91	1.01	0.29	0.75	0.22
16	3.96	0.94	0.26	0.83	0.24
20	4.03	0.88	0.24	0.83	0.23
24	4.09	0.89	0.24	0.67	0.18
28	3.75	0.96	0.29	0.83	0.29
32	3.75	0.99	0.30	0.83	0.25
36	3.88	0.97	0.28	0.75	0.22
40	4.03	0.94	0.26	0.83	0.23
44	4.12	0.84	0.23	0.83	0.23
48	4.25	0.80	0.21	0.67	0.18
52	2.88	0.50	0.20	0.42	0.16
56	2.88	0.50	0.20	0.42	0.16
60	2.88	0.50	0.20	0.42	0.16
64	2.88	0.50	0.20	0.42	0.16
68	2.88	0.50	0.20	0.42	0.16
72	2.88	0.42	0.16	0.25	0.10
74	2.88	0.33	0.13	0.17	0.07
80	2.88	0.24	0.09	0.08	0.03
84	2.88	0.11	0.04	$\simeq$ 0.00	$\simeq$ 0.00
86	none	0.00	0.00	0.00	0.00

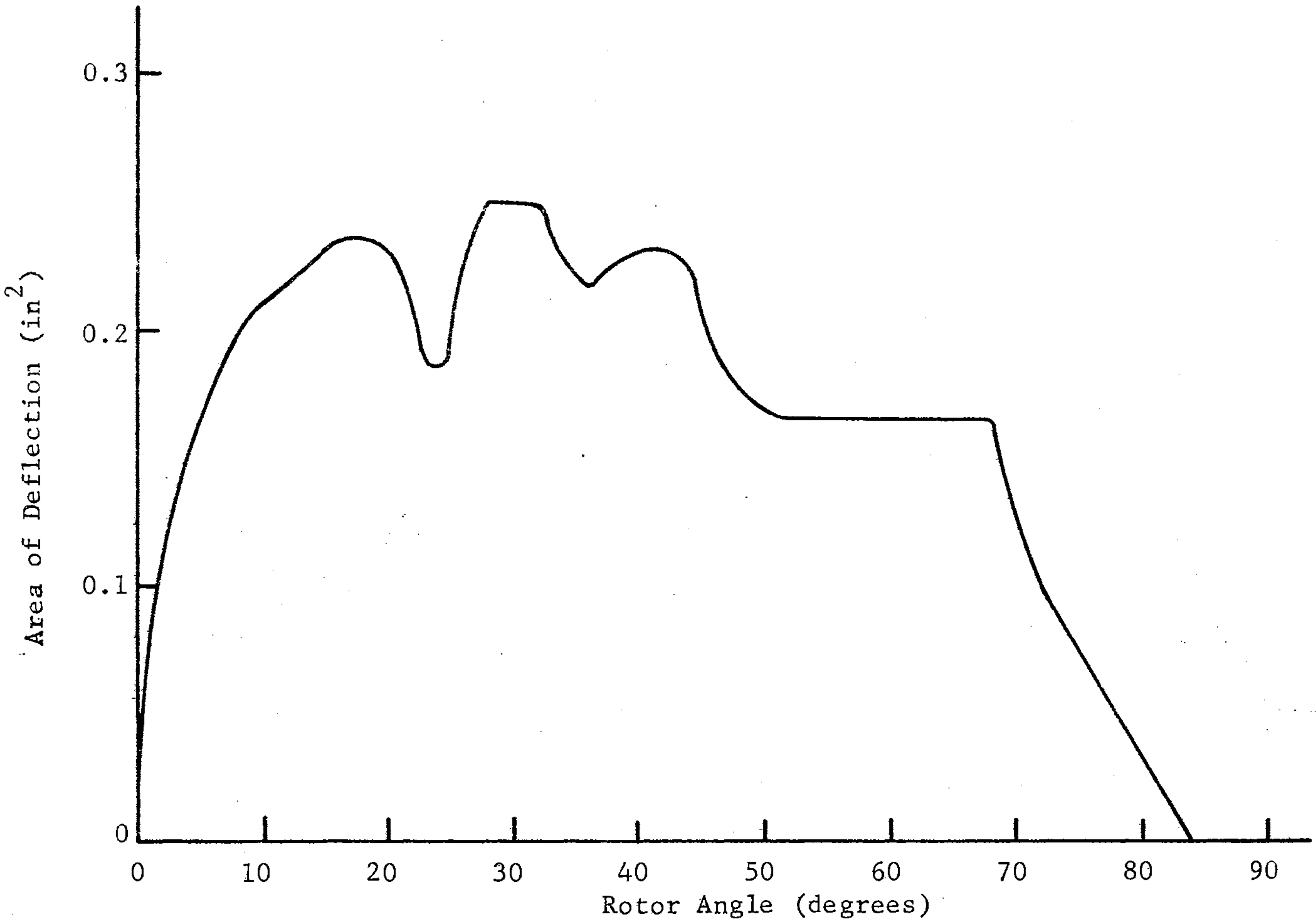


Figure 28. Graph Showing the Relation Between Area of Stalk Deflection and Rotor Position

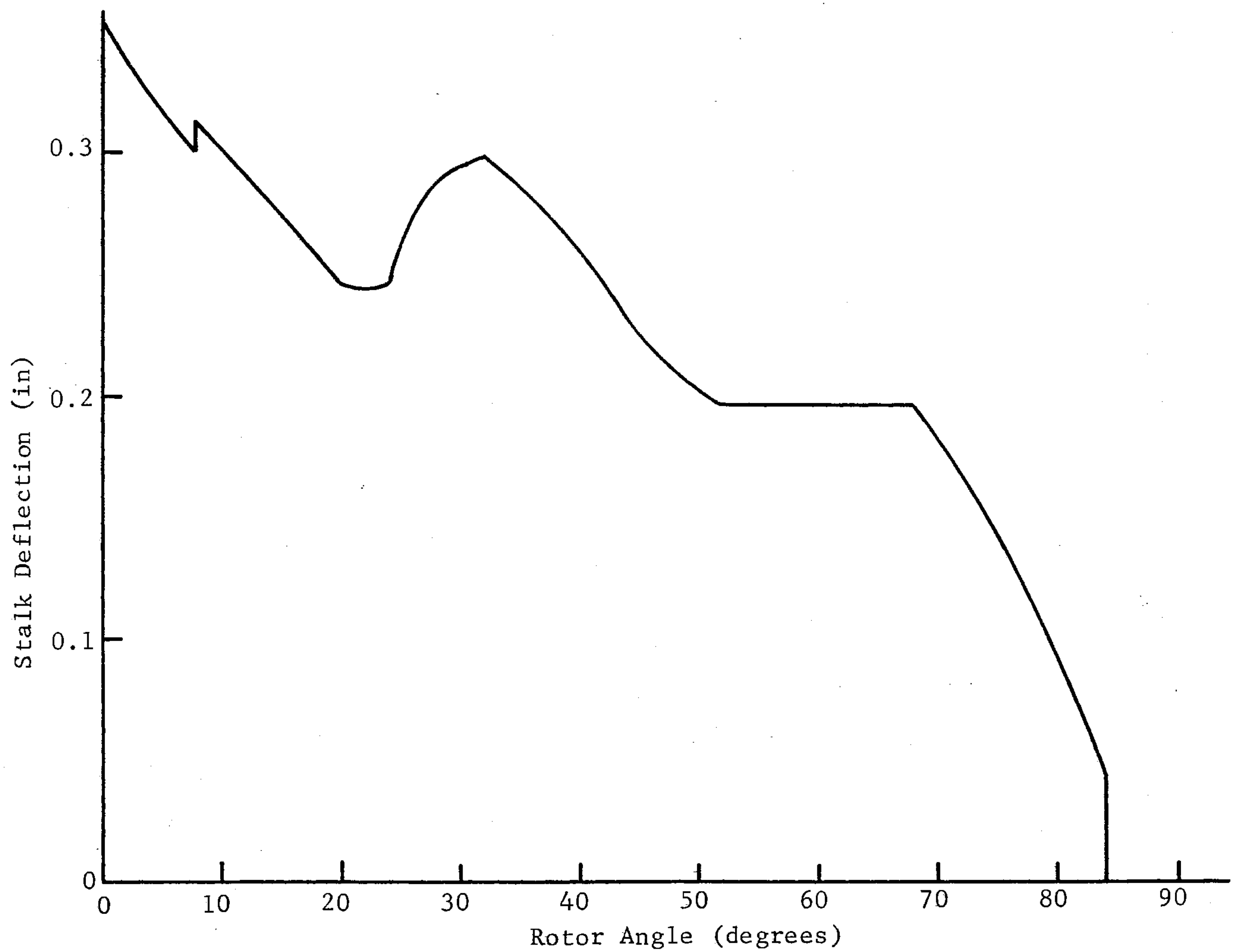


Figure 29. Graph Showing the Relation Between Stalk Deflection and Rotor Position

the cut than is shown in Figures 22 through 25. This is the reverse of the situation encountered with the reciprocating cutterbar where deflection tends to increase stubble uneveness.

The results of this theoretical study of the cutting action of the helical cutterbar indicated that stalk deflection has a negligible effect on stubble height as compared to the basic cutting path followed by a knife edge. An increase in length of stubble of 0.12 in. is small when compared to a possible three and one-half inch variation produced by the cutter itself. It should be noted, however, that the study of the total area of deflection and maximum deflection could be used in the redesign of the cutting unit to provide minimum possible stalk deflection throughout the cutter's rotation. Such a cutter would have to lie within the angle labeled D in Figure 26b at all points throughout its rotation. This would then make the maximum stalk deflection produced by a cutter equal to that produced by the rotor mounting shaft.

One other point should possibly be mentioned at this time. This is in relation to the assumption that a stalk is bent on contact by a cutter such that it lays tangentially to the front edge of the rotor cutting circle as indicated by the line labeled E in Figure 26b. The question then arises as to how far the stalk will snap back before it is severed by the next cutting element. The deflections produced by such an action would tend to increase stubble height beyond the 0.12 in. previously mentioned as maximum. The value, however, is undeterminable without a greatly increased knowledge of the plants' particular physical properties and as such is beyond the scope of this research.

Guard Interference

Considering the reciprocating unit first, using its guard spacing of three in. and a ledger width varying from 0.625 to 1.25 in., the following may be calculated. Open space at the wide, or back, part of the ledger is 1.75 in. or 58.4 percent of the total width while at the narrow, or front, part of the ledger open space is 2.375 in. or 79.2 percent.

For the rotary unit, two pairs of values must be given due to guard spacing being variable and having the two distinct values of 2.5 and 5 in. If the 2.5 in. spacing is considered first, and knowing that ledger width varies from 0.875 to 1.20 in., the following may be calculated. Open space at the wide part of the ledger, that is the front of the guards, is 1.30 in., or only 52 percent open area; however at the narrow part of the guards, the space is 1.625 in. or 65 percent of the total width. If the five in. spacing is considered, open area for the wide portion of the ledgers is 3.8 in. or 76 percent, while at the narrow part of the ledgers there is a 4.125 in. open space or 82.5 percent.

A comparison between the two units is summarized in Table IV. Included in this table is an average value of percent open area for several other makes and types of reciprocating units.

TABLE IV

PERCENT OPEN SPACE BETWEEN GUARDS

Position on Ledger	Compound Helical Cutterbar 2.5 in. Spacing	Compound Helical Cutterbar 5 in. Spacing	Reciprocating Cutterbar Hesston PT-10	Reciprocating Cutterbar Average of Other Units
Wide part	52	76	58	62
Narrow part	65	83	79	74

This table, then shows that the reciprocating unit can have more or less open area than the rotary unit through which stalks may enter the cutting area depending on the guard spacing used in the rotary cutter. If the five in. spacing is used on the helical cutterbar, it has a greater percentage of open space than the reciprocating unit. One point should be mentioned here, however, and that is regarding the shape of the guards and ledgers. The reciprocating unit has the narrowest part of the ledger at the front or leading edge of the guard, while the rotary unit is opposite. Thus in reality, the percent at the narrow part of the reciprocating ledger should be compared with that at the wide part of the rotary ledger. Comparing these two values of 79 and 76 percent, essentially no difference between the two units is found. Thus interference to feeding of stalks into the cutting area, as a result of blockage by the guards, should be equal. This then should not be a factor influencing any difference in the cutting effectiveness experienced between the two units.

CHAPTER V

EQUIPMENT AND PROCEDURE

Equipment and Calibrations

Rotary Speed Measurement

Initially, rotary speed was to be measured by a Tann model 15 Proximit Switch and a six inch aluminum disk having a three-quarter inch diameter steel plug pressed into it. This combination produced a single pulse for each revolution of the disk. This method, however, could give only an average value for a speed over a time interval and could not detect sudden changes in rotary speed. Also in changing the rotary speeds for the field tests this method was completely unsatisfactory and speeds had to be set with a small Jacquet Speed Indicator using a procedure of measuring, making a displacement change, and then remeasuring until the correct cutter rpm was obtained. A much better method would be one allowing a continuous monitoring of speed during the changing and setting operation. Thus for these reasons, the speed measuring method was changed to a tachometer generator and accompanying rpm gauge.

The tachometer and rpm gauge were manufactured by the Servo Tech Co. of Hawthorne, New Jersey. Output of the generator was listed as seven volts per 1000 rpm, with a linearity of 0.1 percent of the output at 3600 rpm being claimed. This unit required a driving torque of

15 oz. in. and was capable of operating in a temperature range from -67° F to 210° F (63).

The tachometer mounted on the helical cutter is shown in Figure 30. The Proximit switch and aluminum disk can be seen in this photograph as they were not removed in the speed conversion, but rather the generator was simply added.

On the helical cutterbar, rotor speed was actually four times that measured by the tachometer. This was a result of the modification of the original measuring system, as the latter did not have the frequency response necessary to measure the high rotary speeds, and a gearing down was used. This 4 to 1 reduction, however, was useful for the tachometer system as the rpm gauge available had a capacity of only 1000 rpm. This reduction then allowed measurement of cutter speeds up to 4000 rpm. The speed reduction was accomplished through the use of a three-quarter inch wide, three-eighths inch pitch gearbelt and two pulleys, one having 18 teeth and the other 72 teeth. On the reciprocating cutter the tachometer speed was only one-half that of the drive shaft. This reduction was used as a result of readily available parts, that is a 30 and a 60 tooth pulley. Again a three-quarter inch wide, three-eighths inch pitch gearbelt was used. Gearbelts were chosen as the drive means because an accurate speed measurement was required and they eliminated any slippage between the driven and drive shafts, giving an exact speed reduction.

On each of the field units the tachometer was connected to the end of the idler shaft by a small universal joint. This universal allowed for any misalignment between the tachometer and the shaft end, eliminating any possible damage that such misalignment could impart to

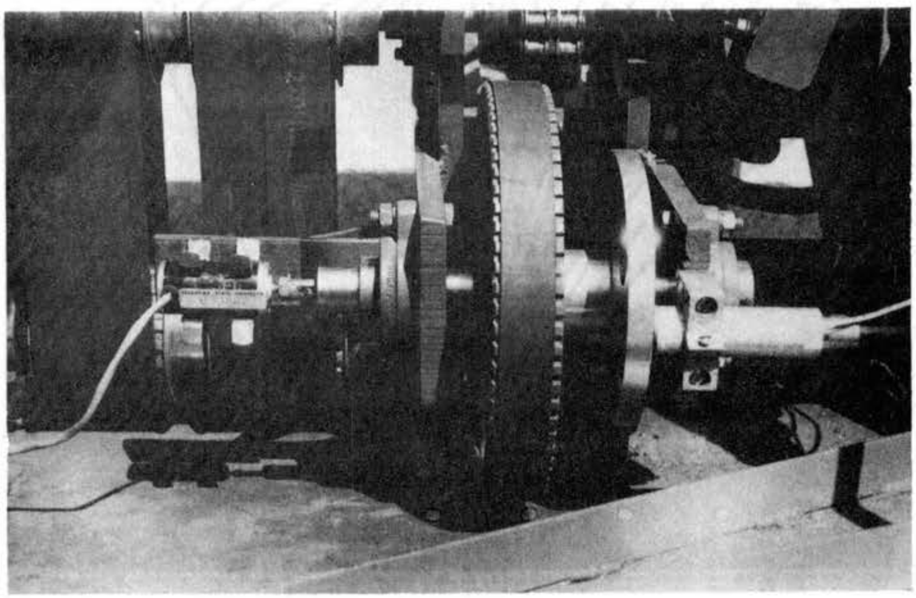


Figure 30. Tachometer Generator Mounted on the Compound Helical Cutterbar

the tachometer.

The tachometer was calibrated for use with the available rpm gauge. The calibrating source was a Jacquet Speed Indicator manufactured by the H. H. Sticht Co., Inc. of New York, New York, and had a guaranteed accuracy of 0.5 percent for the range of speeds calibrated (64).

Ground Speed Calibration

It was decided that a reproducible speed, even if it was not an integer value, would be better for the field tests than a less reproducible, integer speed. For this reason, then, approximate ground speeds were set according to the tractor engine rpm and gearing using a knowledge of the manufacturer's listed operating speeds. To calculate actual ground speeds the time for the tractor to travel between two stakes 100 ft apart was measured four times for each desired combination of gearing and engine rpm. The averaged time was then used to calculate the actual ground speeds. Although some of the speeds so calculated were somewhat strange such as 4.2, 5.3, and 8.8 mph they were reproducible, for the rpm values had been chosen such that they could be readily set again for the field tests. In many cases the engine rpm was that produced by opening the throttle to a stop thus making it readily reproducible. For the other cases where the stop could not be used, an rpm was chosen which was marked on the tractor tachometer, thus allowing resetting to the same value.

Stubble and Cutting Effectiveness Studies

The equipment for these measurements can be classified into two main divisions: 1) that to measure plant density and percent uncut stalks, and 2) that to record stubble height and uneveness.

To determine plant or crop density two devices were used. In row crops, a three foot length of aluminum tubing was used to arbitrarily determine the length over which the stalk count was made. For other crops a one foot square made from four pieces of one-eighth inch by two inch strap iron welded together was used to determine the sampling area. In using each of these pieces of equipment they were arbitrarily dropped into the cut area to help reduce any sampling errors. A view of the square in use is shown in Figure 31.

In determining uncut stalks a wooden dowel lined off in one inch vertical spacings was used. When this was placed on the ground in the sampling area and a specified height was chosen, all stubble longer than this length was then counted as uncut.

