AN INVESTIGATION OF THE MECHANICS OF SEVERING TREES WITH AUGER CUTTERS

By

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ABSTRACT

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The objective of this study was to analyze the mechanics of severing trees with auger type cutters, and to document the force and power requirements as functions of the major variables affecting the process. The focus of the study was on the cutter parameters, helix and rake angles; the machine variables, cutter rotational speed and feed speed; and the workpiece parameters, species of wood and the temperature of the wood being cut.

Cutter geometry was evaluated by the criteria of which combination of parameters produced the lowest value of maximum torque and simultaneously the lowest axial force. With this criteria and the added constraint of selecting a cutter geometry which is maintainable in practice, a cutter configuration with a 40 degree helix angle and 30 degree rake angle was judged to be an optimum compromise. Increasing values of helix angle up to 40 degrees reduce the forces acting on the cutter, but beyond this value the loadings increased. Increasing values of rake angle were beneficial to the performance of the cutter but considerations of the maintainability of the cutter preclude going above 30 degrees.

Investigations of the machine variables, cutter rotational speed and feed speed, showed that these two variables could be combined into a single parameter, feed rate, expressed as the feed per tooth, and the loading on the cutter related to this one parameter. Over the range of

feed rates studied, the main loadings analyzed on the cutter were found to be linearly related to the feed rate. The power requirement of the cutter was found to be dependent on both the cutter rotational speed and the feed speed, rather than only on the feed rate. It was found that at a constant feed speed, or rate at which the cutter is moving through the wood, the horsepower requirement decreased with a decrease in the cutter rotational speed.

The species of the wood being cut and the temperature of the wood were found to have significant effect on the force and power requirements of the cutting process. The forces on the cutter and the power requirements follow the differences in specific gravity and hence the differences in mechanical properties of the wood. Cutting frozen wood was found to increase the loadings on the cutter by 20 to 25 percent over those obtained with green wood.

The process of cutting wood with an auger cutter is a much more complex operation than had been previously analyzed. However, the results obtained by other investigators correlate with the results that were obtained here. A logical expansion of this work would be to extend the basic mathematical models of chip formation which have been developed for the basic cutting processes to the more complex case of the auger cutting process. A successful model of the mechanism of the auger cutting process based on the results obtained in this study would extend the usefulness of these results and increase the efficiency of applying the auger cutting concept to practical cutting situations.

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INTRODUCTION

Forestry in the United States is approaching a position which agriculture in this country has occupied for many years. The industry must increase the production of wood products to meet an ever increasing consumer demand while, simultaneously, it must compensate for the loss of timber producing land to other uses, e.g., urban development, highways, recreational facilities, etc. The demand for forest products has been projected to almost double by the year 2000, while the area of commercial timber land available for the production of forest products is projected to decrease by as much as 5 million acres per decade (23)*. At current levels of annual growth and utilization of available timber, the balance between supply and demand is projected to become critical in the near future, particularly for softwood sawtimber for use in lumber and plywood.

The greatest potential for increasing the wood supply lies in the development of new sources of fiber for the pulp and paper industry. The lumber and plywood industries will continue to require large diameter, high quality sawtimber for their products in the future, but the pulp and paper industry, whose traditional source of supply has been the wood chip, has the ability to utilize material produced from residue and other low valued sources of fiber. Approximately 40 percent of the

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* Number in parentheses refers to literature cited in the bibliography.

annual cut of timber goes into the production of pulp, including almost 20 percent of the annual cut of sawtimber. Therefore, if new sources of supply for the pulp industry can be developed, the drain of sawtimber for pulp can be reduced, and more high quality material will be available for higher valued products.

One of the promising approaches to increasing the supply of fiber for the pulp and paper industry is "short rotation intensive culture" (SRIC) forestry. Basically, the concept consists of establishing plantations of genetically superior trees on well prepared sites, fertilizing and cultivating to maximize early growth at much higher than normal yields per acre, and harvesting whenever the annual growth rate begins to fall off, usually before the trees are 15 years old. Several investigators in various parts of the country have been studying the potential of SRIC systems. Initial results have shown that yields can be as high as seven times that of conventional timber growing systems on a tons/acre/year basis (5, 17, 18, 19). In the North Central region, the growth potential of a populus hybrid (Populus 'Tristis #1) growing on a 4 by 4 foot spacing under intensively cultured conditions has been projected to be about six times that of a natural aspen stand in the same region (5). Some of the other tree species which are felt to be compatible with short rotation systems are cottonwood, sycamore, and red alder.

The potential of SRIC forests as a source of energy is also receiving attention (21). Because of rising fuel costs, depletion of fossil fuel reserves, increasing dependence on imported oil and environmental concerns over use of lower quality fossil fuels, the concept of a renewable source of clean fuel is very attractive. The technological requirements of intensively cultured systems for site preparation, planting, tending, harvesting and processing equipment are not drastically changed by whether the end product is used for pulping or fuel. Thus the development of equipment for intensive culture systems will advance the potential of both fiber and fuel production utilizing silvicultural systems based on intensive management concepts.

Once greenhouse tests and smallplot trials have established the physiological requirements for maximizing the fiber yield from SRIC plantations, the technology must be developed to apply these practices on a commercial basis. Early estimates indicate that a minimum of 8,000 acres of SRIC plantations will be required to economically supply raw material for pulping (4). Early estimates of acreages required for fuel production are in the hundreds of square miles. Considering the investment required to establish a fiber growing system of this magnitude, and the radical changes from a conventional fiber growing system, all aspects of SRIC forestry will have to be thoroughly developed before a company will consider switching its production of raw material to such a system.

The harvesting of the wood fiber grown in SRIC plantations is one aspect of the total system that has to date received little extensive investigation. One advantage of these systems that most investigators stress is that a completely mechanized harvesting operation would reduce labor costs and be more conducive to a year round operation, but the actual implementation of the harvesting has not been extensively studied. The use of standard agricultural silage choppers to harvest short rotation fiber has been evaluated in one instance, but only on very small material (one year old sycamore sprouts less than 1-inch in diameter)

(10). Before short rotation fiber growing systems can be commercially put to use, the harvesting technology will have to be developed to the stage that an economically feasible system will be available that can handle the required acreages.

In addition to the potential of intensively cultured fiber, the use of previously non-commercial tree and brush species have been proposed as a future source of fiber for pulping (9, 25). The development of harvesting systems for intensively cultured fiber would also open the door to the use of so-called "puckerbrush" since the material is quite similar to short rotation trees, and the harvesting requirements of both would be similar.

Two differences that exist between short rotation trees and conventional timber that will have significant bearing on the final design of a harvesting system are the size of the trees at harvest and the spacing between the trees. In the field trials of short rotation systems thus far conducted, the trees at harvest have been less than 5 inches in diameter, and the spacings have varied from 6 feet by 5 feet to as little as 9 inches by 9 inches. Both from the technical and economic points of view, these factors will have a significant bearing on the final design of a harvesting system.

Whole-tree chipping is the most likely system to be used for harvesting short rotation intensively cultured plantations (2). It is a highly mechanized system capable of producing large quantities of wood per-man-day. Besides its advantage of high productivity and reduced labor requirements, the yield per acre of usable wood is greatly increased due to the additional amounts of fiber recovered from the tops, limbs, and the other residue materials normally left in the field following a conventional harvesting operation. Additionally, the site is left in a cleaner condition which is esthetically more acceptable, and subsequent silvicultural operations are facilitated by the lack of debris on the site.

The basic whole-tree chipping system consists of feller-bunchers which sever the trees and accumulate them into bunches for subsequent forwarding to the chipper site, grapple skidders to move the bunches from the forest to the chipper, portable chippers which operate at a woods landing to reduce the whole trees to chips, and chip vans which transport the chips to the mill.

The felling-bunching phase of the harvesting operation is the area where the current technology is the most deficient with respect to harvesting small trees. Current skidding and chipping equipment is basically designed as a multiple-tree operation, so the redesign of current equipment should be merely an adjustment of the current technology to the changed design parameters that the small trees of a SRIC plantation would present. However, the basic design of current feller-bunchers is based on handling one tree at a time. Considering the large trees in conventional forest stands, this approach is reasonable, but for stands of small trees, this assumption effectively puts an upper limit on the potential productivity of the equipment (11).

To achieve a breakthrough in the productivity of felling-bunching, the concept of continuous operation, as opposed to single tree operation, will have to be developed. The concept of continuous felling and bunching can be defined as severing and accumulating the trees in a swath of timberstand on a nonstop basis. Development of this concept will require the methods and machinery by which trees at random locations within the swath and the severed trees can be accumulated into bunches and dropped on the ground for subsequent skidding. To achieve high productivity in stands of small trees, the operation must be continuous in that the machine will not stop to sever and process each tree as it occurs in the swath.

The primary problem involved in developing a continuous feller-buncher, or swath cutter, will be the severing action of the felling device. All existing fellers are designed to handle one tree at a time, alignment between each tree and the machine is critical, and the machine must stop to process each tree. If a means of severing the trees continuously within the cutting swath of the machine can be devised, then the problem is reduced to accumulating the trees into a bunch and dropping them off for subsequent skidding.

There are three primary means by which existing mechanical fellers sever the tree in the felling operation. The most common of these is the mechanical shear. The shear has been developed to the point where it is a highly productive and dependable means of felling timber. The shear's main advantage over other mechanized severing methods is that it is relatively insensitive to dulling. Its main disadvantage is the large force required to drive the blade through larger trees and the stability of the blade itself under these high forces. The shear also has a tendency to split the butt end of the severed log, thus reducing its applicability to felling sawtimber trees. For purposes of a continuous cutter, the shear's main disadvantage is that it requires direct alignment with the individual tree to be severed so that the stem falls between the anvil and the blade.

The second means of severing commonly employed by mechanical fellers is the saw. The manually operated chain saw is the most common application of saws for severing trees, but a few applications have used a saw mounted on a mechanical feller. The main reason for using saws on fellers is to reduce the butt damage that occurs in sawlogs when felling with a shear. The elimination of the butt damage and the ability to handle larger diameter trees are the main advantages of saws; the main disadvantages are that saws are a more mechanically complex system and are highly sensitive to dulling. For a continuous feller, saws would be a possibility for random selection of the trees. However, the sensitivity to dulling and the expense involved in maintaining the system would be major deterrents.

A third severing means employed by some mechanical fellers is the auger cutter. As applied in tree fellers, the auger cutter looks like an elongated milling cutter with either a straight or helical flute configuration. Reduction of butt split was again the motivation for the development of this concept. As opposed to the saw, auger cutters have a simpler mechanical configuration, and the cutter is a heavier unit than the individual tooth saw; thus dulling is a lesser problem than with saws.

The relative advantages and disadvantages of shears, saws and auger cutters are illustrated in Table 1. Based on these comparisons, and not trying to speculate on what new technologies may be developed in the future, the auger cutter concept appears to have the most promise for the development of a continuous feller.

In addition to their potential for a continuous feller-buncher, auger cutters are also the most promising device available for

Table 1. Suitability of severing devices for continuous feller-bunchers.

Type of cutter	Multiple stem cutting	Sensitivity to dulling	Ease of sharpening	Replacement cost	Tree size limitation	Butt damage
Shears	3	1	1	1	3	3
Saws	1	3	3	3	1	1
Auger cutters	1	2	1	2	1	1

1 - Most suitable

2 -

3 - Least suitable

mechanizing the felling of sawtimber trees. Auger cutters eliminate the butt log damage that occurs when using shears, and they are not as limited by tree size as are the shears.

The use of auger cutters for tree fellers is a relatively new concept, and the development of the current machine utilizing this concept has been done on a trial and error basis without sound documentation of the basic design parameters. Before this concept can be used as the basis of the development of a continuous felling device, the technology of auger cutting needs to be expanded. Cutter geometry, force and power requirements, operational characteristics, material and fabrication constraints have to be investigated to establish the parameters on which to base an efficient design.

The objectives of this study were to investigate the mechanics of severing trees with auger cutters and to quantify the basic design parameters needed to efficiently design a continuous felling device utilizing this concept.

EXPERIMENTAL PROCEDURE

Experimental Design

An experimental investigation of auger cutters was conducted to quantify the effects of cutter geometry, workpiece properties and cutting conditions on the forces resulting on the cutter and the power requirements. As previously stated, the auger cutter, as applied to tree fellers, looks like an elongated milling cutter with either a straight or helical flute configuration (Figure 1). The most significant cutter parameters which affect the resultant forces and power requirements of the cutter are the cutter diameter, cutter length, number of flutes, rake angle and helix angle (1). For the main experiment, rake angle and helix angle were studied. Two flutes were used on the experimental cutters to eliminate the confusing effect of having more than one edge cutting simultaneously. A cutter diameter of 2½ inches was used in all tests to minimize the expense of purchasing the experimental units.

Besides the rake and helix angles of the cutter, the variables expected to have the most effect on the results are the feed rate, most conveniently expressed as the feed per tooth, which is a function of the workpiece feed speed, and the cutter rotational speed, species of wood being cut and the temperature of the wood. For the main experiment, a series of 12 cutters constructed with combinations of 3 rake angles and 4 helix angles were evaluated along with 9 feed rates comprised of

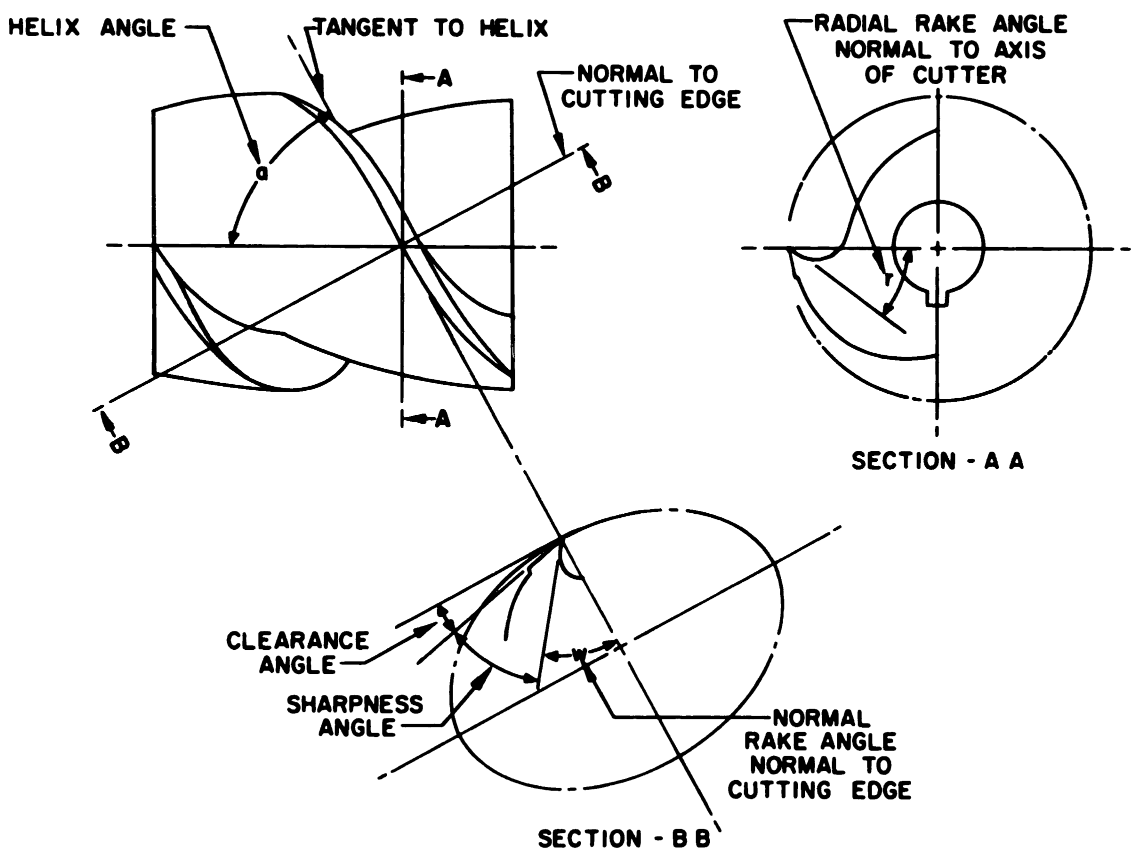


Figure 1 Geometry of auger cutter.

combinations of 3 feed speeds and 3 cutter rotational speeds, on green and frozen samples of 3 timber species--sugar maple, a high density hardwood; quaking aspen, a low density hardwood; and red pine, a softwood. A standard sample width of 2 inches was used in the tests to stay within the power capabilities of the test equipment.