Stubble height and uneveness were recorded by taking photographs of the stubble from the side with a piece of lined posterboard as the background. The posterboard was lined off in one-half inch vertical spacings and six inch horizontal spacings. Two inches on each end of the board were further divided into one-quarter inch vertical spacings. This method allowed a rapid field procedure, and yet did not sacrifice accuracy as the actual stem height could be determined with accuracy in the laboratory. In addition, it gave a permanent record of the stubble configurations left by the various combinations of rotor and ground speed for each of the field machines. A view of the lined board

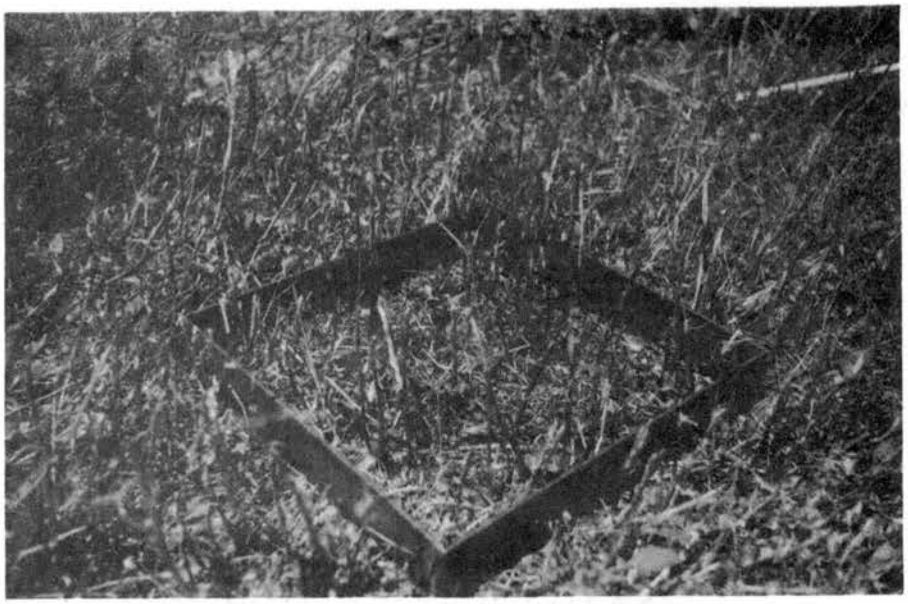


Figure 31. The One Foot Square Being Used to Determine a Sampling Area

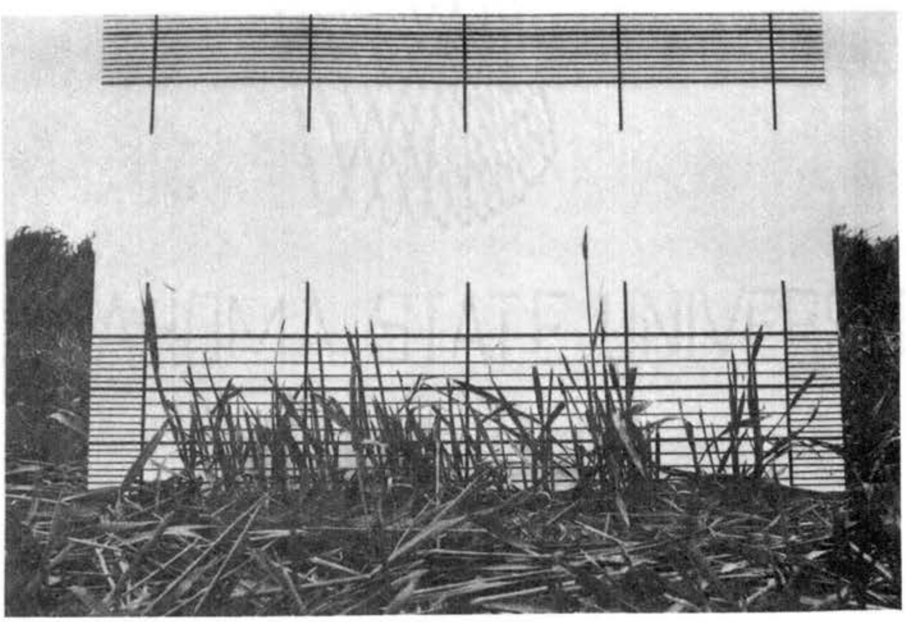


Figure 32. The Lined Posterboard in Use as a Background for the Stubble Photographs

in use is shown in Figure 32.

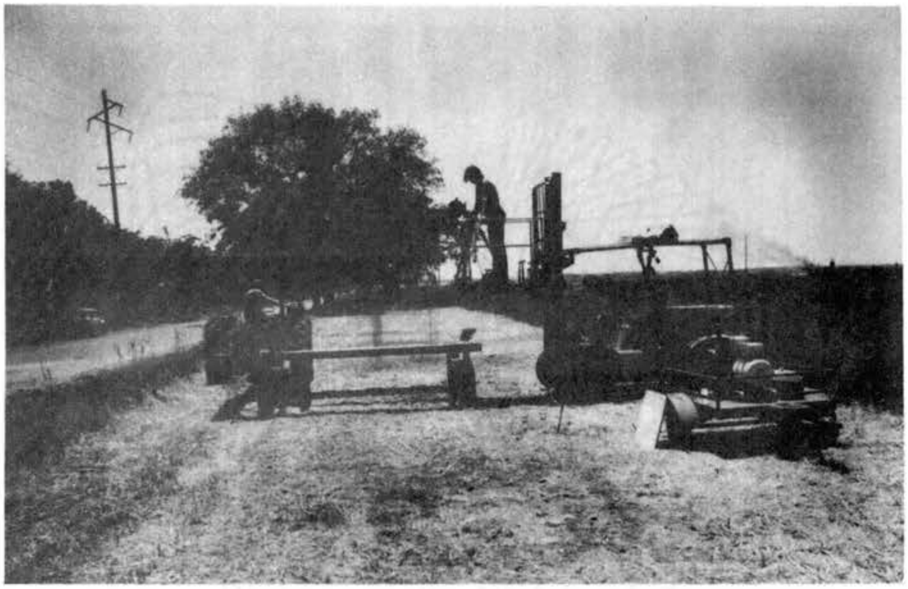
Motion Picture Studies

To study the cutting action and movement of the severed stalks in the field tests, two movie cameras were used. One camera was a 16 mm Bolex model 16 Reflex camera made by Paillard S. A. of Sainte-Croix, Switzerland and was equipped with a Vario-Switar 86EE zoom lens. This camera had a film speed of up to 64 frames per second; thus in viewing the films, the observed cutting action was approximately one-third of the actual operating speed. The second camera was a 16 mm Fastax camera, Category I, model WF3, manufactured by the Revere-Wollensak Division of the 3M Company. A model 116B Superior Electric Co. Powerstat variable transformer provided input voltage to drive the camera. Maximum output of the transformer was 140 volts ac, which gave a maximum speed in excess of 5500 frames per second for a 100 foot roll of film. The camera came equipped with a neon bulb for placing timing marks on the film such that exact film speed could be established (50). A model 3106A Wollensak Pulse Generator was used in conjunction with the neon lamp to place a timing mark on the film each millisecond. Every tenth pulse from this unit had a duration of 100 microseconds, compared to a 30 microsecond duration for the other pulses (34).

To supply power to the Fastax camera, a generator mounted on a two-wheeled trailer was used. The generator had a capacity of 5000 watts and when driven at 1800 rpm by the two cylinder Wisconsin engine, produced 115 or 230 volts at 60 cycles.

As some overhead high speed movies of the cutting action were desired, a large forklift was used to lift and hold the Fastax camera and tripod above the cutterbar. The tripod, which was bolted to a cage-like platform mounted on the forklift, held the camera approximately 15 feet above the cutterbar when the forklift was extended to its maximum height. Since the camera was mounted toward the front of the platform it was possible to center the lens directly above the crop to be cut. A view of the camera mounted on the forklift and the associated field set up is shown in Figure 33a, while Figure 33b shows the field layout employed in the filming of the side views of the cutting action using the Fastax camera. In filming the side views the tripod was not used, but rather the camera was set on a ten inch high block of wood, allowing a more direct side view of the cutting action. To prevent the right hand divider shield from obstructing these side views, two procedures were followed. Firstly the forward half of the shield was removed for the filming sequences. Secondly the camera was located approximately four ft in front and 20 ft to the right of the last stalk to be cut. Although this did give an oblique view of the cutting it prevented the remaining part of the shield from blocking the field of view.

In all of the filming the voltage to the camera was set at 130 volts ac which allowed a speed in excess of 5000 frames per second to be reached at the end of the 100 foot roll of film. Since it took approximately one second to run the 100 ft of film through the camera, turning the camera on at the appropriate time became critical. To solve the problem the distance traveled in one second by the cutterbar at each test speed was calculated. This distance was then measured off backwards from the last stalk to be cut. As the cutterbar passed this point the camera was manually switched on by an observer.



(a)

(b)

Figure 33. The Two Field Set Ups Used in Taking the High Speed Movies: (a) Top Views, and (b) Side Views

Equipment Prepared for Power Measurement

To measure input power to each of the cutting units, three pieces of equipment were obtained and calibrated. Two were pressure transducers, one having a range from 0 to 3000 psig and the other having a range from 0 to 6000 psig. The third piece of equipment was a turbine flowmeter with a range from 2 to 35 gpm. One pressure transducer was mounted on the inlet side of the motor while the other was mounted on the outlet side. The flowmeter was inserted in a straight portion of hose located on the outlet side of the hydraulic motor.

To record the data a Beckman Type R dynograph having eight channels was calibrated. Also made available was an analog computer which could be used to "average" the fluctuating signals produced by each of the pressure transducers and the flowmeter. As the recorder had eight channels, it was then possible to record the original signals along with their "averaged" values in conjunction with the cutter's rotary speed and ground speed. The latter was to be measured by the use of a microswitch and a notched disk mounted on one of the cutterbar's wheels.

All of the power measuring equipment was tested in the laboratory and found to be working satisfactorily. As a check on the measured horsepower values, the hydraulic motor was connected to a water dynamometer through a gearing arrangement. A comparison of the measured hydraulic output horsepower to the horsepower measured by the dynamometer showed only a 1.5 percent error with the hydraulic horsepower being slightly larger. This is as would be expected however, for there would be some losses in the drive system connecting the motor to the dynamometer.

Field Testing Procedures

Sorghum

For the field tests in sorghum only the compound helical cutterbar was tested. Ground speeds of 14, 11.5, 9.0, 6.5, and 4.0 mph were tried in conjunction with cutter speeds of 900, 1800, 2400, 3000, and 3600 rpm. It should be noted that not all combinations were tried, with others of these being run only briefly. This was due to a period of bad weather which followed the initial tests and destroyed the remaining crop before actual field procedures could be established and hence before a systematic data recording procedure was developed.

During these initial tests, then, no movies or still photographs were taken but rather only a visual observation was made as to the cutterbar's performance.

Green Wheat

In the green wheat crop, again only the compound helical cutterbar was tested. Ground speeds varying from 4.2 to 14.2 mph were tried in combination with rotor speeds of 1800, 2400, 3000, and 3600 rpm. Initial tests suggested that ground speeds be reduced to a range of from 4.2 to 8.8 mph and that rotary speeds be limited to 3000 and 3600 rpm.

To investigate the cutter's performance in the green wheat, plant density as well as uncut stalks were then determined for 3000 and 3600 rpm at ground speeds of 4.2, 5.3, 7.0, and 8.8 mph. A minimum of three counts were made for each replication or combination of ground and rotary speeds. To have a visual record of the stubble and cut material as left by the cutterbar, photographs of several of the cut areas as well as of the stubble were taken, with the previously described lined board being used as a background for the stubble photographs.

As a final evaluation of the compound helical cutterbar in the green wheat, movies were made using the Bolex camera operating at both 18 and 64 frames per second. For this filming, however, only one combination of test speeds was used, this being 7 mph and 3600 rpm.

In all of the tests performed in the wheat, a full width cut was made. Thus, in actuality, two tests were performed for each run as the cutterbar had two guard spacings along its length. A 2.5 inch spacing was used on the left side of the cutterbar while a 5 inch spacing was used on the right side. This allowed a comparison to be made between the spacings for each test.

Alfalfa

Initial trial runs were conducted with cutter speeds of 1800, 2400, 3000, and 3600 rpm being used in conjunction with ground speeds varying from 4.2 to 14.2 mph. The results of these runs narrowed the range of rotary speeds to 3000 and 3600 rpm, and ground speeds to 4.2, 5.3, 6.0, 7.0, 7.7, and 8.8 mph for the main tests.

To provide a uniformity to the main tests the field was divided into three 20 foot wide strips. In between the strips and at the field edges the crop was mowed using a rotary brush cutter to provide areas for acceleration and decceleration of the units without having to trample the test crop. In essence, then, only three 20 foot wide strips of uncut alfalfa spaced 20 ft apart were left in the center of the test plot. A completely randomized design consisting of three replications was then layed out utilizing part of each of the uncut strips.

The tests were conducted starting at the western edge of the field with the cutting occurring progressively from the south to the north strip. This procedure was repeated 12 times, each time starting with the southernmost strip. Although each test consisted of cutting an area 20 ft long by 7 ft wide the area in actuality was divided in half longitudinally, as the right half of the cutterbar had a 5 inch guard spacing while the left half had a 2.5 inch guard spacing. This allowed a comparison between the guard spacings to be made for each individual treatment. For all the tests the cutterbar height was held constant in that it was allowed to "float" on the ground surface.

For each test eight stalk counts were made, four for the 5 inch guard spacing and four for the 2.5 inch guard spacing. These counts were made at approximately 2½, 7, 12, and 17½ ft from the beginning of the test plot. In each instance, the count was made in the approximate center of the particular guard spacing. By using such a procedure it was intended that the cut area be evenly divided and eliminate any beginning, end, or side effects, such as shield interference or improper cutterbar height at the beginning or end of a test. This procedure of locating the plots at specific points along the test area changed the main experimental design, however. Instead of having a completely randomized design with four random samples being taken for each test, in actuality the design became a split plot design having completely randomized main plot treatments. The sampling areas or plots then became the sub-plot treatments which were not randomized but had a specific position for all the tests.

In conducting the stalk counts not only were the total stalk densities determined for the one square foot area, but in addition uncut stalks were also counted. An uncut stalk was classified as one having a length greater than four in. In measuring this height the stalks were not straightened out but rather were measured as they would have been encountered by the cutters. Variations in ground uneveness over the sampling area were also taken into account and an average surface was used for the stubble length measurements. Following the counting procedure, photographs of the stubble were made for each test using the lined board as a background.

As a final evaluation of the cutting action, movies were taken using the Bolex camera operating at 64 frames per second and the Fastax camera operating at 5000 frames per second. In filming, only a strip of crop was cut rather than using the whole cutterbar length. The strips of alfalfa were approximately 1½ to 2 ft wide, and 4 ft long. The use of only part of the cutterbar for the filming was done to eliminate obstruction of the rotor during the cutting operation and hence to provide a clear, unobstructed view. For the movies, the cutter was operated at 3600 rpm and 7 mph, with only side views being filmed.

The reciprocating cutterbar was also tested in alfalfa to facilitate comparison between the two units. Unlike the compound helical cutterbar only one rotary speed, 800 rpm, was tested with ground speeds being varied from 4.2 to 8.8 mph. Initial tests suggested a reduction in ground speed to a maximum of 7.0 mph which was then used in the main experiments. Again a 20 foot length was cut for each test with a completely randomized design consisting of three replications being established.

Stalk counts were made as for the compound helical cutterbar except that two levels of height were used as the division between cut and uncut stalks. The two lengths were three and four in. Only six samples were taken per plot, but this represents more samples than were made for the rotary unit as there was no difference in configuration over the length of the reciprocating cutterbar. Thus six samples per treatment were made in comparison to four for the rotary unit. Three of the counts were made on the left half and the other three were made on the right half of the test area. These counts were at 2½ and 17½ ft from the beginning of the cut with the third at 10 ft. As for the compound helical cutterbar, however, this procedure changed the main experimental design to one of a split plot design having completely randomized main treatments with sub-treatments or plots having fixed locations. Photographs of the stubble using the lined board as a background were made with several overall views of the cut areas also being taken.

Fall Rye

As all the available alfalfa crop had been completely cut in the previous tests and a more detailed study of the cutting action was desired, another crop was located. This was a strip of fall rye 40 ft by 300 ft lying alongside a road. Since cutting of individual stalks was desired instead of the cutting of larger strips, all of the rye was cut down except for eight, four foot long strips located 20 ft apart. The excess material was cut using the rotary brush cutter that had been employed in setting up of the alfalfa field, and a small rotary lawn mower. The remaining strips were thinned so as to have stalks at no less than 1½ inch spacings. To further aid in the visibility of the cutting action, the bottom leaves on each stalk were removed for a height up to eight in. In addition, the material cut in the clearing operation was raked from between the stalks as well as on each end and side of the rows.

The final step for each run involved the taking of still photographs of the stubble left by the cutter using the lined board as a background. In addition, views of the orientation of the cut crop, along with photographs of any cut material remaining on the cutterbar, were made.

Modified Cutterbar Tests

Three types of modifications were made to the cutterbar. These were the addition of a shield above the cutters, the addition of disks between the cutters, and the combination of these two.

The shield was made from a piece of 18 gauge galvanized sheet metal with a lip turned upward to add strength to its leading edge. To further strengthen the shield a channel section, made from the same metal, was spot welded to the top of it. This was done to ensure that the shield would not vibrate or bend into the cutters causing possible damage. The shield was held in place by eight 8-40 machine screws which were screwed into holes that were drilled and tapped into the top of the bearing mounts. It was located such that the leading edge was directly above the center of the rotor shaft. As the shield was 42 in. long, only half of the cutterbar was modified allowing for easy comparison between the modified and unmodified sections in the tests. A view of the shield in place is shown in Figure 34.