Because of the anisotropic nature of wood, the orientation of the cutter to the wood during the cutting process must be controlled to avoid confounding the results with the variations in mechanical properties (6). For this experiment, the feed direction of the cutter was taken to be perpendicular to the grain direction of the wood. This is the orientation that a cutter would take if it were being used to fell a standing tree. Significant differences in mechanical properties are also observed between the spring and summerwood portions of the wood structure (24). To minimize the effect of these differences, all the 2-inch by 4-inch samples cut from the sample logs were oriented so that the 4-inch dimension of the sample 2 x 4 was orientated perpendicular to a diameter of the original log (Figure 2). In this way a sample was obtained where the measurements could be made while the cutter was operating perpendicularly to a radius of the original log, thus balancing the effect of the differences between the spring and summerwood portions of the wood.

For each species, the tests were run as a factorial experiment in a randomized block design. Rake angle, helix angle and feed rate were evaluated in a randomized factorial experiment with 3 replications per cell with the frozen and green wood comprising the blocks. Using this design, analysis of variance techniques were used to evaluate the effect of the rake and helix angles, feed rate, temperature and interaction

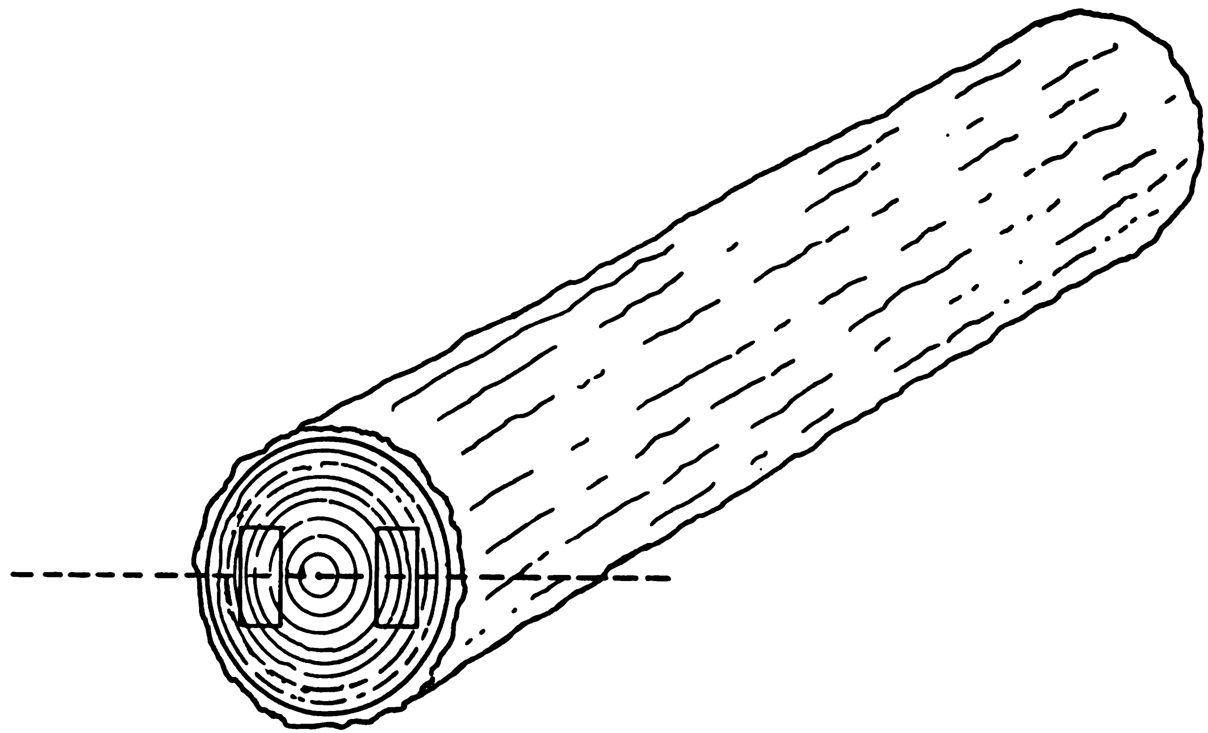


Figure 2 Orientation of sample material in original log.

between the variables. Regression analysis was then used to relate the results to the cutter parameters and feed conditions and determine optimum values of these variables.

The test runs made can be summarized as follows:

Rake angle	3
Helix angle	x 4
Feed rate	x 9
Replications	x 3
	324
Temperature	x 2
	648
Species	x 3
Total	1944

Cutters

The nomenclature of an auger cutter is shown in Figure 1. The cutter parameters which can be expected to affect the resultant forces on the cutter and the power requirements are the cutter diameters, number of flutes, rake angle and helix angle. Because of the significant expense involved in procuring experimental cutters, it was decided to hold the cutter diameter and number of flutes constant, and to investigate rake angle and helix angle in detail, as the available literature indicated rake and helix angles as being the most significant of the parameters (1).

For the experimental cutters, a nominal diameter of 2½ inches and a two flute configuration were chosen. A nominal clearance angle of 10 degrees was specified. By contract with an independent machine shop which specializes in fabricating such devices, 12 experimental cutters were acquired (Figure 3). These 12 units varied in rake angle (15, 30 and 45 degrees) and helix angle (0, 20, 40 and 60 degrees) so that each combination of rake and helix angle were represented as follows:

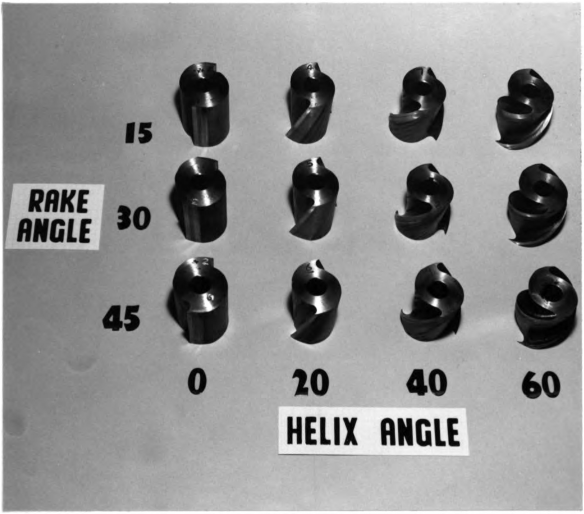


Figure 3 Experimental auger cutters.

Cutter number	Normal rake angle (degrees)	Helix angle (degrees)
1	15	0
2	30	0
3	45	0
4	15	20
5	30	20
6	45	20
7	15	40
8	30	40
9	45	40
10	15	60
11	30	60
12	45	60

The cutters were fabricated from a medium carbon alloy steel and induction hardened to maintain a ductile core while bringing the tooth area to a hardness of 58-60 Rockwell C.

Subsequent to receiving the experimental cutters, measurements were made to document the actual geometry of each unit. A Stocker and Yale Inc. Model 11MB tool analyzer was used to measure helix angle, radial rake and clearance angle on each flute from each end, and diameter on each cutter. A plaster mold of each cutter flute was also made which could be sawed in half so that the radial rake and clearance angles for each flute could be measured with the tool analyzer at the center of each flute.

Normal rake angle is related to radial rake angle by the following expression (1):

$$\tan w = \tan r \cos a$$

where,

w = normal rake angle

r = radial rake angle

a = helix angle.

This expression was used to relate the measured values of radial rake angle to the corresponding value of the normal rake angle. Table 2 lists the specified and measured parameters for each of the 12 cutters. As can be seen from Table 2, some errors were apparent in the manufacture of the experimental cutters. Discrepancies of up to 4^{o} in the helix angle and up to 7^{o} in the normal rake angle were found. In the discussions which follow, the nominal values of the helix and normal rake angle will be used, but the results must be tempered with the knowledge of the discrepancies that were found. Errors in the clearance angle are also apparent, but the errors are generally on the high side, and it is not felt that they will have a significant effect on the results.

The sharpness of the cutter is a significant parameter in determining the forces and power requirements of the cutting process. For this study, the cutters were resharpened using standard machine shop practice after each 27 test runs, which was the number of tests conducted with each cutter on each species within each replication. The objective was to maintain a "work sharp" edge throughout the test program, meaning that the cutters were not allowed to dull excessively but were not kept in a freshly sharpened condition either.

Sample Material

Three tree species were selected for use as sample material--sugar maple (Acer saccharum), a high density hardwood; bigtooth aspen (Populus grandidentata), a low density hardwood; and red pine (Pinus resinosa), a softwood. Besides providing a range of wood densities, these three species are commercially important as sawtimber and as such, are species on which the auger cutter may be used.

Table 2. Specified and measured parameters for the twelve experimental auger cutters.

Cutter no.	Specified Normal rake angle	Specified Helix angle	Specified Clearance angle	Nominal Sharpness angle	Measured radial rake angle
1	15	0	10	65	14
2	30	0	10	50	34
3	45	0	10	35	38
4	15	20	10	65	16
5	30	20	10	50	33
6	45	20	10	35	48
7	15	40	10	65	22
8	30	40	10	50	44
9	45	40	10	35	56
10	15	60	10	65	27
11	30	60	10	50	46
12	45	60	10	35	64

All angles given in degrees

Table 2. (Con't.)

Cutter no.	Calculated normal rake angle	Deviation of normal rake angle	Measured helix angle	Deviation of helix angle	Measured clearance angle	Deviation of clearance angle
1	14	1	0	0	13	3
2	34	4	0	0	13	3
3	38	7	0	0	13	3
4	15	0	18	2	15	5
5	32	2	16	4	13	3
6	46	1	19	1	14	4
7	18	3	37	3	9	1
8	36	6	40	0	11	1
9	49	4	39	1	14	4
10	16	1	56	4	8	2
11	28	2	59	1	8	2
12	47	2	58	2	11	1

All angles given in degrees

Sample trees were obtained from several locations within Baraga County, Michigan, where access to forests owned by the Ford Forestry Center, of Michigan Technological University, and the Baraga State Forest, Michigan Department of Natural Resources, was obtained. A total of 26 trees were cut to obtain the required number of samples for the green material and 20 trees for the samples run as frozen wood. The green samples were cut during the period August 7-10, 1978, and the frozen material was cut during the period November 7-9, 1978. The material cut for the frozen tests was not yet naturally frozen at this point in time, but the trees were well into their dormant period, and it wasn't felt that cutting then and artificially freezing the sample blocks at a later point would affect the test results. Enough trees of each species were cut to supply 20 suitable logs for both the green and frozen samples. Each tree cut was measured to obtain d.b.h. (diameter at breast height) and total height and was marked with a north line to indicate the original orientation of the tree.

After felling, each tree was bucked into as many 8-foot lengths as were available. Each 8-foot log was measured for diameter at each end and total length. Each bolt was given an identifying number so that every eventual sample could be traced back to its original tree. Discs were cut at 8-foot intervals from each tree, and these discs were taken back to the lab for determination of tree age, specific gravity, green density and moisture content. For these properties, the bark was excluded and only the wood considered. The procedures contained in TAPPI Standard T 18 m-53 were followed in making these determinations (22). Tables 3 through 8 summarize the basic tree properties and the samples that were obtained from each tree.

The material properties expected to have the most effect on the cutting operation are the specific gravity and moisture content (24). Specific gravity in wood directly affects the strength properties and thus, the forces and power requirements found in the wood cutting process. Tables 3 through 8 show that the specific gravity values of the sample trees chosen for aspen and red pine fell quite close together. This leads to the expectation that the force and power requirements found for these two species will be quite similar. This expectation is borne out in the discussions which follow. Moisture content can have a very significant effect on forces and power requirements in wood cutting operations (24). In this work, the moisture content was maintained at green conditions so its effect over a range of values was not documented.

The logs were transported to a commercial sawmill to be converted into suitable 2 x 4's from which samples could be cut. Two 2 x 4's were cut from each log according to the specification discussed earlier. These 2 x 4's were then taken to the laboratory and stored in a controlled humidity room to maintain the original moisture conditions. After cutting the 6-inch test samples from the 2 x 4's, the samples were bagged in plastic and stored under controlled conditions until the tests were run. The samples run at green conditions were stored at 40° F., while the frozen material was kept at 30° F. A total of 1,359 samples were prepared from the green material and 1,284 samples from the frozen material from which the 972 samples used in each series of tests were selected randomly.

Table 3. Summary of aspen trees cut for green samples

Tree number	d.b.h. (inches)	Number of bolts	Age (yrs.)	Specific gravity	Green Density (Lb/Ft^3)	Moisture content	Number of samples	Samples used for tests
3-1	11.7	3	68	.410	43.7	41.2	71	47
3-2	11.0	3	71	.410	42.8	40.2	74	56
3-3	11.0	3	76	.410	42.0	39.1	74	45
3-4	12.5	3	73	.423	44.6	40.8	79	53
3-5	11.4	3	69	.424	44.0	39.9	71	48
3-6	10.7	3	70	.419	42.4	38.4	79	53
3-8	10.1	2	72	.410	45.1	43.2	41	22
Ave.	11.2		71	.415	43.5	40.4		
Total		20					489	324

Table 4. Summary of sugar maple trees cut for green samples

Tree number	d.b.h. (inches)	Number of bolts	Age (yrs.)	Specific gravity	Green Density (Lb/Ft^3)	Moisture content	Number of samples	Samples used for tests
2-1	11.1	2	80	.594	54.8	32.3	43	34
2-2	11.5	2	86	.581	55.5	34.6	44	36
2-3	11.6	2	82	.670	60.1	30.4	45	37
2-4	12.2	2	79	.622	56.1	30.9	48	34
2-5	12.5	2	76	.613	56.2	31.9	38	31
2-6	10.2	1	57	.605	55.0	31.3	24	17
2-7	11.0	1	75	.607	55.0	31.1	20	17
2-8	11.6	2	77	.592	52.5	29.6	51	37
2-9	11.8	1	68	.653	60.2	32.2	15	9
2-10	10.9	1	66	.600	57.7	35.1	19	16
2-11	13.1	1	78	.643	59.4	32.5	26	19
2-12	11.8	1	55	.590	56.6	34.9	25	21
2-14	12.2	1	63	.604	55.2	31.8	24	16
Ave.	11.6		72	.613	56.5	32.2		
Total		20					422	324