Only two disks were made, thus giving a modified length of

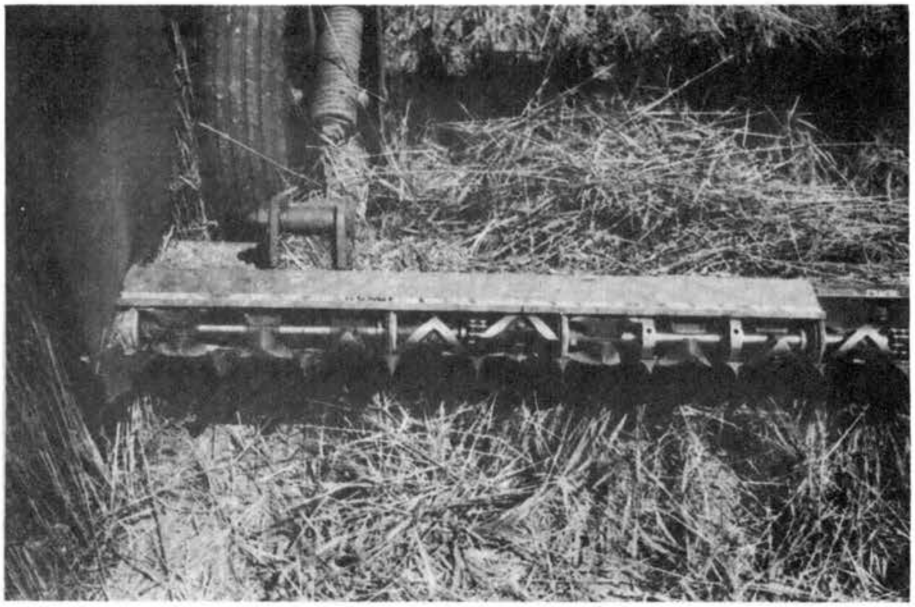


Figure 34. Modification of the Cutterbar Using the Shield

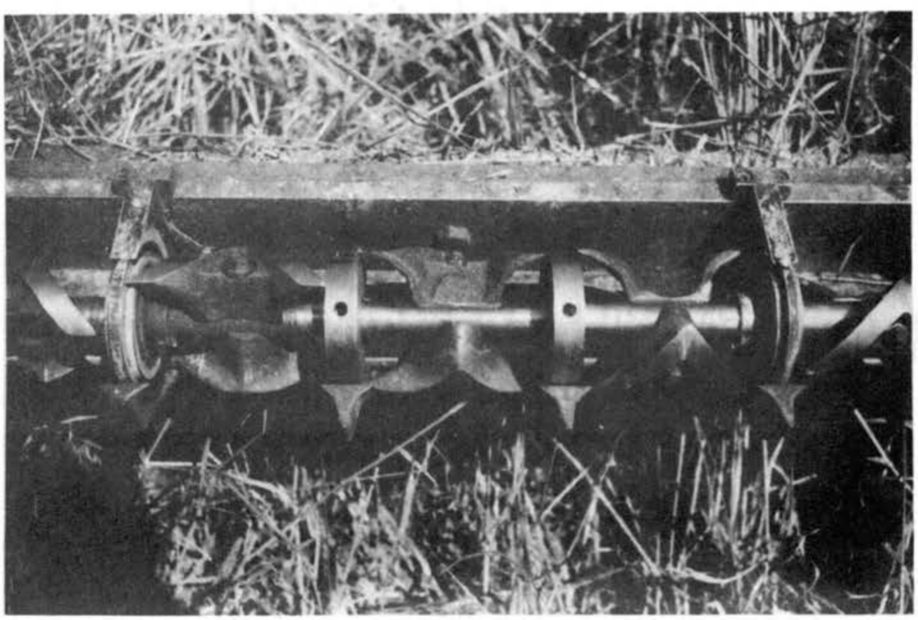


Figure 35. Modification of the Cutterbar Using the Disks

cutterbar of 15 in. The disks were cut from a section of $3\frac{1}{2}$ inch round bar stock and were faced off in a lathe, with one being eleven-sixteenths in. thick and the other three-quarters in. thick. This difference was made to accommodate the variations in clearance existing between cutter pairs. The center of each disk was drilled to one in. such that a slip fit on the one inch shaft was attained. Each disk was held in place by a single one-quarter inch by one and three-quarter inch spring pin which was driven into a one-quarter inch hole drilled through the disk center and the shaft. When mounted in place, the cutters in all but one instance actually extended over the outside of the disks, leaving no clearance between the cutters and disks. In the other case the cutter was only one sixty-fourth in. short of the disk. A view of the disks as mounted on the cutterbar is shown in Figure 35.

For the testing of the modifications a wheat crop in the soft dough stage was used. Testing of each of the three modifications began with visual observations being made for both 4 and 7 mph in combination with cutter speeds of 1800 and 3600 rpm. These tests were then followed by the taking of both still and moving pictures.

Movies using the Bolex camera operating at 64 frames per second were made; for some of the filming sequences the whole cutterbar was used, giving three different cutter configurations: the unmodified cutterbar, the shielded cutterbar, and the disks and shielded cutterbar together. In still other tests only the modified cutterbar was used while in a few instances only the section of the cutterbar having both disks and shield was filmed in operation. This latter was accomplished by mowing all but a narrow strip of crop; the compound helical cutterbar was then guided so as to cut this strip with the desired portion of the cutterbar. For all of the filming sequences only one ground and one rotary speed were used, that was 7 mph and 3600 rpm. Following several of these tests photographs of the stubble, cut crop, and cutterbar were made.

For the detailed studies using the high speed Fastax camera, only two tests, both side views, were filmed. The cutter was operated at 7 mph and 3600 rpm with one test using the disks alone, and the other using the disks and shield together. For these tests, as in the rye, it was desired to cut only individual stalks; hence two, four foot long rows of stalks were left 20 ft apart. The stalks were again thinned such that there was no less than one and one-half in. between them with all the surrounding material again being cut and raked away. The bottom leaves, as in the rye, were removed to promote better visibility.

CHAPTER VI

PRESENTATION AND ANALYSIS OF THE RESULTS

Sorghum

The field tests on sorghum were conducted in early March, with the crop having been planted the previous summer. As a lengthy wet period had existed throughout the fall and winter months the crop was in very poor condition. In many instances the stalks were lying on the ground or were disposed at various angles above the ground surface. Even the stalks that were left standing were generally in poor shape, however. The pith was wet and rotting in some cases while the outsides of the stalks were very tough and stringy in nature.

Initial tests showed a problem with feeding of the stalks into the cutters past the guards. This was a result of the leaning stalks laying across two guards, thus prohibiting the feeding of succeeding stalks into the cutting area. This problem was remedied by the removal of the middle guards, that is guard spacing was changed from 2.5 to 5 in.

The following discussion deals with the operation of the unit on a first hand visual observation of the cutting process. No photographs, movies, or stubble measurements were made for as mentioned earlier, heavy rains returned and completely destroyed the crop before any systematic study could be conducted.

Low ground speeds or low rotary speeds in combination with each other or with higher speeds produced ineffective cutting. It appeared as though on contact with the knife, the stalk was simply bent forward rather than being cut. The cutterbar frame then passed over the stalk, preventing any cutting. The best cutting performance appeared to occur for the combination of the higher ground speeds with the higher rotary speeds. The reason for such findings appeared to be that minimum ground and rotary speeds were required for a blade to contact a stalk and then sever it. To investigate this theory the cutter was operated at various rotary speeds while being driven forward very slowly. Even with the author holding the top of a stalk to preventit from bending forward, no cutting occurred. Rather a shredding effect took place where the rotor contacted the plant. In appearance the rotor acted as if it were a solid cylinder revolving about a horizontal axis. This action then prevented the plant from moving within the outer diameter of the rotor; hence no perpendicular contact between the plants and knife edges could occur and cutting was absent. Such behavior would explain the necessity of high ground speeds, for the plants must be able to penetrate within the rotor diameter for cutting to take place. The high rotary speeds would then be necessary to compliment the ground speeds such that a blade would always be present to sever the next stalk.

The question arises as to why cutting did not occur for the combination of low ground and rotary speeds. At such a combination the feed rate was equal to that for the higher speeds thus feeding of the stalks into the cutters was not the problem. Rather the difficulty lay in the ineffective cutting produced as a result of knife speeds being so low that impact cutting could not take place.

In observing the cutting in progress it was noted that the stalks generally fell back over the cutterbar with some being lifted to a vertical height of one to two ft. On falling to the ground the stalks attained an orientation parallel to the direction of travel of the cutterbar with their transverse movement appearing to be negligible. In some instances cut stalks were retained on the cutterbar and lay in between two cutting elements or were wrapped around the shaft. A few stalks were also found laying over the vertical portion of the angle forming the cutterbar frame.

Generally the stubble height appeared to be fairly uniform with most of the stalks having been cut in a single motion. In a few instances, however, the stubble appeared to show signs of double cutting in that two discrete bevels were found on the cut surface. In comparing stubble height to cutterbar height no definite figures can be given. It appeared, however, as though the majority of the stalks had been cut off in the middle of the cutting zone, that is half way up the curved guard-ledger assembly.

Green Wheat

The wheat crop was a hard red winter variety, having been planted in the fall of 1972. The field tests took place in April 1973 when the crop was within 10 days to 2 weeks of heading. Crop height generally varied from 18 to 24 in.

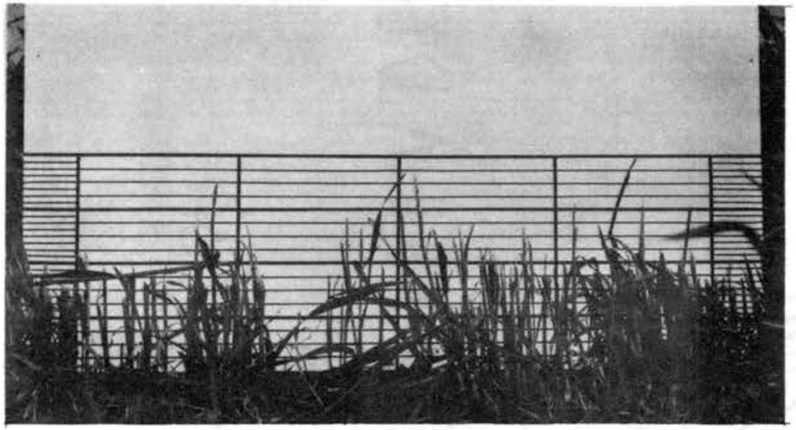
The field tests started with a rotor speed of 1800 rpm and ground speeds varying from 3.3 to 8.8 mph. At all of the combinations tried it was found that the cut material wrapped itself around the central shaft between the cutter pairs. This wrapping continued until no more crop could feed into the cutters as the outside diameter of the material became equal to that of the rotor. At this point cutting stopped and the cutterbar essentially became a solid cylinder pushing the uncut crop forward and finally beneath it. The same results were found for a rotor speed of 2400 rpm. For this reason, then, no further testing was conducted at either 1800 or 2400 rpm.

At 3000 and 3600 rpm wrapping of the cut material was greatly reduced. Although some buildup did occur during cutting, it cleared itself when forward motion of the cutterbar ceased. In observing the unit in use it was noted that at the low ground speed of 3.3 mph, little was cut. It appeared as though the crop was simply pushed ahead of the cutter without entering the cutting zone. This would then agree with the results found in the sorghum tests where the crop was not cut due to the blades appearing as a solid revolving cylinder. At the highest ground speeds, the feed rate was too great, as the cutter appeared to become immersed in a mass of cut stalks and simply pushed the uncut material forward and then passed over it. The reason for this appeared to be inadequate movement of the cut material away from the cutter, leading to clogging. As mentioned, too fast or too slow a ground speed produced ineffective cutting. In fact for a given rotary speed and tractor engine speed only one gear appeared to produce the best cutting. For the 3600 rpm rotor speed this was at 7.0 mph, while for the 3000 rmp speed, it occurred at 5.3 mph. In calculation of the feed rates it was found that at 3600 rpm the feed rate was 2.02 in./rev, while at 3000 rpm it was 1.86 in./rev. Thus a visual observation showed the cutter to perform best in a very limited range with the best cutting occurring at a feed rate of approximately two in./rev.

In the hopes of gathering a more sound basis for such conclusions, additional tests were run for rotary speeds of 3000 and 3600 rpm. Stubble counts were made at a minimum of three locations per test; the results are listed in Appendix B. The data shown therein is essentially meaningless however, for the variation within a given replication is much greater than the average variation between ground speeds.

The reason for these doubtful results was the pattern of the crop left uncut. Rather than the uncut stalks being distributed relatively evenly over the entire area, they appeared as strips. In some cases a length of satisfactory cutting was followed by a section of completely uncut stalks which in turn was followed by a length of satisfactorily cut stubble. This patchiness then led to errors for unless a very large sample size was used, the results were easily biased. To take a larger sample was not possible however, since the crop was being mowed at the time the tests were run and time was limited. One result of the stubble counts might be the determination of how well the cutter was actually performing. Rather than an estimated 30 percent uncut crop, in actuality an overall average of only 16 percent was found.

As mentioned earlier, photographs of the stubble were made using the lined board as a background. In taking the photographs, some of which are shown in Figure 36, areas were chosen in which most of the crop had been cut. This was done simply because if there was no cutting, stubble height could not be studied. The four views are for a rotor speed of 3000 rpm and ground speeds of 4.2, 5.3, 7.0, and 8.8 mph. In studying these photographs it should be remembered that for the tests the cutterbar was allowed to "float" on the ground surface,



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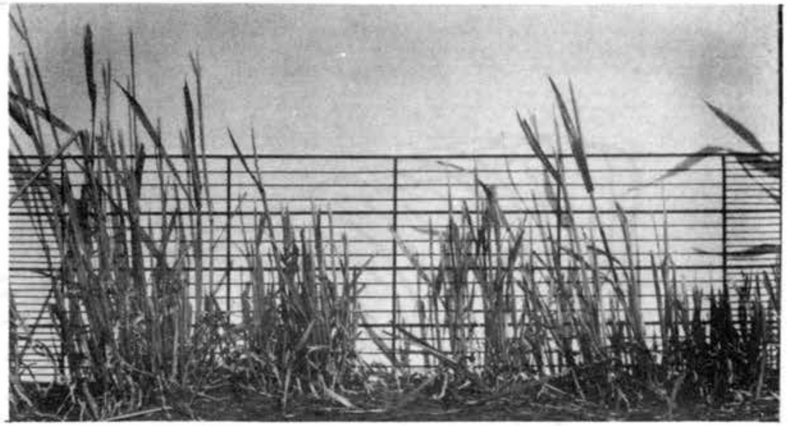

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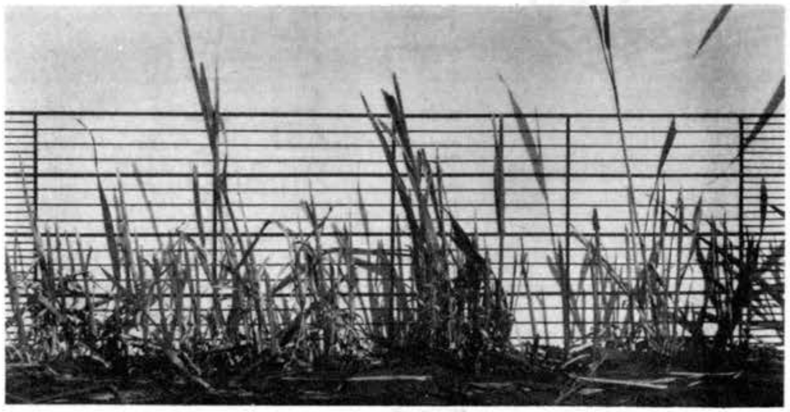


(c)

(d)

Figure 36. Four Views of the Stubble Left in Green Wheat by the Compound Helical Cutterbar Operating at 3000 Rpm and (a) 4.2 Mph, (b) 5.3 Mph, (c) 7.0 Mph, and (d) 8.8 Mph

resulting in the top of the cutterbar lying approximately one and one-fourth in. above the ground surface. At all speeds the tallest stubble shown is at least seven in. with many stalks extending above eight in. The 5.3 mph test shows just how much stubble length can vary over a small area. Within a single clump, stubble height can be seen to vary from two and one-half in. to better than eight in. Thus two stalks that appear to be spaced no more than two in. from one another varied five and one-half in. in length.

Originally it had been hoped that these photographs could have been used to draw a graph or plot of the variation in stubble height for comparison with the theoretical plots given in Chapter IV. This could not be done due to the great variations in stubble height just described for rather than varying uniformly, stubble lengths were intermingled. Theoretically stubble height should have varied from 0.1 in. for 4.2 mph to 0.4 in. for the 8.8 mph test. These measurements are based on the assumptions that: 1) double cutting does occur, and 2) stalks are cut upon first contact with a knife edge. Even if double cutting did not occur, stubble lengths would vary by only 2.4 in. rather than by the tremendous amounts recorded. Obviously then, the plants were not cut upon first contact with the cutters, but were hit and bent forward. This can be emphasized by considering that the top of the cutters was only four and three-quarters in. above the ground, thus any stubble longer than this had to be deflected forward before being cut. One other suggestion that might possibly account for the great variation in stubble might be that some double cutting did occur, producing the shorter stalks. Other stalks, however, did not have sufficient opposing force necessary for impact cutting and hence were left long.

As a final evaluation of the helical cutterbar's performance in green wheat, the movies filmed at 64 frames per second were viewed. One observation made was that the cut material was thrown much higher than had been observed in the field. In actuality portions of the crop were thrown as high as five ft. above the cutterbar. The films also showed the cut material to be thrown upward in bunches rather than in a continuous manner as was expected. It thus appeared as though the material built up on the cutterbar and finally was thrown from the cutting area. Possibly some of the bunches could be attributed to the unwinding of cut material from the shaft. One other observation was made in viewing the films. This was the direction in which the cut material was thrown, for rather than the upward and backward movement that had been expected, some of the crop was actually thrown forward. Part of this could be attributed to the unwinding of the cut material from the shaft but it did not appear that this was the sole reason. Any material thrown forward could encounter the cutters again, and increase plugging or at least hinder feeding of the uncut crop into the cutting area.

Before this discussion concerning the evaluation of the compound helical cutterbar operating in wheat can be left one point should be mentioned. In all the tests, one half of the cutterbar had the 5 inch guard spacing, while the other half had the 2.5 inch guard spacing. In no instances were any discernible differences observed in the performance of either half of the cutterbar, disagreeing with observations made in the sorghum.

Alfalfa

The alfalfa crop was tested during the latter part of April 1973. At this time the crop was within one to two weeks of flowering. Crop height generally varied from 15 to 18 in.