Table 5. Summary of red pine trees cut for green samples

Tree number	d.b.h. (inches)	Number of bolts	Age (yrs.)	Specific gravity	Green density (Lb/Ft^3)	Moisture content	Number of samples	Samples used for tests
4-1	12.2	4	75	.416	54.9	52.7	90	66
4-2	12.2	4	76	.449	59.1	52.6	88	61
4-3	12.0	4	75	.399	51.3	51.2	89	67
4-4	11.6	4	79	.396	53.9	54.1	86	62
4-5	12.5	4	76	.394	52.0	52.6	95	68
Ave.	12.1		76	.411	54.2	52.6		
Total		20					448	324

Table 6. Summary of aspen trees cut for frozen samples

Tree number	d.b.h. (inches)	Number of bolts	Age (yrs.)	Specific gravity	Green Density (Lb/Ft^3)	Moisture content	Number of samples	Samples used for tests
6-1	12.2	3	74	.392	46.5	47.5	79	49
6-2	11.7	3	70	.396	45.8	45.9	75	43
6-3	11.3	3	71	.393	44.0	44.1	83	56
6-4	11.8	3	69	.394	44.7	43.7	67	40
6-5	11.6	3	72	.386	45.1	46.6	81	57
6-6	11.5	3	73	.344	41.3	48.0	72	45
6-7	10.2	2	63	.363	41.5	45.3	48	34
Ave.	11.5		70	.381	44.1	45.9		
Total		20					505	324

Table 7. Summary of sugar maple trees cut for frozen samples

Tree number	d.b.h. (inches)	Number of bolts	Age (yrs.)	Specific gravity	Green density (Lb/Ft^3)	Moisture content	Number of samples	Samples used for tests
5-1	12.9	2	61	.612	59.6	36.0	45	37
5-2	10.1	1	63	.642	61.5	34.9	17	15
5-3	10.3	2	51	.597	59.6	37.5	45	33
5-4	11.7	3	61	.599	59.3	36.9	59	49
5-5	11.6	3	58	.599	60.0	37.6	62	47
5-6	12.9	3	55	.589	58.8	37.6	66	50
5-7	10.8	2	61	.604	59.4	36.5	40	34
5-8	12.3	4	59	.611	60.0	36.4	73	59
Ave.	11.6		59	.607	59.8	36.7		
Total		20					407	324

Table 8. Summary of red pine trees cut for frozen samples

Test number	d.b.h. (inches)	Number of bolts	Age (yrs.)	Specific gravity	Green density (Lb/Ft^3)	Moisture content	Number of samples	Samples used for tests
7-1	10.4	4	72	.408	55.3	54.0	86	68
7-2	10.5	4	74	.410	53.7	52.3	71	63
7-3	12.3	4	79	.384	51.3	53.2	75	69
7-4	12.0	4	74	.426	56.6	53.1	72	64
7-5	10.3	4	71	.423	56.4	53.2	68	60
Ave.	11.1		74	.410	54.7	53.2		
Total		20					372	324

Test Equipment

A Brown and Sharp No. 2 plain milling machine was acquired for use as a test device. An arbor was fabricated which would hold the cutters on the spindle plus would provide a suitable section for a strain gage bridge to monitor the torque being exerted on the cutter (Figure 4). The milling machine has a selection of 18 possible spindle speeds covering a range of 40 to 1530 rpm and 18 possible table feed speeds over a range of ½ to 20¼ inches per minute. Of the possible combinations, 3 spindle rpm's of 520, 980, and 1530 were selected to use in the test program along with 3 table speeds of 6-3/4, 13, and 20¼ inches per minute. A factorial combination of these spindle and table speeds provide the 9 feed rates used in the test program. Each of the speed settings was calibrated and the actual cutter feed rate calculated using the relationship.

$$F = \frac{V}{2n}$$

where,

F = cutter feed rate in inches/tooth

V = table speed in inches/minute

n = spindle speed in rpm.

Table 9 shows the nominal and measured speeds for the table and spindle settings and the calculated feed rate for each of the combinations.

A special fixture was fabricated to secure the sample blocks. The fixture was mounted on top of a 3 dimensional load measuring platform which was secured to the table of the mill. The three-component measuring platform used was a Kristal Model 9257 A piezoelectric transducer built for the measurement of forces in three orthogonal directions

Figure 4 Arbor for mounting experimental auger cutters with strain gage torque transducer.

Table 9. Machine settings for test conditions.

Nominal spindle rpm	Measured spindle rpm	Nominal table speed in/min	Measured table speed in/min	Cutter feed rate in/tooth x 10^{-4}
520	535	6-3/4	7.03	66
		13	13.43	130
		20-1/4	20.93	200
980	1006	6-3/4	7.03	35
		13	13.43	67
		20-1/4	20.93	100
1530	1567	6-3/4	7.03	22
		13	13.43	43
		20-1/4	20.93	67

(Figure 5) (8). For each of the three force components a proportional charge is set up in the measuring platform. These charges are fed into charge amplifiers where they are converted into proportional voltages which can be displaced or recorded as required. The particular unit used in this study has a unique feature which makes it particularly useful. Due to the construction of the unit, the point of application of the forces to be measured can be anywhere in the space above the surface of the platform without affecting the measurement. This was of importance because the cutting action of the auger cutter changes location as the cutting edge rotates through its cycle. Thus, the self compensating feature of the device automatically adjusts for the changes in the point of application of the forces.

The measurement of torque on the arbor was accomplished using a 4-arm strain gage bridge arranged to measure torque (Figure 6) (3). Three hundred fifty ohm gages were used to increase sensitivity. The signal from the strain gage bridge was amplified using a CEC model 1-161 amplifier and fed into a CEC model 5-124A recording oscillograph. Figure 7 illustrates the complete test setup and the associated instrumentation. Both the torque transducer and the three-component force measurement platform were calibrated using dead weights before the test program was conducted.

Due to the rotary cutting action of the auger cutter, each 180 degree rotation of each cutting edge will experience a change in cutting condition from cutting against the grain to cutting with the grain to cutting against the grain. This change in cutting conditions has a significant effect on the resultant forces. A cutter position indicator was incorporated into the test setup to monitor the angular displacement

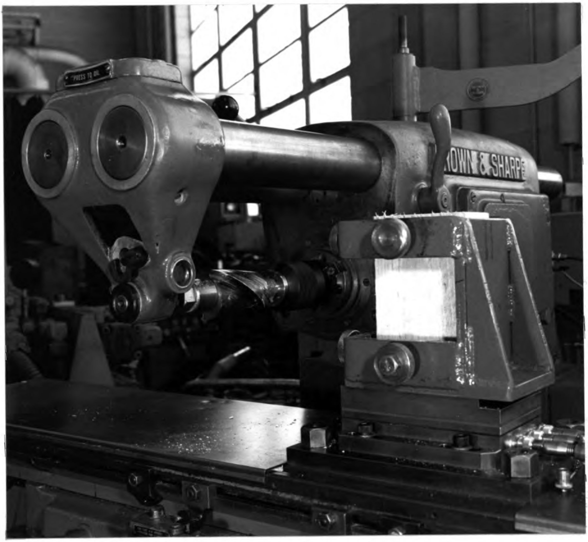


Figure 5 Three component force transducer and fixture for securing sample blocks.

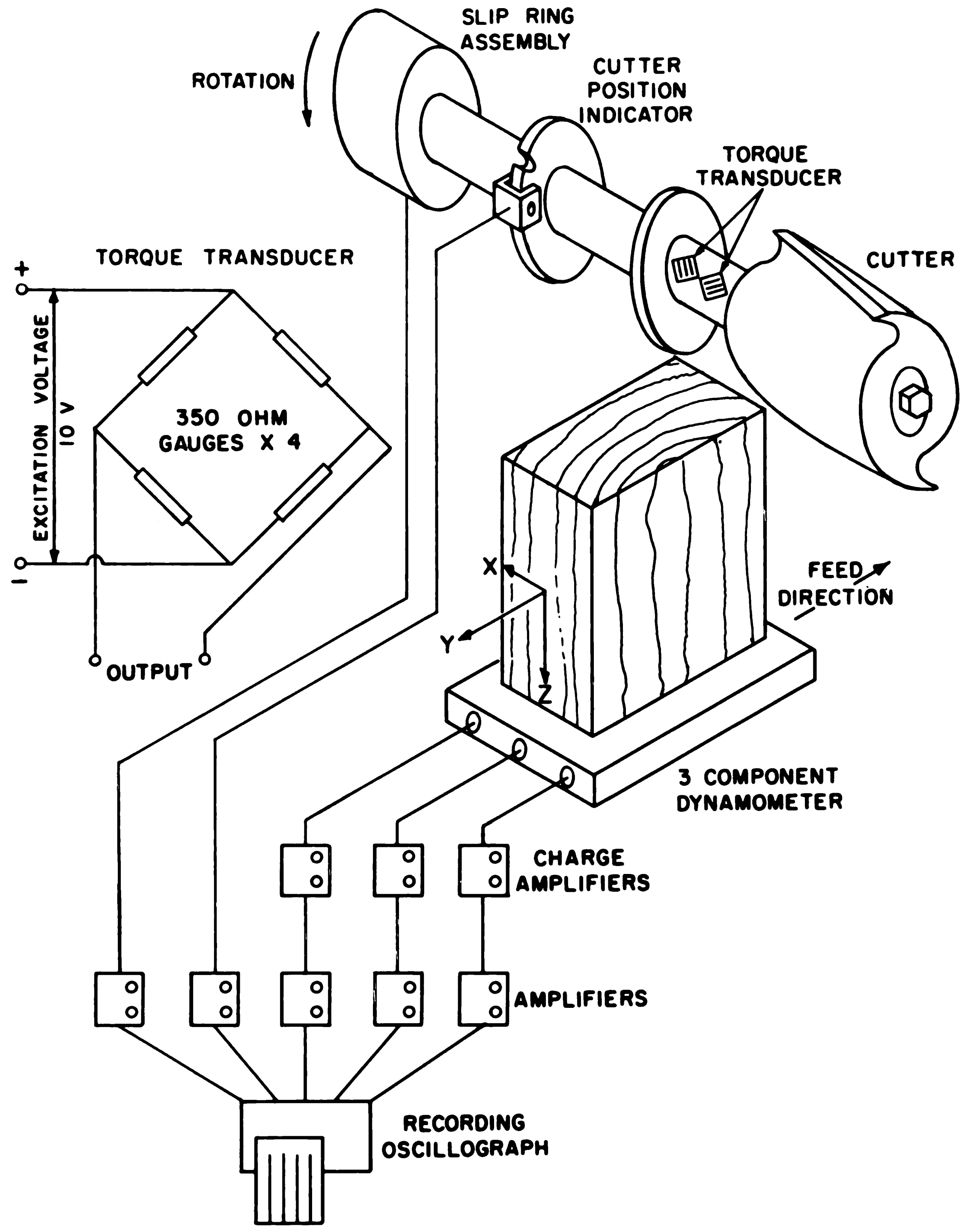


Figure 6 Schematic of instrumentation system.

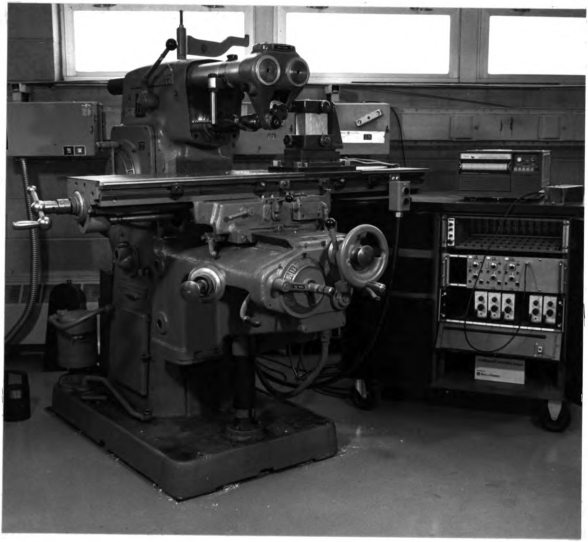


Figure 7 Equipment set up and instrumentation system for experimental studies.

of the cutting edge and provide a means of relating the results to the cutting condition being experienced at any given time (Figure 8). Continuous recordings of all variables were thus made with the ability to locate the angular position of the cutter at any given time.

Data Analysis

For each test run, the forces on the workpiece and the torque on the arbor holding the cutter were recorded at the point on the sample where the cutter was just reaching the imaginary radius of the original log (Figure 9). This was done to maintain a constant orientation between the cutter and the principal directions of the samples for all tests conducted. For analysis of the data, one revolution of the cutter was picked from the strip chart recordings where the loading had reached a steady condition. Selection of one cycle was done by picking two successive marks put on the recording by the cutter position indicator (Figure 10).

From the cycle thus selected for each test run, the maximum and minimum value of each force and the torque were picked off the recording. After converting to pounds or inch-pounds, the results were divided by the sample width to put the results on a per inch of cut basis. This was done to permit easy extrapolation to other widths of cut. The actual rotational speed of the cutter was also calculated from the length of the cycle on the recording and the paper speed of the recorder. The calculated rpm of the cutter was used with the measured torque to calculate the horsepower requirement of the cutting.

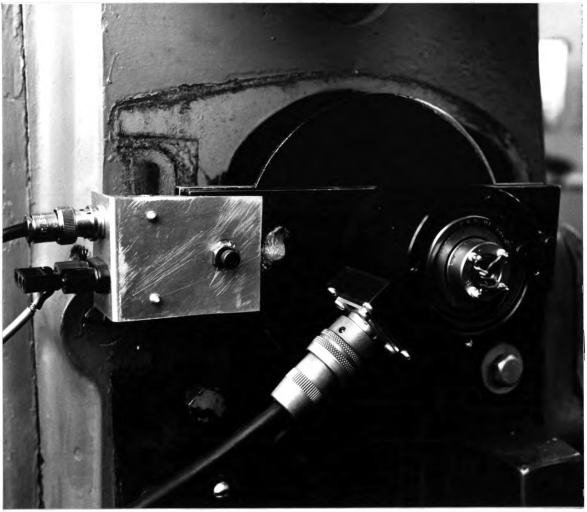


Figure 8 Cutter position indicator.