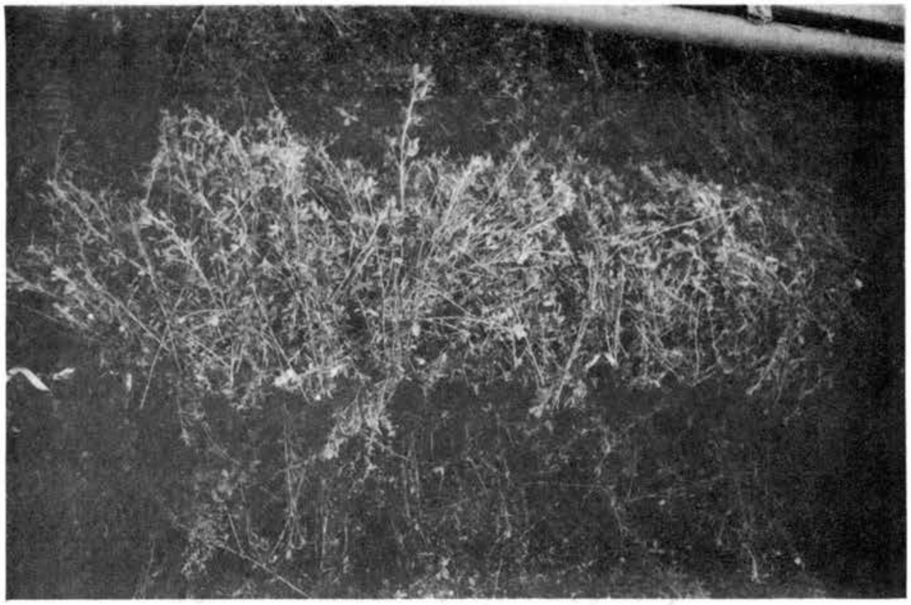
The initial tests in the alfalfa showed essentially the same results as those found for green wheat. That is, at rotary speeds of 1800 and 2400 rpm the cut material wrapped itself around the central shaft between the pairs of cutting elements, until its diameter equaled that of the cutters. At this point cutting essentially stopped as no more crop could be fed into the cutting area. At 3000 and 3600 rpm more wrapping was found than had been noted in the wheat; however when forward motion of the cutterbar ceased the wrapped material began to tear itself from the shaft, as had occurred in the wheat.

For ground speeds greater than 8.8 mph plugging of the cutterbar was a great problem even at the highest rotary speed. The clogging appeared to be due to the fact that too much material was being fed into the cutters at any one time. The cut material was then not moved away from the cutting area fast enough and hence restricted feeding of the uncut stalks. At the very low ground speeds it again appeared as though the cutters were acting like a solid revolving cylinder preventing the uncut material from entering the cutting area. It was then decided that for these two reasons, the plugging and the wrapping, the main experiments should be limited to rotary speeds of 3000 and 3600 rpm and to ground speeds of 4.2, 5.3, 6.0, 7.0, 7.7, and 8.8 mph.

Visual Observations

In the main tests of the compound helical cutterbar two general trends were noted with regard to the unit's overall performance. Firstly, the portion of the cutterbar having the 5 inch guard spacing appeared to leave less uncut material in most instances compared to the 2.5 inch guard spacing. The most logical explanation for such results would be reduced interference to feeding of the uncut crop into the cutters, for the 5 inch spacing. The second trend observed was that the cutting quality decreased from the beginning to the end of each 20 foot test plot. This was due to the build up of cut material on the cutterbar not only from wrapping around the shaft but also from the material which was found protruding top first from the area between the cutters and the vertical section of the frame. In all instances almost all of the cut material was carried to the end of the 20 foot test strip and only at the beginning of a test were any cut stalks found on the ground. In many instances, at the end of a test strip, the cutters were all but covered in cut material, thus essentially revolving within a bridgework formed by the cut stalks. Intermingled with the longer stalks was also found a great quantity of finely chopped material which had obviously come into contact with the knife edges many times. Two views of the plugged situation existing at the end of a test are shown in Figure 37.

In observing the plots it was noted that a quantity of chopped material was found throughout the length of the test area on the ground surface. In several instances, evidence of double cutting could be seen as some of the stubble had been partially cut through a second



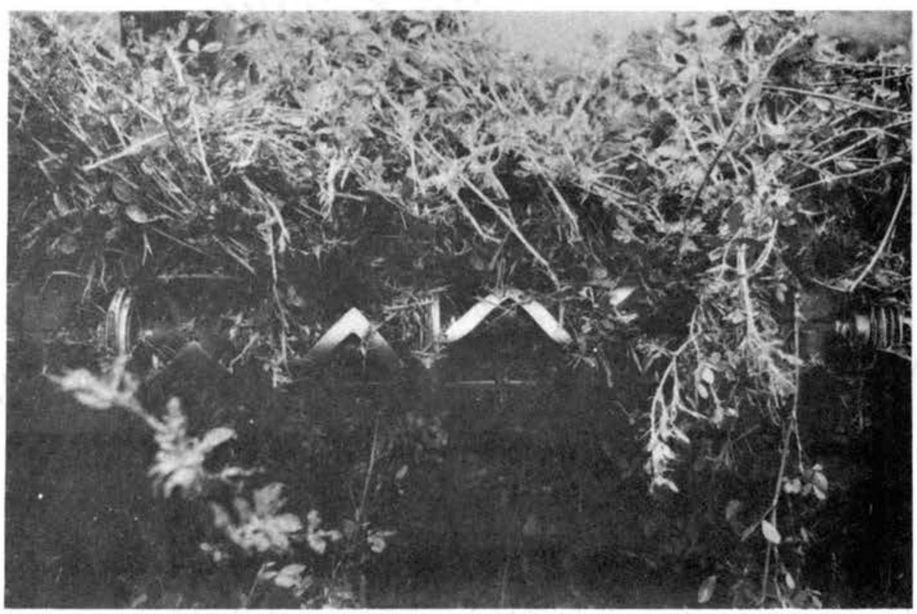
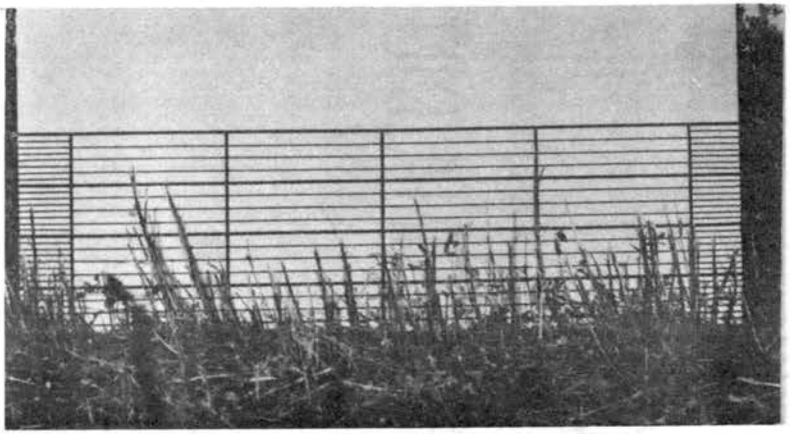


Figure 37. Two Views of the Plugged Cutterbar at the End of a Test

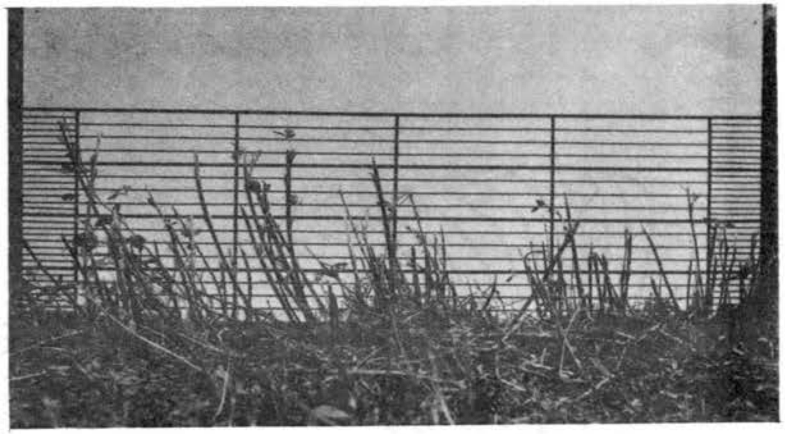
time. Generally the stubble appeared to have a very rough appearance for rather than being cleanly cut it appeared to be almost torn with some stalks "shaved" over a length of three in.

Figure 38 shows four representative views of stubble left by the cutter at 3000 rpm while Figure 39 shows four representative views of the stubble left by the cutter operating at 3600 rpm. It should be noted that for all these cases, machine travel was from right to left with all photographs being taken within the first five ft. of the test plot.

In viewing these eight photographs in Figures 38 and 39, no general trend was found. As occurred in the wheat, short stubble was found intermingled among tall stubble with stubble lengths varying from 2 in. to greater than 8 in. within a very small area. Thus as for the wheat it was impossible to construct a plot of actual stubble height to compare to theoretical lengths. Rather the photographs can be used only as a visual observation of how the cut plots appeared, for little quantitative data of value may be obtained from them. It can be noted, however, that the great majority of stalks appear to be three to four in. tall. Theoretically they should not be taller than 1-3/4 in. if double cutting occurs or greater than 3-1/2 in. if no double cutting occurs. These latter figures were based on the 8.8 mph ground speed; if, however, 4.2 mph is considered these values should have been only 1-3/8 and 3 in. respectively. It is difficult to assume that no double cutting occurred and that the majority of the crop was cut at the extreme front part of the knife's path rather than throughout the entire cutting zone. Thus some form of interference or deflection must have occurred for the majority of the stalks, otherwise



(a)



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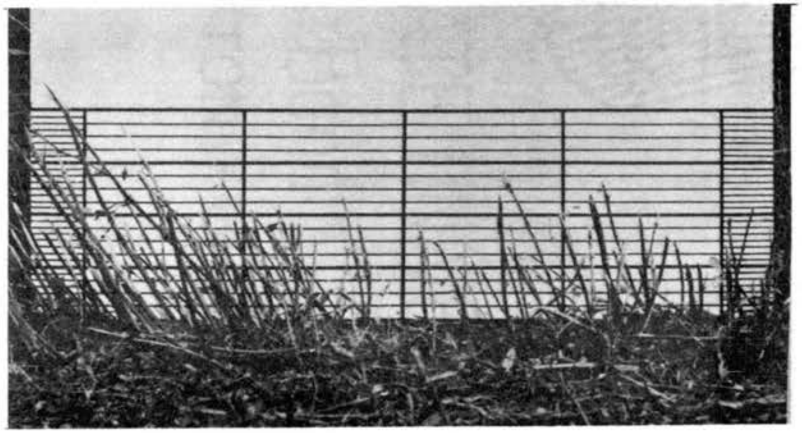

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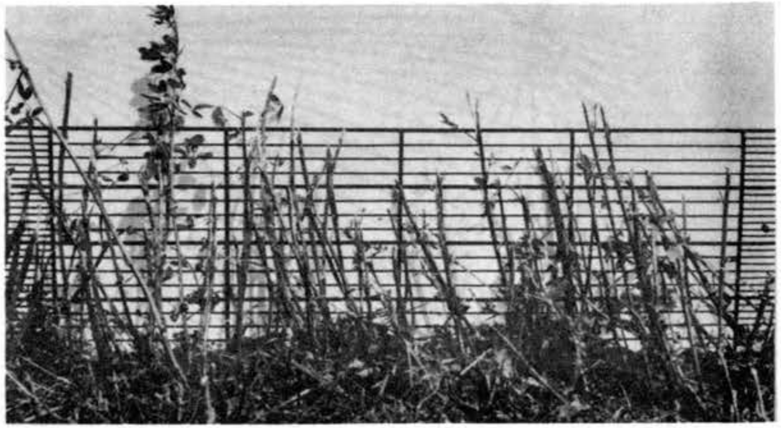
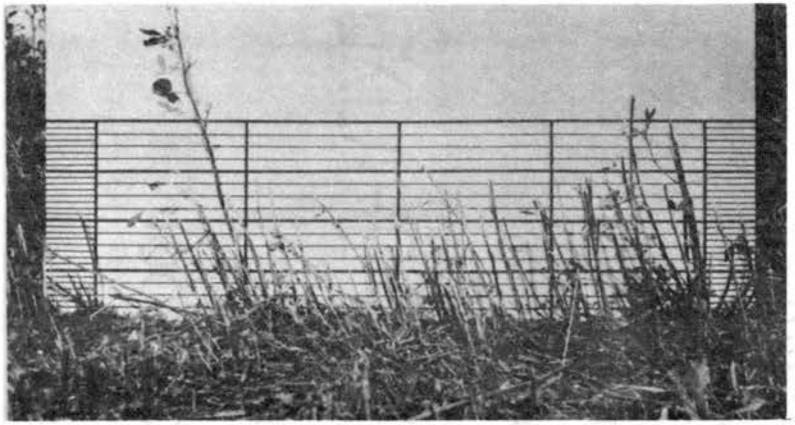
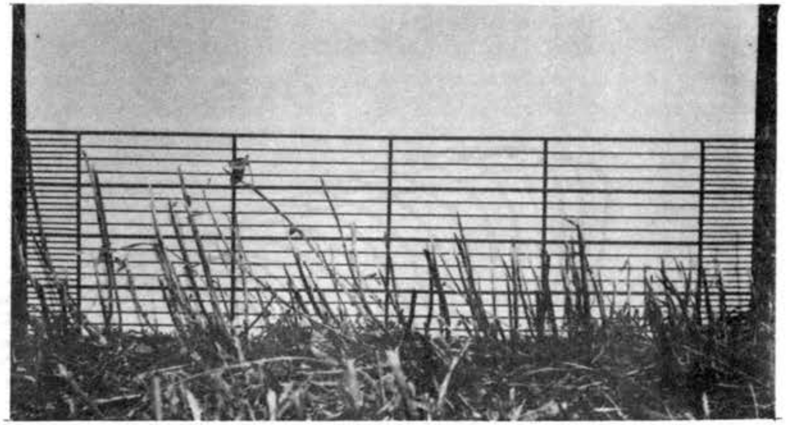


(d)

Figure 38. Four Views of the Stubble Left in Alfalfa by the Compound Helical Cutterbar Operating at 3000 Rpm and (a) 4.2 Mph, (b) 5.3 Mph, (c) 7.0 Mph, (d) 8.8 Mph



(a)



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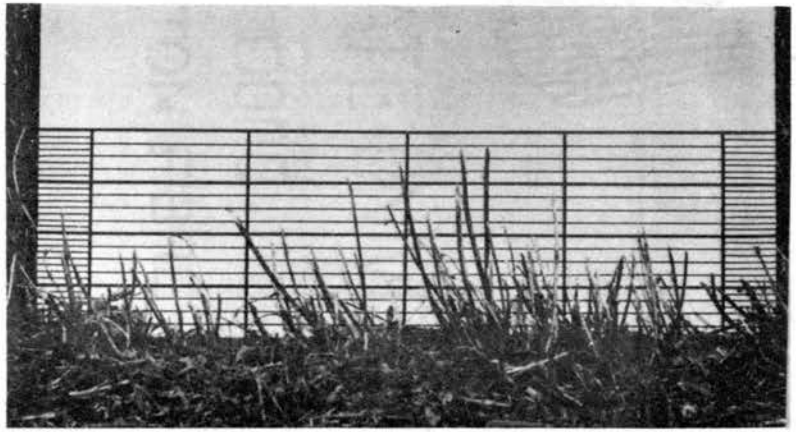

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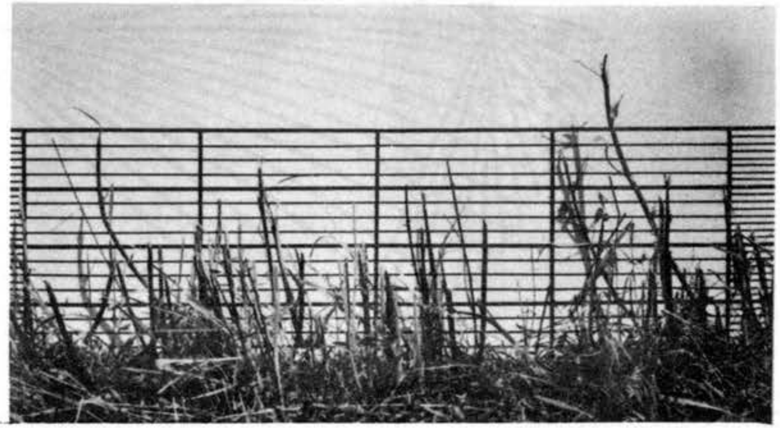


(d)

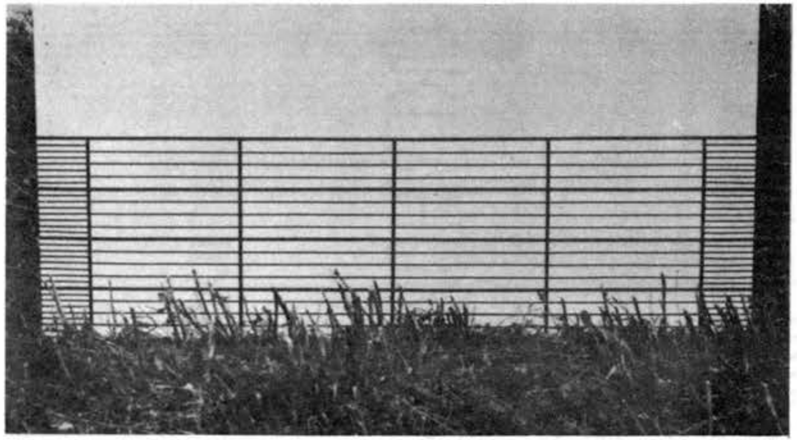
Figure 39. Four Views of the Stubble Left in Alfalfa by the Compound Hellical Cutterbar Operating at 3600 Rpm and (a) 4.2 Mph, (b) 5.3 Mph, (c) 7.0 Mph, and (d) 8.8 Mph

such a stubble pattern could not possibly have been formed. One possible explanation might be that the stalks were not cut on initial contact but were pushed forward and cut on their second contact with the knife, or pushed sideways and finally cut by two element shear.

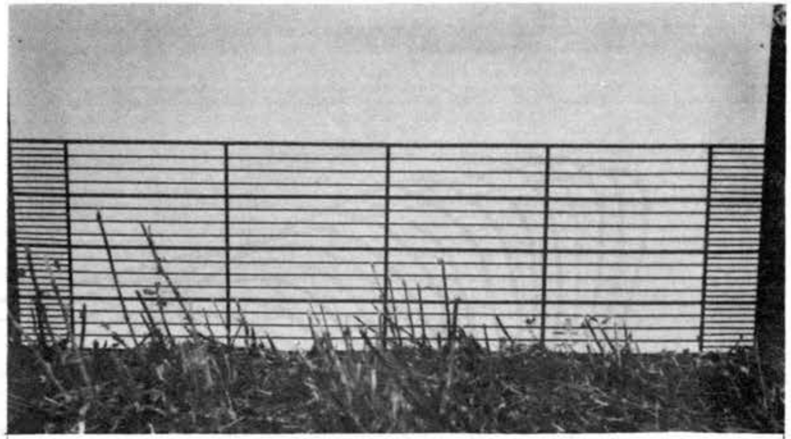
Several general trends were also noted for the reciprocating cutterbar. It should be mentioned here that not all of the tests were completed with the reciprocating unit, as the drive shaft bent, making the machine inoperable.

As with the compound helical cutterbar the cut material was generally carried to the end of the 20 foot test strip. As the cut material built up on the cutterbar, cutting decreased and in some instances essentially stopped. This was expected to some degree as the machine had been originally built to be used in conjunction with a reel and conditioner. The sloped section at the back of the cutterbar had been reduced but it obviously was still too large as the cut material collected upon it. Figure 40 shows four representative samples of the stubble left by the reciprocating cutterbar. Again all the photographs were taken at the beginning of the test strip with the machine moving from right to left. In viewing these four photographs it should be kept in mind that maximum operating speed for this particular cutterbar should have been only five mph as was pointed out in Chapter IV.

The maximum stubble length of six in. occurred at 8.8 mph, which is almost double the recommended maximum speed. For all of the slower speeds stubble lengths on the order of two in. were the average with a few odd stalks being somewhat longer, or as short as three-quarters in. tall. In comparing the photographs of Figure 40 it can be seen that



(a)



(b)

(c)

(d)

Figure 40. Four Views of the Stubble Left in Alfalfa by the Reciprocating Cutterbar for Ground Speeds of (a) 4.2 Mph, (b) 5.3 Mph, (c) 7.0 Mph, and (d) 8.8 Mph

the 4.2 mph test gave the best performance as far as cutting is concerned with the 8.8 mph test being better than any of the results for the compound helical cutterbar.

Figure 41 shows a comparison between the cuts left on individual stalks by each unit. The top row of stalks was cut by the compound helical cutterbar while the bottom row was cut by the reciprocating unit. The picture shows the very ragged condition of the stubble as left by the compound helical cutterbar, for in some cases the stalk is peeled for a length greater than three in. The stubble actually appeared very similar to that left by the rotary brush cutter used for preparing the field for the tests. It can be further noted that many of the stalks had longer slopes associated with their cut areas than would theoretically be expected, thus indicating the stalks were bent forward before being successfully cut. On the other hand the reciprocating cutterbar left a clean cut stubble with tearing being virtually nonexistent. This latter was expected for since two element shear was used in the cutting process the stalks were cut approximately perpendicular to their axis.

Stubble Counts

For the compound helical cutterbar the four inch length was chosen as the division between cut and uncut stalks simply because a three inch length would have shown the cutter to produce only 10 percent successful cutting. For the reciprocating unit both three and four in. were used such that a direct comparison could be made as well as having a lower value more on the order of theoretical stubble lengths available. The data taken for the compound helical cutterbar is given in

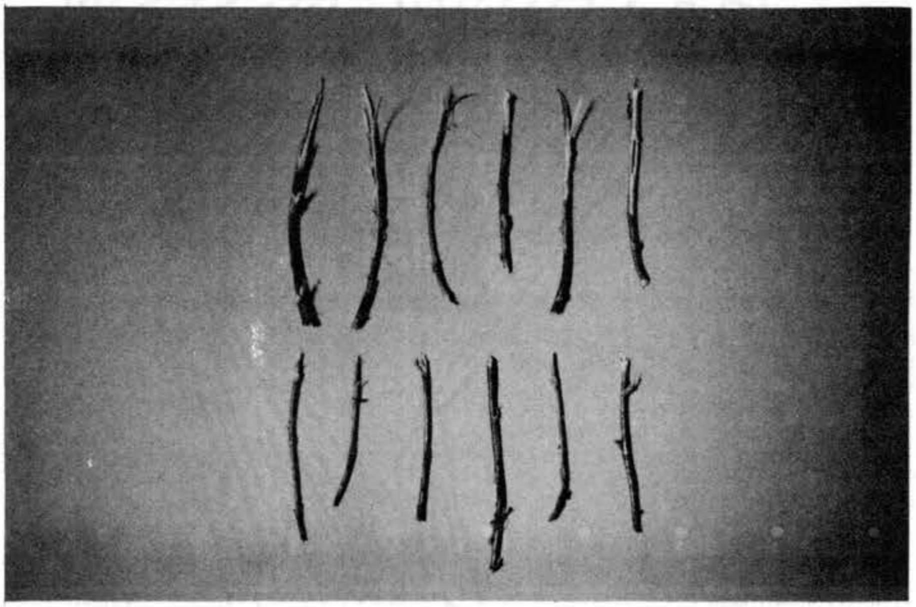


Figure 41. Comparison Between the Cuts Made on Individual Stalks by the Compound Helical Cutterbar, Top Row; and by the Reciprocating Cutterbar, Bottom Row. In Each Case the Cut of Interest is to the Top of the Stalk

Appendix C, while the data for the reciprocating unit is listed in Appendix D.

An analysis of variance, on various combinations of the data given in Appendices C and D, was made using the Statistical Analysis System (SAS) computer program. In the case of the compound helical cutterbar all of the data listed in Appendix C was used. For the reciprocating unit some data was deleted and two values were assumed to make the data uniform such that each test consisted of six observations and two replications, thus simplifying procedures. The third replication for the 6.0 mph tests was deleted and a third set of plots was added to the second replication at 4.2 mph. The data added was a duplicate of values from the first replication. The reason for the lack of these values at 4.2 mph was that the reciprocating unit's drive shaft bent in the middle of this particular test; hence it was not completed. The 8.8 mph test was omitted simply because it was not part of the main tests but rather had been run only for comparison purposes.

Table V lists the overall means for the compound helical cutterbar for each combination of speeds at each guard spacing. The analysis of variance for the data taken from the compound helical cutterbar tests is given in Table XI of Appendix E. Since the two guard spacings were included in this analysis, a split, split plot design existed with the two levels of subplots being guard spacing and sampling plots. In Table XI and all other tables in Appendix E, the abbreviations used are as follows: a) rotor speed - ROTSPD, b) ground speed - GRDSPD, and c) guard spacing - GDSP.

Table XI shows that at the 0.01 level of rejection, the effect of guard spacing was found to be significant. The effect of plots was the

TABLE V

OVERALL MEANS FOR THE COMPOUND HELICAL CUTTERBAR

Rpm	Mph	Percent Uncut	
		2.5 Inch Guard Spacing	5 Inch Guard Spacing
3000	4.2	30.2	24.6
	5.3	34.2	29.9
	6.0	40.5	34.6
	7.0	29.4	20.6
	7.7	39.2	36.0
	8.8	32.2	25.1
3600	4.2	35.8	24.8
	5.3	37.9	26.2
	6.0	35.7	28.8
	7.0	30.6	19.8
	7.7	28.9	24.1
	8.8	33.6	31.4
Average at 3000 Rpm		34.2	28.5
Average at 3600 Rpm		33.8	25.9
Overall Average		34.0	27.2

only other factor found to be significant at this level. Thus if these results are considered in conjunction with the overall average given in Table V, there is better than a 99 percent probability that a difference in the two guard spacings actually exists, with the 5 inch spacing being the preferred one.

As a further investigation of the data an analysis of variance was made on the data for the 5 inch guard spacing alone. The results are listed in Table XII of Appendix E. Since there is only one guard spacing the statistical design has been simplified to a split plot design.

Table XII shows that no significant difference at the 0.01 level was detected among either of the main treatments or their interaction, however a significant difference among the plots was again detected at the 0.01 level. Included in the table is a breakdown of the sum of squares and mean squares for the plots into linear, quadratic, and cubic effects. Almost all of the total sum of squares was reduced by the linear effect indicating a very strong linear trend in relation to the plots. Table VI lists the overall means for each of the four plots for a guard spacing of 5 in. This table along with the analysis of variance shows that the percent uncut was generally increasing linearily as the compound helical cutterbar moved along the 20 foot test strip, thus agreeing with visual observations.

Table VII lists the overall means for the reciprocating cutterbar while Table XIII of Appendix E presents the analysis of variance for this data. Table XIII shows that a significant difference at the 0.01 level was detected between the two heights of stalk measurement used to distinguish between cut and uncut crop. No significant differences in ground speed were detected at the 0.01 level. A significant

TABLE VI

OVERALL MEANS FOR EACH PLOT SEPARATELY
FOR THE 5 INCH GUARD SPACING

Plot	Percent Uncut
1	18.7
2	23.5
3	29.8
4	36.6

TABLE VII

OVERALL MEANS FOR THE RECIPROCATING
CUTTERBAR

Ground Speed	Percent Uncut	
	3 Inch Height	4 Inch Height
4.2	26.7	13.4
5.3	28.6	15.4
6.0	21.0	7.6
7.0	27.8	17.7

difference at the same level was found, however, between the plots with the interaction between plots and ground speed also being significant, That is, the trend throughout the plots varied with ground speed. This was noted in the field for as ground speed increased the cut material tended to vibrate off or be drug off the cutterbar. Thus, at some of the higher speeds the quality of cut at the end of the test was better than at some of the lower speeds, and this was reflected in the analysis of variance by the significant interaction. Since this interaction was found significant, no breakdown of the plots into linear, quadratic, or cubic effects was made.

As plot 3 presented rather erroneous results in fluctuating from speed to speed rather than following a general trend it was dropped from the data. A new analysis of variance was made using only plots 1 and 2 from each test, thus eliminating either the very high or very low values associated with plot 3. The analysis of variance for the four inch length alone is presented in Table XIV of Appendix E.

Table XIV shows that a significant difference among ground speeds was detected at the 0.01 level. Similarly a significant difference was detected between the plots. Table VIII lists the percent uncut for the four ground speeds with plot 3 omitted for both the three and four inch levels of measurement. If this table is considered in relation to the level of significance found earlier, the difference detected by the analysis of variance was for speeds of 4.2 and 6.0 mph as compared to 5.3 and 7.0 mph. An analysis of variance was also run for the data with the third plot omitted using the three inch height. No significant difference in speeds was detected at the 0.01 level, however the level of significance was found to be 0.015.

TABLE VIII

OVERALL MEANS FOR THE RECIPROCATING CUTTERBAR WITH PLOT 3 DELETED

Ground Speed	Percent Uncut	
	3 Inch Height	4 Inch Height
4.2	15.8	4.2
5.3	25.1	13.3
6.0	21.5	6.3
7.0	27.1	18.7

The next logical step in the analysis of the stalk counts would be a comparison between the two field units. For this comparison a ground speed of 7.0 mph and 3600 rpm was used for the compount helical cutterbar while the ground speed of 4.2 mph was used for the reciprocating cutterbar. The respective percents uncut for these two conditions were 19.8 percent and 4.2 percent.

The calculated t value was found to be 3.38, while the tabulated t at the 0.01 level was found to be 3.18. The t test then showed a difference in the means to exist at the 0.01 level. The 99 percent confidence interval for the differences in the means was found to be (0.96, 31.87). Thus a difference in the two units' performances was detected for the speeds tested. If the means for these speeds are compared it is obvious that the reciprocating cutterbar performed better.

High Speed Motion Picture Studies

Although the photographic quality of the high speed movies was very good the information attainable was somewhat limited. The main reason for this was that too many stalks were in view and in contact with the cutterbar at any one time, Thus it was very difficult to discern individual stalks and even more difficult to follow a single stalk through cutting and trajection as it became lost in the greater mass of cut and uncut material. Through repeated viewing of the films using a 16 mm projector operating at normal speed and on a frame by frame basis it was possible to discern two distinct motions however. An attempt to follow individual stalks, using a Vanguard Motion Analyzer, failed as they were lost in the great quantity of material cut.

One observation made was that many of the stalks were contacted twice by the cutting edge of the rotor. This indicated that impact cutting was not readily occurring, possibly due to too low a knife speed. As the stalks were not cut on initial contact, stubble lengths would be greater than theoretical values. Thus this could account for some of the long stubble found in the plots.

The second observed occurrence was the hooking of the uncut stalks by the tips of the cutters. Sketches of this action are shown in Figure 42. These are only sketches, however, of what was observed in viewing the films, for approximate 25 degree increments of cutter rotation. Part (a) of this figure shows the stalk just beginning to be hooked by the cutter tip. Up to this point the stalk had not been cut but contact between it and the knife edge of the cutter had occurred.

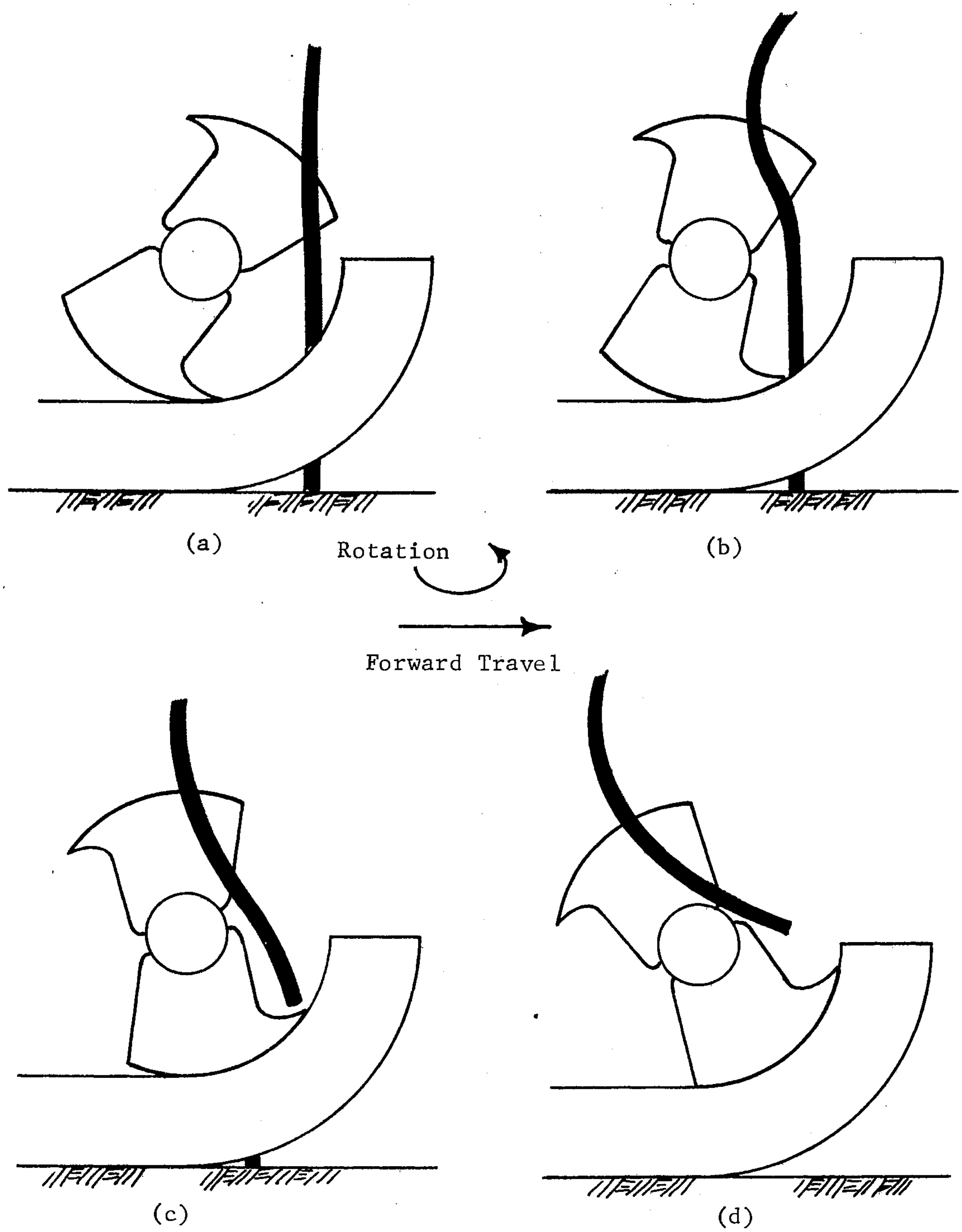


Figure 42. Sketches Showing the Hooking of a Stalk for 25 Degree Intervals of Cutter Rotation

In part (b) of Figure 42, the hooking of the stalk has progressed to the point that the stalk has a large bend in it; however, it is still attached to the ground. In part (c) of this same figure, the stalk has separated from its base, for its end is just visible above the guard. This separation of the stalk could occur in three ways: 1) failure of the stalk in tension, 2) failure of the stalk as the hooking action pulls it against the second knife edge, or 3) failure of the stalk as it is pulled between the second cutter and the ledger. Although the stalk appears to have been trajected upward by the cutting, it was not. Rather it was carried upward by the second cutter of the pair. In part (d) of Figure 42 the stalk is carried over the central mounting shaft and wrapping begins.

Insofar as trajection of the severed stalks was concerned two patterns were observed in viewing the movies. In a few instances a stalk was thrown forward while in other cases it appeared as though they were trajected upward and backward. The majority of stalks, however, were "hooked" by the cutter tips.

Two other possibilities were suggested after viewing the films which could possibly account for the wrapping problem, however direct evidence was not specifically noted. One was cutting of the stalks which were then thrown upwards but not out of the diameter of the cutters. As the cutters came around, the stalk base could be caught and wrapped around the shaft. The other possibility might be that as the stalks were cut, the angle on the knife edge might throw them sideways into the next cutter. Wrapping might then be initiated as the base of the stalk was pulled back and under by the second cutter as it revolved.

Due to the uncertainty of these explanations, a more exhaustive study of the cutting action was undertaken using the Fastax high speed camera.

Fall Rye

As for the alfalfa, the photographic quality of all the films was very good. The side views of the cutting were excellent as the stalks appeared white against the dark background of the left hand divider shield. In the top views, however, the stalks were not readily discernible as they appeared almost the same shade as the ground beneath them.

In studying the movies all were first viewed using a 16 mm projector at normal speed and then operating on a frame by frame basis. The various trends in stalk movement were noted and located by frame number from a marked frame. These particular films were then viewed on a Vanguard Motion Analyzer and traces of the stalks were made at suitably spaced intervals. In the case of the top views the stalks were not discernible for an extended period of time to allow a trace of their motion to be made.