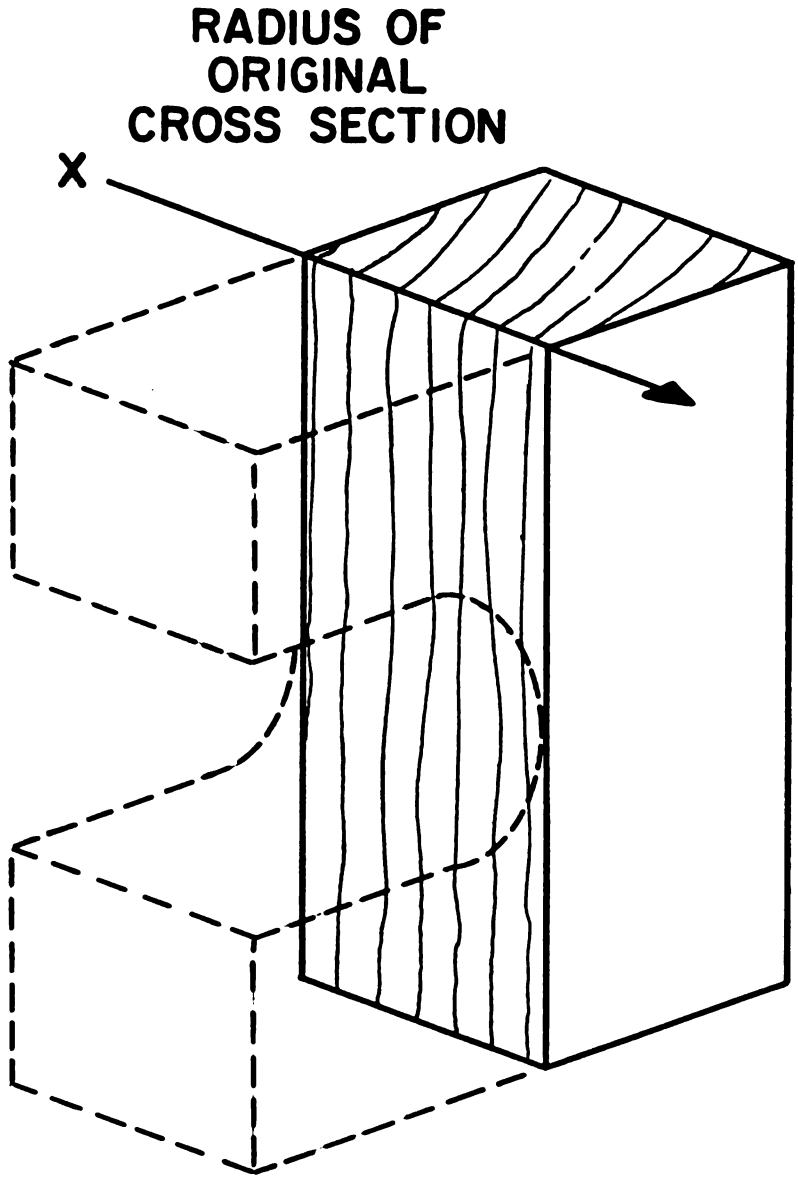


Figure 9 Location on sample blocks for recording of test data.

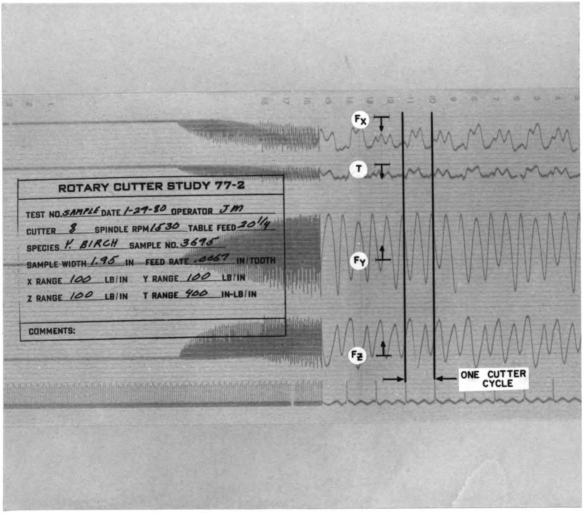


Figure 10 Example of oscillograph output recording forces and torque on cutter.

EXPERIMENTAL RESULTS

Cutter Geometry

An evaluation of an operation as complex as the auger cutting process, with its several independent variables and numerous possible output variables, initially requires a selection of the criteria by which its performance will be judged. This work will consider the maximum recorded torque and the maximum recorded axial force as being the variables upon which selection of the optimum values of cutter geometry will be based. The maximum torque is included because it is directly related to the horsepower requirement of the cutting operation, and it is dependent on both the Y and Z forces as measured in the experiment. The Y and Z forces are both cyclical in nature, and when measured in the Y and Z directions as done here, would have to be resolved into a radial and tangential component to be of significant value to an evaluation of cutter parameters. The torque, as measured, is related to the tangential component of the resultant force by the cutter diameter, and thus besides relating the power requirement of the cutting, partially relates the force loading on the cutter. The axial force is significant from the aspect of the design of a subsequent cutting device using this concept. Particularly when considering thrust loads on bearing supports and structural requirements of the supporting frame, the axial force would be significant in the design calculations.

The use of the maximum recorded torque and axial force implies that the criteria for an optimum cutter would be the combination of rake and helix angle that simultaneously produces the lowest value of torque and axial force. However, it soon becomes obvious that a compromise will be required as the geometry that will produce the lowest torque readings will not be the same as those that produce the lowest axial force. This will become evident in the discussion which follows.

The analysis of variance tests performed on the data showed all of the major variables, species, helix angle, rake angle, table speed, spindle r.p.m. and temperature, to have significant effect on the results. The effect of these variables accounted for 71 percent of the variation found in the analysis of maximum torque and 76 percent of the variation found in the analysis of maximum axial force. Following is a discussion of the effect of each variable on the selected outputs.

The helix angle is the single most important variable affecting the axial force, F_x. Sixty-two percent of the total variation in F_x is accounted for by the helix angle. As would be expected, increasing values of helix angle create increasing values of F_x. The effect is basically linear from 0^o to 40^o with a greater increase from 40^o to 60^o as shown in the following tabulation.

Helix angle (degrees)	Average F_x* (lb/in)	Increment in F_x (lb/in)
0	0	-
20	21	21
40	42	21
60	77	35

*Averaged for all tests

Increasing rake angle has the effect of decreasing F_x, the average decrease from 15° to 45° rake angles being 30 percent. This result is consistent for the three species considered and both for green and frozen wood (Figures 11 and 12). The frozen wood showed an average increase in F_x of 26 percent over the green material. The average values of F_x for the aspen, maple and pine by helix angle and green and frozen wood are summarized in Table 10.

Spindle r.p.m. and table feed speed have consistent effects over the range of the three species, green or frozen wood and the twelve combinations of rake and helix angle. Increasing values of spindle r.p.m. decrease the axial force while increasing values of table feed speed increase the axial force. The general effect of the variables is illustrated in Figure 13 for sugar maple cut in the green condition. The results for the other species and the frozen samples follow the same general trends. Further discussion of the effect of spindle r.p.m. and table feed speed will be included in a later section where their combination into a feed rate value and its effect on the cutter performance will be considered. Further consideration of these two variables for selection of an optimum cutter geometry is not required.

The analysis of variance on the maximum torque (T_{max}) indicated that all the main variables, species, helix angle, rake angle, table speed, spindle r.p.m. and temperature, have a significant effect on the results. These main variables account for 71 percent of the variation found in the results, but unlike the axial force analysis, no one variable has a dominant effect. Spindle r.p.m. has the greatest effect but only accounts for 18 percent of the variation in the data.

Figure 11 Maximum axial force vs. helix and rake angles for green wood by species.