After making several traces of the stalks in a side view it was found that six different trajectories or paths were followed by the cut stalks. These were as follows: 1) cut and thrown vertically upward, 2) cut and the base thrown forward, 3) cut and thrown both upward and forward (in viewing the movies it appeared as though these stalks were actually trajected up and over the cutterbar), 4) cut, then carried over the shaft by the cutter and finally thrown backwards over the cutterbar, 5) cut, then carried around the central shaft by the cutter and finally thrown back against the vertical angle of the frame, where they were carried along, and 6) not cut, then hooked by the cutter tip and broken, finally being thrown back against the vertical angle of the frame where they were carried along. Six representative views of these paths are shown in Figures 43 through 48 respectively. Since the camera was located at an oblique angle to the row of stalks, it should be noted in viewing these figures that the plane of the paper on which they are drawn is not the same as that in which the stalks or cutterbar moved. In each figure the distance shown separating the individual traces is not equal to the distance the cutterbar actually traveled from one trace to the next. Rather the cutterbar traveled a much shorter distance and the traces were spread out for clarity such that they did not overlap one another. On the right hand side of each of Figures 43 through 48 the first and last traces of the stalks were superimposed to give a comparison of how the final viewed position of the stalk was related to its original location. The "x's" at ground level indicate the position of the leading edge of the guards for each of these two traces. The distance between them, shown in inches, is then the total distance that the cutterbar moved forward from the first to the last trace drawn. The final view given is the final view as seen in the movies and not the final resting position of the stalks.

By far the majority of the stalks did not follow the paths in which they were thrown clear of the cutterbar but rather followed those shown in Figures 47 and 48. Wrapping of the cut material would then follow in one of two ways. First is the possibility that the stalks continued to be carried around the central shaft by the cutter. Second, as the area between the cutters and the vertical section of the

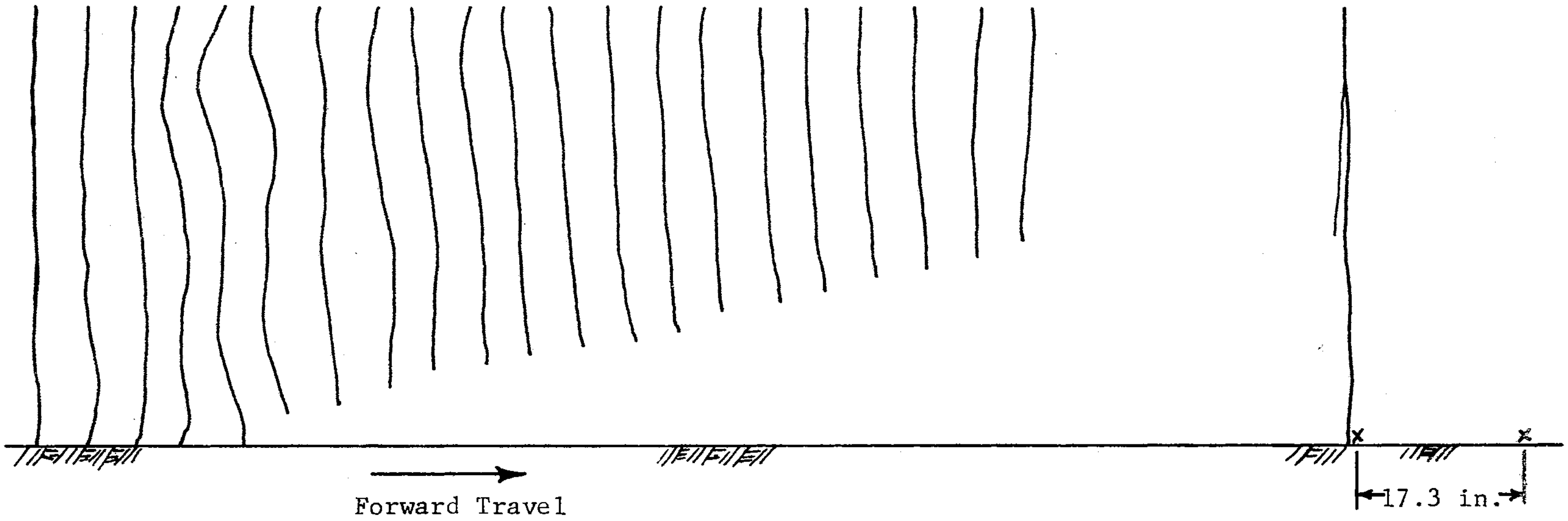


Figure 43. Path Followed by a Stalk Which is Cut and Thrown Upward

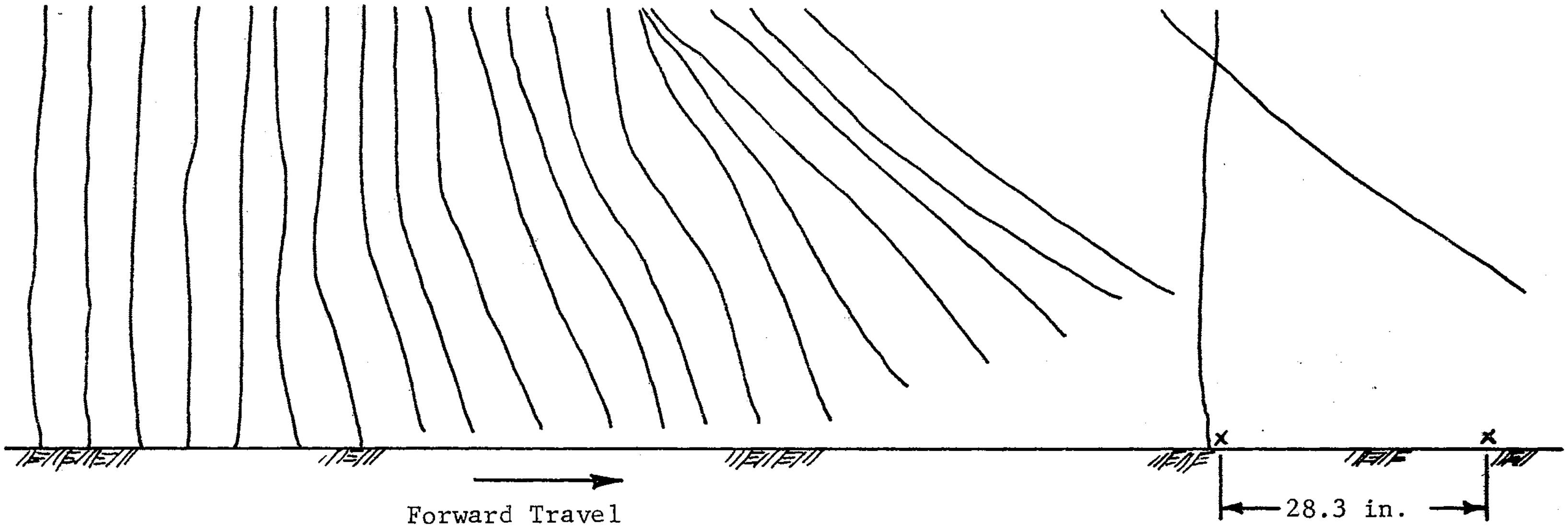


Figure 44. Path Followed by a Stalk Which is Cut and Thrown Forward

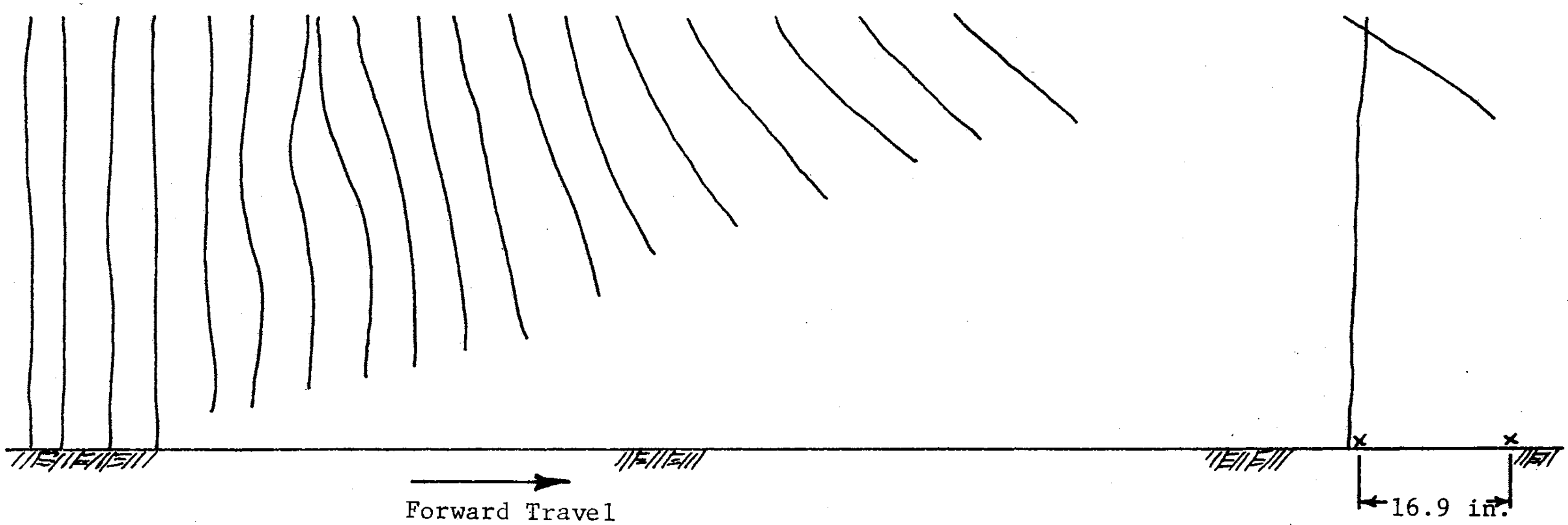


Figure 45. Path Followed by a Stalk Which is Cut and Thrown Upward and Forward

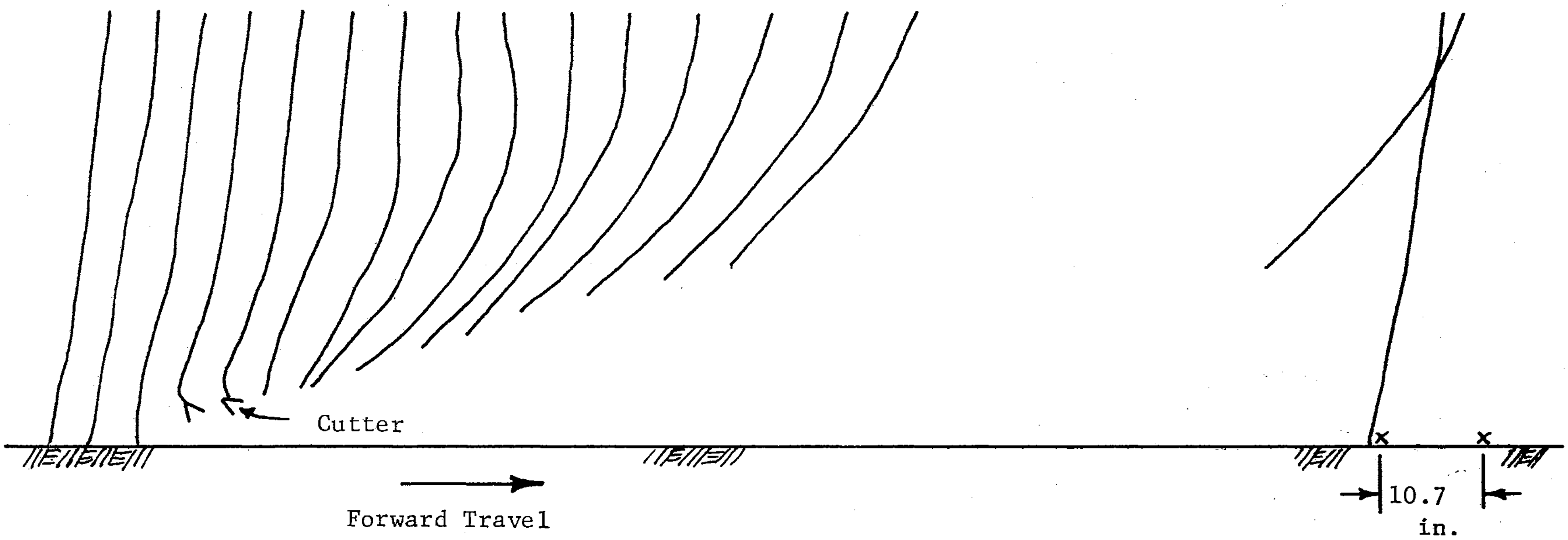


Figure 46. Path Followed by a Stalk Which is Cut and Carried Over the Shaft by the Cutters and Then Thrown Backwards Over the Cutterbar

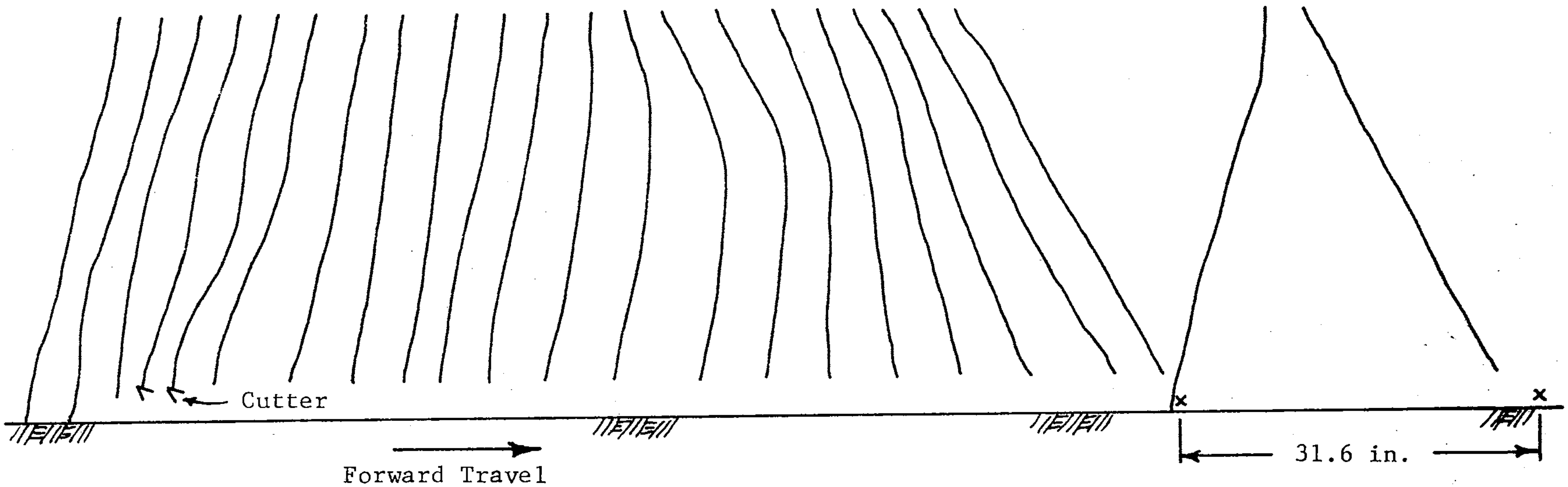


Figure 47. Path Followed by a Stalk Which is Cut and Carried Over the Shaft by the Cutters and Then Thrown Against the Vertical Section of the Cutterbar Frame Where it is Dragged Along

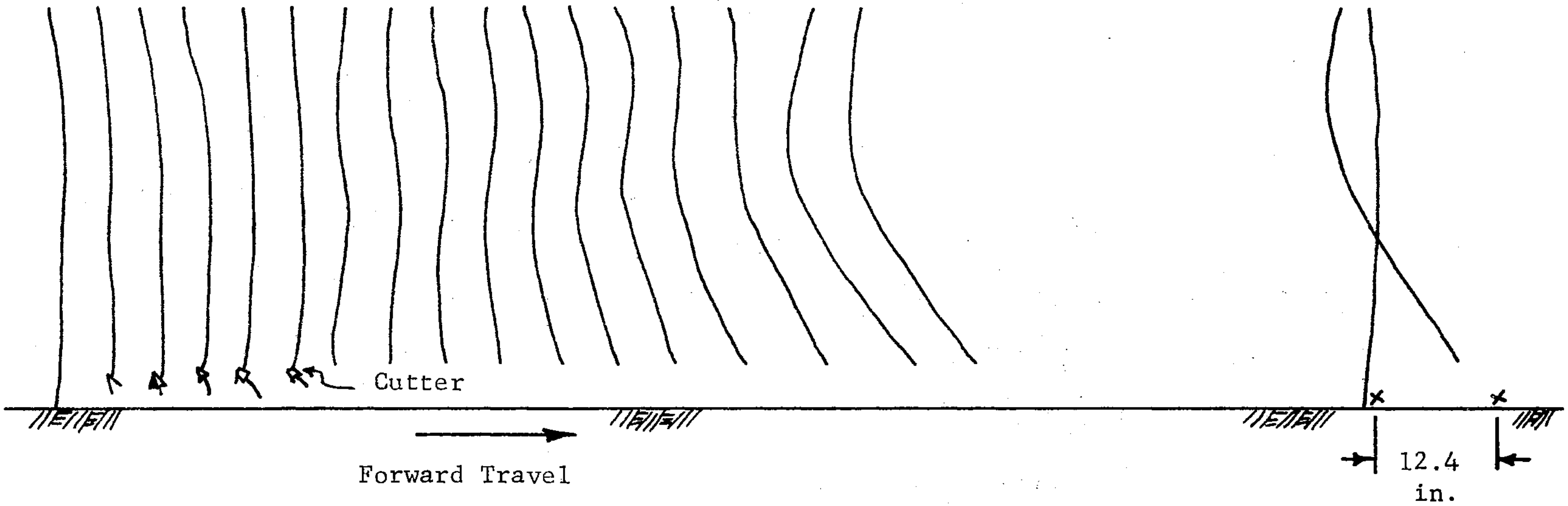


Figure 48. Path Followed by a Stalk Which is Not Cut But is Hooked and Broken Off, Then Thrown Back Against the Vertical Section of the Cutterbar Frame, Where it is Dragged Along

cutterbar frame became filled with cut stalks, the revolving cutters could easily grab this material and drag it down under to begin the wrapping process.

It was observed in the top views of the cutting action that as a stalk came into contact with a cutter, it was either cut and carried to the ledger or simply carried to the ledger where it was cut by two element shear. The stalk then continued to move sideways across the ledger and in some cases went as far as the center of the next cutting pair. Such an action would add to the plugging of the cutterbar in two ways. Firstly, if thrown into another cutter it could easily be caught by the second cutter moving backwards over the central shaft. This would then lead to wrapping of the stalk around the shaft or else the stalk would be thrown into the area between the cutters and cutter-bar frame. Secondly, if the stalks were thrown simultaneously from two cutters into the area above the guards they could collide or become entangled. Such a larger mass would likely be more subject to being hooked and wrapped by the cutter tips than would a single stalk.

In both the top and side views, it was seen that more than one contact between the knife edge and the stalk occurred. This again showed that impact cutting was not readily occurring and would account for the increased stubble length found in the field tests.

Modified Cutterbar Tests

In testing the modified cutterbar the shield alone appeared to have little if any beneficial effect. The cut material continued to wrap itself around the central shaft until the entire area below the shield became solidly filled with both cut and wrapped material. The area to the rear of the cutter was filled with a quantity of chopped material which had obviously been cut many times, as the shield held it from escaping. Many stalks were found to be bent around the leading edge of the shield with the base of the stalk being inside the shield and the top laying over it. These stalks were held in place and dragged along, thus acting as a sled onto which other stalks fell and were carried along. The end result was that the cutterbar became completely buried in material both inside and outside the shield. When such a condition was reached the cutterbar acted as a solid mass and simply pushed the uncut crop forward and under it.

A section of the cutterbar containing the disks is shown in Figure 49, after it had cut approximately a 10 foot length of wheat. This photograph shows that wrapping of the cut material between the cutter pairs where the disks were located was nonexistent, whereas the rest of the cutterbar exhibited wrapping to a large degree between cutter pairs. The area behind the cutters can be seen to still have a large quantity of cut stalks extending upward from it. Thus although the wrapping appears to have been eliminated by the disks, cut crop was still being carried over the cutters and deposited in the area between them and the vertical section of the main cutterbar frame.

Figure 50 shows the appearance of the cutterbar, including a section using both the shield and the disks together, after cutting. The photograph also shows a portion of the cutterbar which had not been modified as well as a section in which the shield alone was used. Wrapping of the cut material where the shield and disks were used together was eliminated. Some stalks were bent around the leading edge of the shield; this occurred, however, only for the areas where the

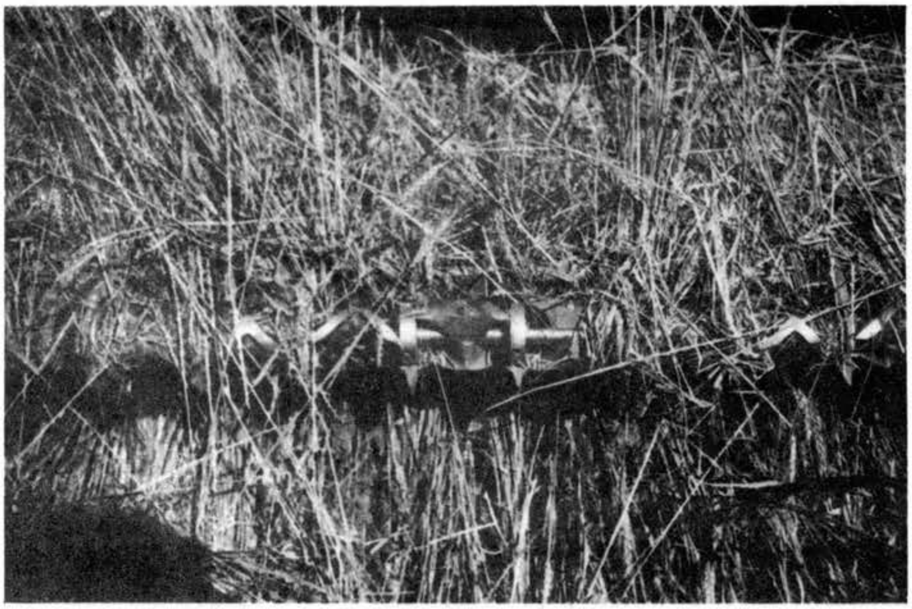


Figure 49. View of the Cutterbar Showing the Effect of the Disks

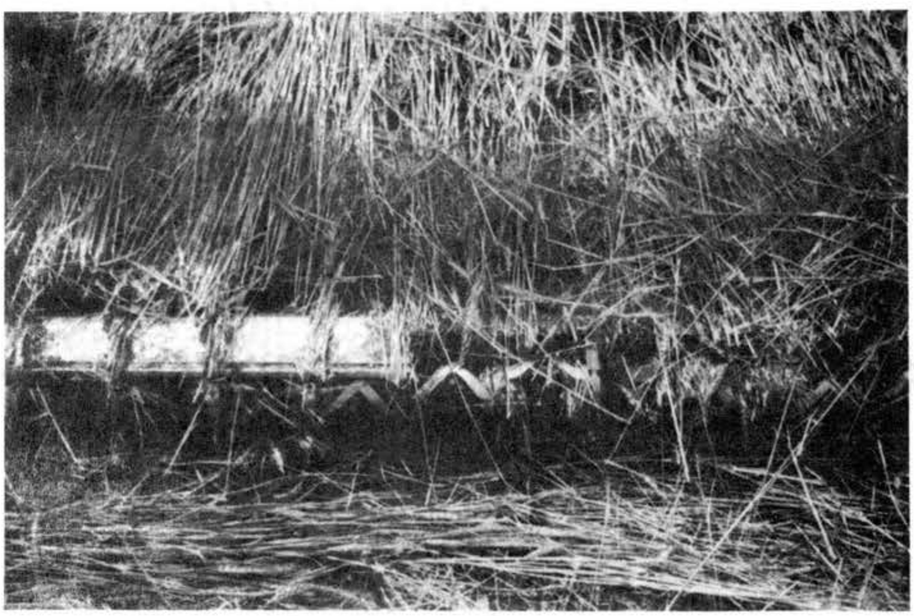


Figure 50. View of the Cutterbar Showing the Effect of the Disks and Shield

cutters did not come into contact with the shield, that is where the disks or bearing mounts were located. For taking of the photographs the cut material had been removed from the top of the shield such that this phenomenon could be viewed. Again a large quantity of chopped material was found in the area between the cutters and the vertical section of the angle frame. This indicated that some stalks had been dragged under the shield where they were chopped up, or the ends of the stalks that were not thrown above the shield had been cut off as the cutters passed under it.

The disks and shield together proved best as far as plugging, wrapping and then carrying along of the cut material was concerned. This combination provided a great improvement over the unmodified cutterbar.

The high speed movies were again of good quality with the light colored stalks being easily discernible against the dark background of the left hand divider shield. In the movie taken of the modification using the disks alone it was observed that of the 21 stalks in the row, 18 were cut and carried over the central shaft by the cutters. They were then thrown into the area between the cutters and the vertical portion of the cutterbar frame. Of the three remaining stalks, one was cut and thrown forward, one could not be followed due to the combination of a dust cloud and the other stalks, while the third was thrown back over the vertical frame of the cutterbar. In the latter case the stalk probably would also have been thrown into the area behind the cutters had it not broken as it was being lifted over the shaft. As it broke, the cutters no longer had control of the stalk, thus it could not be thrown down behind the cutters.

As it was observed that no trajection upward or upward and forward was found, this would suggest that perhaps such trajection had been occurring in the other tests as the stalks slipped sideways off the cutters. Since the disks prevented sideways motion this trajection was eliminated and the stalks were forced to be carried over the central axis by the cutters. This then refutes one earlier theory that sideways motion of the stalks could lead only to increased plugging and wrapping. Although it does add to the wrapping problem it also leads to some of the more favorable trajection patterns.

In viewing the movie it was seen that each stalk was struck at least twice by the knife. This again shows that single element impact cutting was not readily occurring, and accounts for the increased stubble lengths. Such action would indicate too slow a knife speed or perhaps dull knives.

In viewing the high speed movie of the cutting action, taken of the section of the modified cutterbar using the disks and shield together, a problem in following the stalks was found. This was due to the cut stalks remaining on the shield and then obstructing the view. However through repeated viewing of the films on a 16 mm projector, both at normal speed and on a frame by frame basis, two general observations were made in addition to noting that the stalks were again contacted more than once by the knife edges.

As when the disks were used alone, most of the stalks were lifted up by the cutters and then carried. Because of the shield, however, the stalks could not be carried all of the way around and thrown against the vertical angle. When the stalk contacted the shield two different patterns were observed. In most cases the base of the stalk, which was below the shield, was bent by the cutter around the shield edge. This portion was not cut off and in some cases it was struck three or four times by the knife, each time simply folding back under the shield. Since the stalk was wrapped around the edge of the shield it was dragged along with the cutterbar. In other cases, the end of the stalk was severed as the cutter passed under the shield. The top portion of the stalk then appeared to bounce off the shield in an upward and forward manner. This was possibly due not only to the bounce but also to the energy which had been stored in the stem during the time it was bent and lifted up over the shaft by the cutters.

CHAPTER VII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FURTHER WORK

Summary

Present cutting methods employed on agricultural machines for the harvest of crops are far from ideal. They are limited in speed of operation and have high energy and wear losses. The research conducted and reported herein deals with the design, construction, and field testing of a new cutting unit. The compound helical cutterbar had been previously tested in the laboratory and had shown possibilities not only for cutting but also for trajection of the severed stalks from the cutting area. The objectives of this study were then to:

1. Modify the original design and fabrication procedure developed by Bledsoe to achieve the following:

   A. a design that allows easy replacement of the various components of the cutting unit, and

   B. a method of manufacture that can be used in mass production of the components.

2. Determine a method to correct the loss of edge on the cutting surfaces brought about through usage.

3. Observe and evaluate the unit in the field to determine the optimum combination of design and operating parameters with

consideration being given to power requirement, speed of operation, and quality of cut.

4. Compare the new cutting unit to a reciprocating cutterbar to determine whether it has significant advantages over the present system to warrant its practical use.

The cutters and guard-ledgers for the field unit were constructed following basic design criteria established in laboratory tests. The cutters were designed on the basis of four criteria: 1) a diameter of 3.5 in., 2) a knife angle of 46°, 3) a bevel angle of 30°, and 4) sharp blades; while the guard-ledger assemblies followed two basic design criteria: 1) a 5° ledger angle and 2) a 45° bevel angle.

Casting was chosen as the method of manufacture as it simplified production procedures. Each of the cutter halves and guards were cast with integral knives and thus eliminated the need for blade attachment and further simplified production methods. A single cutting unit consisted of two cutter halves bolted to a one inch diameter shaft. The main cutterbar frame was a section of angle iron seven ft long. The guards were attached to the underside of the angle with provision being made for both a 2.5 inch and a 5 inch guard spacing.

The cutterbar was mounted to a frame and running gear salvaged from a pull type windrower. Power to drive the cutters was supplied by a hydraulic system consisting of a variable displacement pump and motor. Such a system was chosen as it would allow for easy measurement of input power to the cutters and yet was capable of operating at any speed from 0 to 3900 rpm independent of ground speed and tractor rpm. A seven foot reciprocating unit for use in a comparison test was modified to allow powering by the same hydraulic system.

The compound helical cutterbar was tested in several crops with a comparison being run between it and the reciprocating unit in alfalfa. The compound helical cutterbar was tested at rotary speeds varying from 1800 to 3600 rpm and for ground speeds from 3.3 to 14.2 mph. The reciprocating unit was operated for a range of ground speeds of 4.2 to 8.8 mph. In the alfalfa each unit was tested using a completely randomized design. Evaluation was made on the basis of percent uncut left by each machine over the 20 foot test length. A length of four in. was chosen as the division between cut and uncut stalks.

For the compound helical cutterbar a series of top and side views of the cutting action were filmed using a high speed camera. This was done to try to determine where the difficulties lay in the cutting and trajection of the stalks.

Finally three modifications in the original cutterbar design were made and field tested. High speed movies of the modifications in use were made.

Conclusions

1. High cutter speeds in conjunction with low ground speeds produced little cutting, for the cutters appeared as a solid revolving cylinder which prevented the stalks from coming into contact with the knife edges.

2. High ground speeds led to rapid plugging of the cutterbar and ineffective cutting as the feed rate was too great to allow time for adequate removal of the cut stalks.

3. Low rotary speeds produced ineffective cutting as knife speeds were below that required to produce impact cutting.

4. Wrapping of cut stalks around the central shaft between the cutters was a great problem, particularly for rotor speeds of 1800 and 2400 rpm.

5. In alfalfa no significant difference, at the 0.01 level, in percent uncut was found to exist among ground speeds or rotor speeds for the ranges tested. The lowest average value of 20 percent uncut was found at seven mph and 3600 rpm.

6. In alfalfa a significant difference between the guard spacings was found, at the 0.01 level, with the 5 inch spacing proving superior due to a reduced interference to feeding.

7. In alfalfa a significant difference, at the 0.01 level, in percent uncut was found to exist between the reciprocating and compound helical cutterbars. Overall means were found to be 22 and 30 percent respectively.

8. Generally, cutting did not occur on initial contact between the stalks and knife edges. This was a result of either low knife speeds or dull knives, or a combination of both. As the stalks were not cut on initial contact, stubble lengths were increased.

9. Six basic stalk trajection patterns were found upon analysis of the high speed movies: 1) cut and thrown vertically upward, 2) cut and the base thrown forward, 3) cut and thrown both forward and upward, 4) cut, then carried over the central shaft by the cutter and thrown backwards over the cutterbar, 5) cut, then carried over the central shaft by the cutter and finally thrown back against the vertical angle of the frame where they were carried along, and 6) not cut, then hooked by the cutter tip and broken, finally being thrown against the vertical angle of the frame where they were carried along.

10. The majority of the stalks were not thrown clear of the cutterbar. Instead they followed the last two paths listed above, thus accounting for the wrapping and plugging found on the cutterbar.

11. Tests of the modifications showed the shield alone to have little if any beneficial effect. The disks alone eliminated the wrapping between the cutters, while the disks and shield together eliminated the wrapping and helped reduce the plugging.

12. As initially designed, the compound helical cutterbar offers no advantages over the reciprocating cutterbar as far as cutting performance is concerned. However, the unit does have possibilities as the modifications have indicated, and hence warrants further modification and testing.

Recommendations for Further Work

As this research involved the initial field testing of a new machine, recommendations for further work in the form of modifications and their testing were expected. The following modifications are suggested on the basis of the knowledge obtained in the field tests.

1. Change the cutter locations such that they overlap one another, eliminating the area where wrapping begins. Such a change would also entail redesign of the bearing mounts such that the cutters could revolve as closely as possible to them, eliminating wrapping in this area.

2. Remove the guards, as they would no longer be needed after the changes in cutter location had been made, as described in 1. above.

3. Change the main cutterbar frame such that the vertical portion behind the cutters is eliminated or at least reduced to prevent stalks

from hanging in this area.

4. Sharpen the leading edge of the shield and locate it such that minimal clearance between it and the cutters occurs, thus prohibiting stalks from wrapping around its leading edge.

5. Sharpen the knife edges and/or increase knife speed such that cutting occurs on initial contact between the plant and the rotor.

6. Change the design of the cutters such that they appear as a straight line rather than V-shaped in a top view.

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APPENDIX A

ANALOG COMPUTER WIRING DETAILS

Assuming a coordinate system as shown in Figure 51 and a cutter moving with a linear velocity V and a rotor angular velocity ω, the following equations may be written concerning the position of point P:

$$x = Vt + R \sin \omega t$$

$$y = R - R \cos \omega t$$

Differentiating with respect to time obtains:

$$\dot{x} = V + R\omega \cos \omega t$$

$$\dot{y} = R\omega \sin \omega t$$

Now, let $z = R \sin \omega t$

Differentiating, $\dot{z} = R\omega \cos \omega t$

Then, $\dot{y} = \omega z$

and $\dot{z} = \omega R - u$, where $u = \omega y = \omega R - \dot{z}$

Initial conditions:

At $t = 0$, $x = 0$

$y = 0$

Through appropriate time and magnitude scaling after selecting maximum values for the variables, the scaled circuit may be drawn as shown in Figure 52. A value of $\beta = 400$ was used in the time scaling.

It then becomes a simple matter to change linear velocity or angular velocity of the cutter. If linear velocity is to be changed, the initial condition on amplifier number three must be changed. If cutter angular velocity is to be changed, three circuit changes must be made. The initial conditions on amplifier number eight must be changed along with the settings of the two potentiometers labeled $\omega 1$ and $\omega 2$.

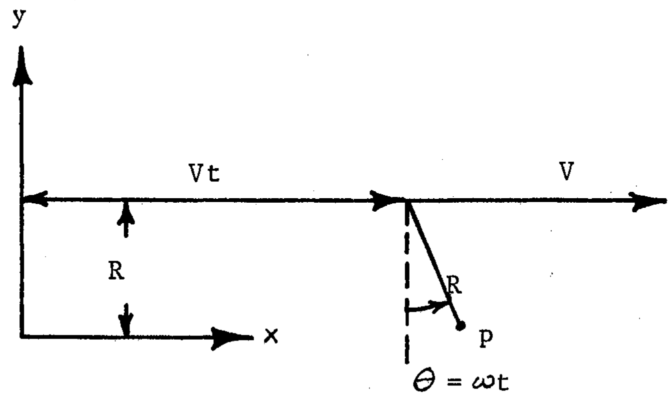

Figure 51. Definition of Coordinate System and Variables

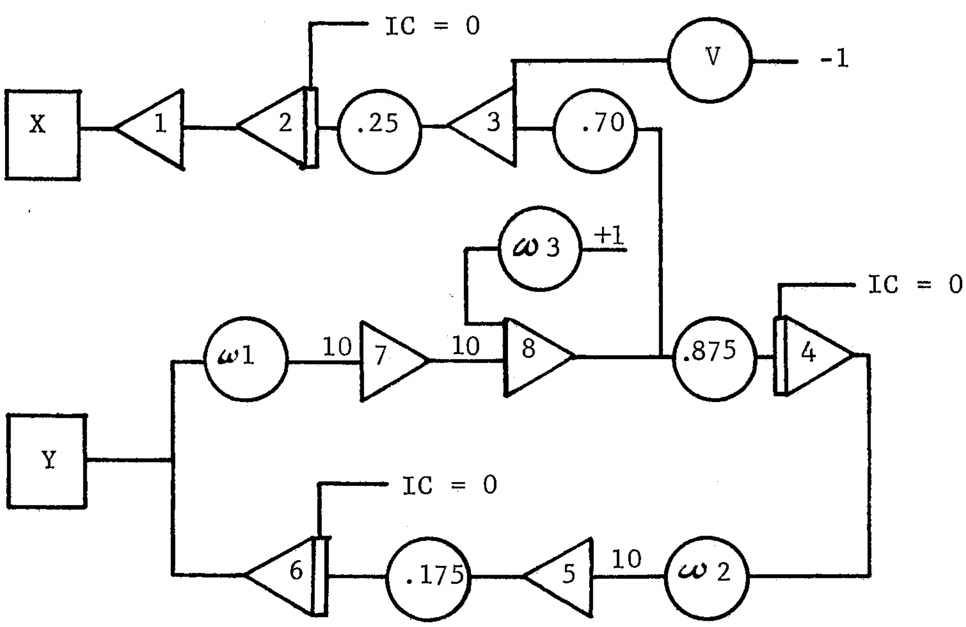

Figure 52. Scaled Circuit Diagram

The values for each of these pots for various combinations of rotor speed and ground speed are given in Tables IX and X.

TABLE IX

SETTINGS FOR POTS FOR DIFFERENT ROTARY SPEEDS

Pots	Rpm			
	3600	2800	2000	1200
ω1	0.270	0.209	0.149	0.090
ω2	0.108	0.0836	0.0596	0.0360
ω3	0.943	0.732	0.522	0.315

TABLE X

SETTINGS OF POT FOR DIFFERENT GROUND SPEEDS

Mph	14	10	7	4
Pot V	0.246	0.176	0.123	0.070

APPENDIX B

STALK COUNTS MADE IN GREEN WHEAT FOR THE COMPOUND HELICAL CUTTERBAR

3000 Rpm

Mph	Replication I Total Stalks	Replication I Uncut Stalks	Replication I Percent Uncut	Replication II Total Stalks	Replication II Uncut Stalks	Replication II Percent Uncut	Replication III Total Stalks	Replication III Uncut Stalks	Replication III Percent Uncut	Average Percent Uncut
8.8	87	19	21.8							
	78	25	32.0							
	92	13	14.1							22.8
	98	23	23.5							
7.0	94	19	20.2	71	17	23.9	104	14	13.5	
	82	9	11.0	84	12	14.3	78	9	11.5	
	111	6	5.4	89	18	20.2	77	8	10.4	13.6
	109	18	16.5	89	2	2.2	120	19	15.8	
	103	12	11.6							
6.0	138	19	13.8	75	14	5.3				
	65	8	12.3	116	13	11.2				
	68	3	4.4	62	3	4.8				11.7
	49	14	28.6	38	5	13.2				
5.3	79	0	0.0	73	14	19.2	103	14	13.6	
	91	3	3.3	71	7	9.8	65	18	27.7	
	101	3	3.0	120	12	10.0	62	9	14.5	12.0
	60	5	8.3	62	20	32.2	134	10	7.5	
	149	11	7.4							
4.2	156	11	7.0	93	20	21.5	49	3	6.1	
	95	14	14.7	86	13	15.1	74	9	12.2	
	154	30	19.5	150	21	14.0	87	2	2.3	8.0
	83	22	26.5	94	13	13.8	89	10	11.2	
	63	17	27.0							

3600 Rpm

Mph	Replication I			Replication II			Average Percent Uncut
	Total Stalks	Uncut Stalks	Percent Uncut	Total Stalks	Uncut Stalks	Percent Uncut	
8.8	101	10	9.9	128	7	5.5	
	115	10	8.7	126	9	7.1	8.2
	82	6	7.3	178	19	10.7	
7.0	107	0	0.0	97	9	9.3	
	96	5	5.2	70	13	18.6	14.2
	111	4	3.6	33	16	48.5	
5.3	105	7	4.7	67	13	19.4	
	129	14	10.8	85	13	15.3	14.5
	116	23	19.9	181	31	17.1	

APPENDIX C

STALK COUNTS MADE IN ALFALFA FOR THE COMPOUND HELICAL CUTTERBAR

3000 Rpm

Mph	Guard Spacing (inches)	Replication I Total Stalks	Replication I Uncut Stalks	Replication I Percent Uncut	Replication II Total Stalks	Replication II Uncut Stalks	Replication II Percent Uncut	Replication III Total Stalks	Replication III Uncut Stalks	Replication III Percent Uncut	Average Percent Uncut
4.2	2.5	57	11	19.3	57	14	24.6	76	11	14.5	30.3
		71	13	18.3	67	16	23.9	45	9	20.0	
		78	18	23.3	46	22	47.8	63	21	33.3	
		43	14	32.6	30	21	70.0	65	23	35.4	
	5	32	4	12.5	52	12	23.1	60	7	11.7	27.5
		33	6	18.2	47	16	34.0	51	9	17.6	
		44	9	20.5	55	9	16.4	53	16	30.2	
		58	14	24.1	36	15	41.7	31	14	45.2	
5.3	2.5	64	17	26.6	53	7	13.2	39	11	28.2	34.2
		51	10	19.6	53	12	22.6	59	34	57.6	
		59	25	42.4	36	8	22.2	40	10	25.0	
		24	14	58.3	56	22	39.3	63	35	55.6	
	5	49	11	22.4	44	9	20.4	56	12	21.4	32.0
		39	4	10.2	34	18	52.9	69	22	31.9	
		50	19	38.0	39	14	35.9	32	8	25.0	
		55	8	14.5	27	7	25.9	20	12	60.0	
6.0	2.5	42	9	21.4	49	18	36.7	53	22	41.5	40.5
		55	22	40.0	56	16	28.6	47	20	42.6	
		54	19	35.2	33	13	39.4	54	19	35.2	
		62	26	41.9	55	27	49.1	48	36	75.0	
	5	48	6	12.5	51	16	31.4	66	20	30.3	37.7
		44	11	25.0	31	17	51.6	54	24	44.4	
		43	10	23.2	37	11	29.7	55	27	49.1	
		42	13	31.0	33	9	27.3	33	21	63.6	

3000 Rpm (Continued)

Mph	Guard Spacing (inches)	Replication I Total Stalks	Replication I Uncut Stalks	Replication I Percent Uncut	Replication II Total Stalks	Replication II Uncut Stalks	Replication II Percent Uncut	Replication III Total Stalks	Replication III Uncut Stalks	Replication III Percent Uncut	Average Percent Uncut
7.0	2.5	56	5	8.9	45	12	26.7	54	22	40.7	
		43	13	30.2	49	14	28.6	50	17	34.0	29.4
		59	12	20.3	45	12	26.7	42	13	31.0	
		49	17	34.7	49	23	46.9	53	13	24.5	
	5	48	3	6.2	43	6	14.0	54	12	22.2	
		41	5	12.2	39	4	10.2	41	8	19.5	25.0
		36	7	19.4	46	9	19.6	46	17	37.0	
		48	9	18.8	49	17	34.7	33	11	33.3	
7.7	2.5	48	25	52.1	26	7	26.9	71	10	14.1	
		55	26	47.3	47	18	38.3	67	24	35.8	39.2
		66	25	33.3	48	20	41.7	50	16	32.0	
		51	25	49.0	40	18	45.0	47	26	55.3	
	5	53	29	54.7	36	4	11.1	44	7	15.9	
		50	27	54.0	29	11	37.9	50	16	32.0	37.6
		50	24	48.0	50	14	28.0	52	18	34.6	
		68	19	27.9	42	10	23.8	44	28	63.6	
8.8	2.5	50	8	16.0	46	12	26.1	67	16	23.9	
		63	15	23.8	58	7	12.1	46	23	50.0	32.2
		87	37	42.5	54	30	55.6	51	12	23.5	
		33	11	33.3	67	22	32.8	55	26	47.3	
	5	56	6	10.7	27	5	18.5	43	11	25.6	
		52	7	13.5	62	6	9.7	57	14	24.6	28.6
		81	20	24.7	52	14	26.9	77	34	44.2	
		79	18	22.8	59	15	25.4	59	32	54.2	

3600 Rpm

Mph	Guard Spacing (inches)	Replication I Total Stalks	Replication I Uncut Stalks	Replication I Percent Uncut	Replication II Total Stalks	Replication II Uncut Stalks	Replication II Percent Uncut	Replication III Total Stalks	Replication III Uncut Stalks	Replication III Percent Uncut	Average Percent Uncut
4.2	2.5	52	25	48.1	61	13	21.3	44	16	36.4	
		40	8	20.0	39	11	28.2	61	15	24.6	35.8
		41	12	29.3	66	47	71.2	28	8	28.6	
		36	12	33.3	59	21	35.6	36	19	52.8	
	5	54	17	31.5	58	9	15.5	41	12	29.3	
		42	5	11.9	55	7	12.7	55	8	14.5	30.3
		51	13	25.5	41	14	34.1	51	11	21.6	
		57	12	21.0	51	19	37.2	58	25	43.1	
5.3	2.5	53	26	49.0	53	20	37.7	68	16	23.5	
		56	12	21.4	55	19	34.5	54	15	27.8	37.9
		43	26	60.5	62	12	19.4	59	27	45.8	
		57	19	33.3	47	12	25.5	51	39	76.5	
	5	54	12	22.2	43	7	16.3	61	7	11.5	
		43	5	11.6	28	5	17.8	49	23	46.9	32.0
		54	14	25.9	61	11	18.0	39	14	35.9	
		39	7	17.9	66	27	40.9	57	28	49.1	
6.0	2.5	52	20	38.5	72	15	20.8	48	15	31.2	
		39	14	35.9	59	19	32.2	61	11	18.0	35.7
		45	13	28.9	59	21	35.6	48	16	33.3	
		36	20	55.6	33	16	48.5	44	22	50.0	
	5	35	5	14.3	43	4	9.3	47	10	21.3	
		34	15	44.1	52	8	15.4	32	9	28.1	32.2
		48	11	22.9	39	12	30.8	44	12	27.3	
		51	22	43.1	63	31	49.2	38	15	39.5	

3600 Rpm (Continued)

Mph	Guard Spacing (inches)	Replication I			Replication II			Replication III			Average Percent Uncut
		Total Stalks	Uncut Stalks	Percent Uncut	Total Stalks	Uncut Stalks	Percent Uncut	Total Stalks	Uncut Stalks	Percent Uncut	
7.0	2.5	55	29	52.7	55	16	29.1	60	17	28.3	
		71	12	16.9	41	10	24.4	51	12	23.5	30.6
		39	11	28.2	52	11	21.2	71	20	28.2	
		46	24	52.2	51	14	27.4	71	25	35.3	
	5	39	18	46.2	54	5	9.2	69	9	13.0	
		46	5	10.9	67	9	13.4	65	8	12.2	25.2
		47	11	23.4	45	11	24.4	53	10	18.9	
		48	10	20.8	32	9	28.1	70	12	17.1	
7.7	2.5	43	6	14.0	51	6	11.8	45	7	15.6	
		59	14	23.7	46	11	23.9	42	8	19.0	28.9
		52	12	23.1	39	7	17.9	51	20	39.2	
		53	21	39.6	67	41	61.2	33	19	57.6	
	5	47	2	4.2	53	4	7.5	54	9	16.7	
		42	3	7.1	36	5	13.9	46	7	15.2	26.5
		53	22	41.5	55	20	36.4	67	19	28.4	
		44	9	20.4	48	32	66.7	70	22	31.4	
8.8	2.5	49	2	4.1	47	16	34.0	57	8	14.0	
		23	6	26.1	56	7	12.5	40	15	37.5	33.6
		57	22	38.6	58	19	32.8	49	19	38.8	
		49	31	63.3	51	23	45.1	30	17	56.7	
	5	42	4	9.5	49	6	12.2	52	11	21.2	
		36	7	19.4	48	11	22.9	54	15	27.8	32.5
		49	30	61.2	37	4	10.8	35	13	37.1	
		61	50	82.0	63	22	34.9	42	16	38.1	

APPENDIX D

STALK COUNTS MADE IN ALFALFA FOR THE RECIPROCATING CUTTERBAR

Mph	Height of Measure (inches)	Replication I			Replication II			Replication III			Average Percent Uncut
		Total Stalks	Uncut Stalks	Percent Uncut	Total Stalks	Uncut Stalks	Percent Uncut	Total Stalks	Uncut Stalks	Percent Uncut	
4.2	4	47	0	0	55	1	1.8				
		60	1	1.7	63	3	4.8				
		54	4	7.4	60	3	5.0				9.7
		34	3	8.8	76	3	3.9				
		41	10	24.4							
		53	21	39.6							
	3	47	0	0	55	10	18.2				
		60	6	10.0	63	7	11.1				
		54	13	24.1	60	8	13.3				22.4
		34	13	38.2	76	9	11.8				
		41	18	43.9							
		53	28	52.8							
5.3	4	43	3	7.0	65	5	7.7				
		50	7	14.0	56	9	16.1				
		68	6	8.8	75	15	20.0				15.4
		57	8	14.0	43	8	18.6				
		53	9	17.0	39	8	20.5				
		70	18	25.7	57	9	15.8				
	3	43	7	16.3	65	9	13.8				
		50	9	18.0	56	19	33.9				
		68	10	14.7	75	30	40.0				28.6
		57	18	31.6	43	14	32.6				
		53	17	32.1	39	13	33.3				
		70	29	41.4	57	20	35.1				

Mph	Height of Measure (inches)	Replication I			Replication II			Replication III			Average Percent Uncut
		Total Stalks	Uncut Stalks	Percent Uncut	Total Stalks	Uncut Stalks	Percent Uncut	Total Stalks	Uncut Stalks	Percent Uncut	
6.0	4	69	3	4.3	38	2	5.3	63	3	4.8	
		64	1	1.6	38	5	13.2	33	0	0.0	
		53	1	1.9	63	3	4.8	78	10	12.8	8.8
		61	7	11.5	39	3	7.7	34	6	17.6	
		70	5	7.1	54	4	7.4	76	10	13.2	
		92	9	9.8	36	6	16.7	59	11	18.6	
	3	69	11	15.9	38	8	21.0	63	5	7.9	
		64	5	7.8	38	11	28.9	33	6	18.2	
		53	6	11.3	63	11	17.5	76	25	32.0	23.3
		61	19	31.1	39	15	38.5	34	16	47.0	
		70	11	15.7	54	10	18.5	76	19	25.0	
		92	21	22.8	36	8	22.2	59	22	37.3	
7.0	4	46	9	19.6	54	10	18.5				
		57	5	8.8	56	6	10.7				
		67	16	23.9	65	18	27.7				17.7
		44	9	20.4	70	14	20.0				
		61	13	21.3	37	3	8.1				
		55	9	16.4	48	8	16.7				
	3	46	17	37.0	54	15	27.8				
		57	8	14.0	56	9	16.1				
		67	18	26.9	65	20	30.8				27.8
		44	17	38.6	70	18	25.7				
		61	27	44.3	37	8	21.6				
		55	14	25.4	48	12	25.0				

Mph	Height of Measure (inches)	Replication I			Replication II			Replication III			Average Percent Uncut
		Total Stalks	Uncut Stalks	Percent Uncut	Total Stalks	Uncut Stalks	Percent Uncut	Total Stalks	Uncut Stalks	Percent Uncut	
8.8	4	39	12	30.8							
		64	22	34.4							
		48	20	41.7							44.4
		28	12	42.8							
		45	27	60.0							
		44	25	56.8							
	3	39	15	38.5							
		64	41	64.1							
		48	28	58.3							63.0
		28	23	82.1							
		45	30	66.7							
		44	30	68.2							

APPENDIX E

ANALYSIS OF VARIANCE TABLES

TABLE XI

ANALYSIS OF VARIANCE FOR THE COMPOUND HELICAL CUTTERBAR - BOTH GUARD SPACINGS

Source	DF	SS	MS	F	Observed Significance
ROTSPD	1	180.2	180.2	<1	
GRDSPD	5	2688.5	537.7	1.78	0.16
GRDSPD X ROTSPD	5	1924.6	384.9	1.27	0.32
Error "A"	24	7250.1	302.1		
GDSP	1	3400.5	3400.5	32.53	<0.001
GDSP X ROTSPD	1	74.4	74.4	<1	
GDSP X GRDSPD	5	302.3	60.4	<1	
GDSP X ROTSPD X GRDSPD	5	270.9	54.2	<1	
Error "B"	24	2508.7	104.5		
PLOT	3	14724.9	4908.3	24.92	<0.001
PLOT X ROTSPD	3	945.0	315.0	1.60	0.20
PLOT X GRDSPD	15	2778.0	185.2	<1	
PLOT X ROTSPD X GRDSPD	15	2416.7	161.1	<1	
Error "C"	72	14180.0	196.9		
PLOT X GDSP	3	386.5	128.8	1.44	0.24
PLOT X GDSP X ROTSPD	3	99.1	33.0	<1	
PLOT X GDSP X GNDSPD	15	1113.6	74.2	<1	
PLOT X GDSP X ROTSPD X GNDSPD	15	790.1	52.7	<1	
Error "D"	72	6419.6	89.2		
Total	287	62453.7			

TABLE XII

ANALYSIS OF VARIANCE FOR THE COMPOUND HELICAL CUTTERBAR - 5 INCH GUARD SPACING

Source	DF	SS	MS	F	Observed Significance
GRDSPD	5	2048.2	409.6	1.58	0.21
ROTSPD	1	243.1	243.1	<1	
GRDSPD X ROTSPD	5	1137.2	227.4	<1	
Error "A"	24	6224.1	259.3		
PLOT	3	6563.6	2187.9	15.79	<0.001
Linear Effect	1	6526.6	6526.6	47.12	<0.001
Quadratic Effect	1	34.8	34.8	<1	
Cubic Effect	1	2.2	2.2	<1	
PLOT X GRDSPD	15	1869.9	124.6	<1	
PLOT X ROTSPD	3	551.4	183.8	1.33	0.23
PLOT X GRDSPD X ROTSPD	15	1526.4	101.8	<1	
Error "B"	72	9973.3	138.5		
Total	143	30137.2			

TABLE XIII

ANALYSIS OF VARIANCE FOR THE RECIPROCATING CUTTERBAR

Source	DF	SS	MS	F	Observed Significance
GNDSPD	3	1055.0	351.7	3.94	0.12
Error "A"	4	357.3	89.3		
INCHES	1	3722.6	3722.6	120.71	<0.001
GNDSPD X INCHES	3	44.8	14.9	<1	
Error "B"	4	92.5	30.8		
PLOT	2	2712.6	1356.3	26.80	<0.001
PLOT X GNDSPD	6	3253.9	542.3	10.71	<0.001
PLOT X INCHES	2	91.7	45.8	<1	
PLOT X GNDSPD X INCHES	6	158.2	26.4	<1	
Error "C"	64	3239.2	50.6		
Total	95	14727.8			

TABLE XIV

ANALYSIS OF VARIANCE FOR THE RECIPROCATING
CUTTERBAR WITH PLOT 3 DELETED

Source	DF	SS	MS	F	Observed Significance
GNDSPD	3	1062.1	354.0	22.58	<0.001
Error "A"	4	62.7	15.7		
PLOT	1	151.4	151.4	8.55	0.009
PLOT X GNDSPD	3	68.1	22.7	1.28	0.32
Error "B"	20	353.9	17.7		
Total	31	1698.2			

VITA

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