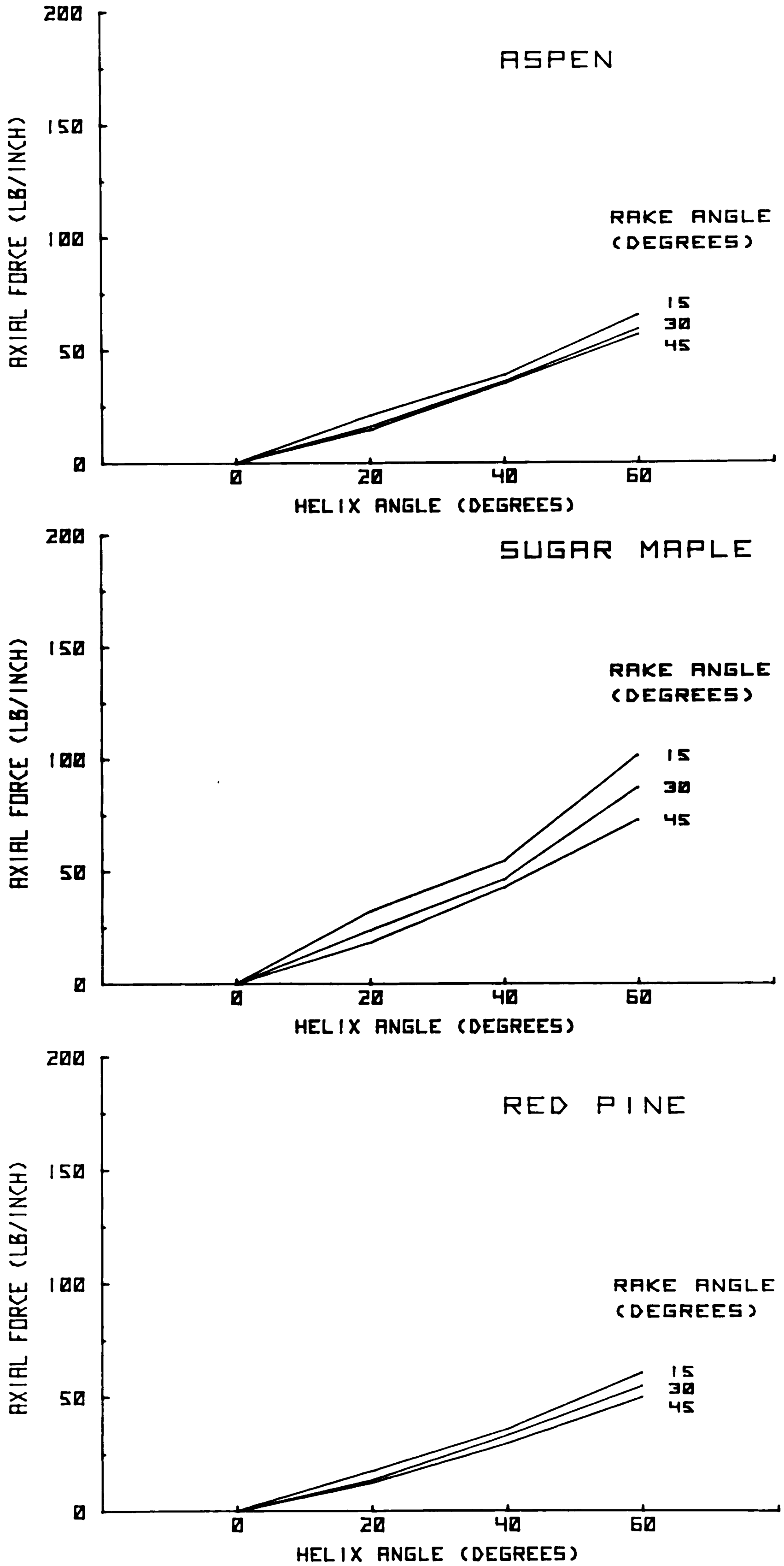

ASPEN
AXIAL FORCE (LB/INCH)
200
150
100
50
0
RAKE ANGLE
(DEGREES)
15
30
45
0
20
40
60
HELIX ANGLE (DEGREES)
SUGAR MAPLE
AXIAL FORCE (LB/INCH)
200
150
100
50
0
RAKE ANGLE
(DEGREES)
15
30
45
0
20
40
60
HELIX ANGLE (DEGREES)
RED PINE
AXIAL FORCE (LB/INCH)
200
150
100
50
0
RAKE ANGLE
(DEGREES)
15
30
45
0
20
40
60
HELIX ANGLE (DEGREES)

Figure 11

Figure 12 Maximum axial force vs. helix and rake angles for frozen wood by species.

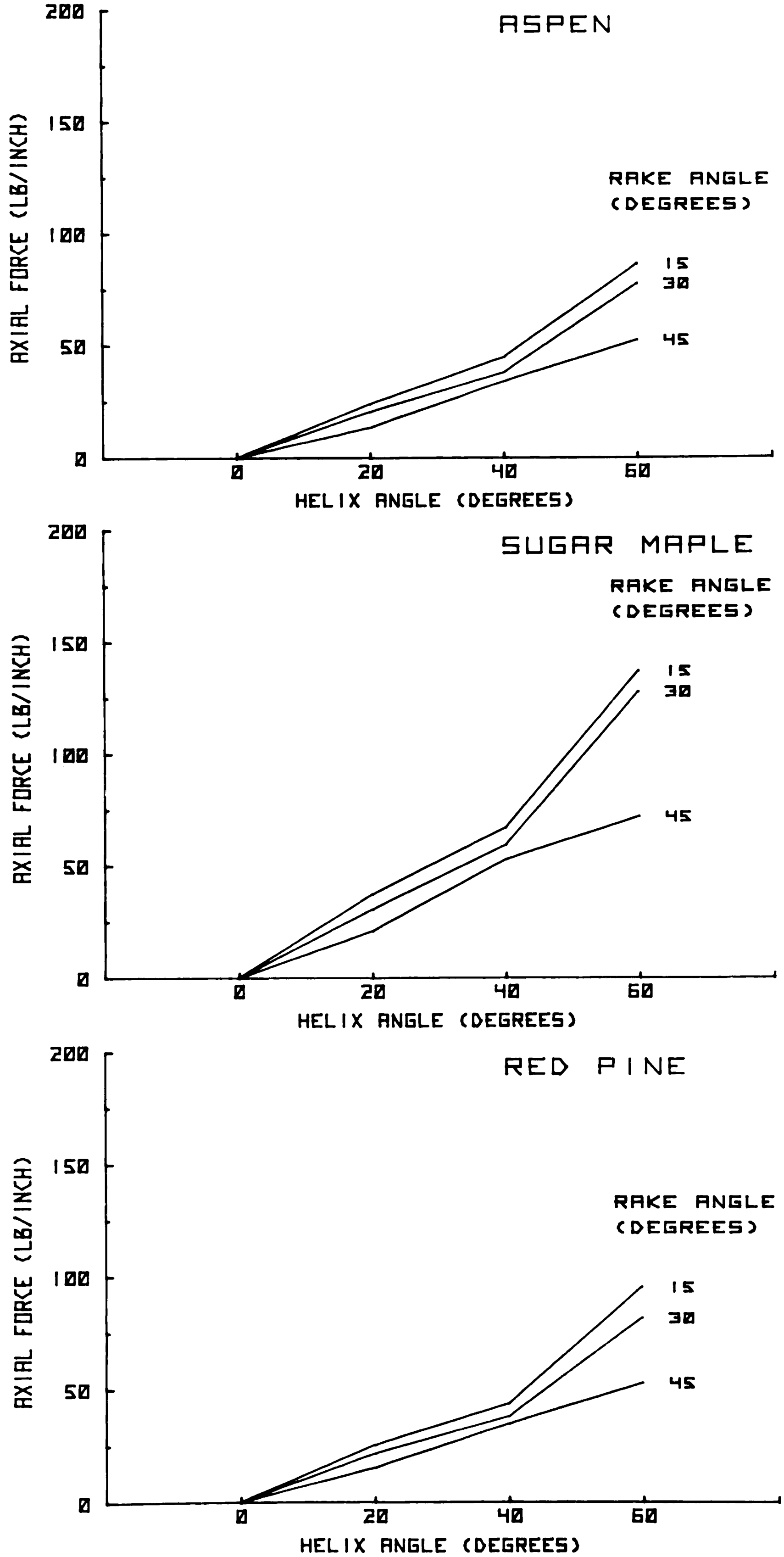

ASPEN
AXIAL FORCE (LB/INCH)
200
150
100
50
0
0
20
40
60
HELIX ANGLE (DEGREES)
RAKE ANGLE (DEGREES)
15
30
45
SUGAR MAPLE
AXIAL FORCE (LB/INCH)
200
150
100
50
0
0
20
40
60
HELIX ANGLE (DEGREES)
RAKE ANGLE (DEGREES)
15
30
45
RED PINE
AXIAL FORCE (LB/INCH)
200
150
100
50
0
0
20
40
60
HELIX ANGLE (DEGREES)
RAKE ANGLE (DEGREES)
15
30
45

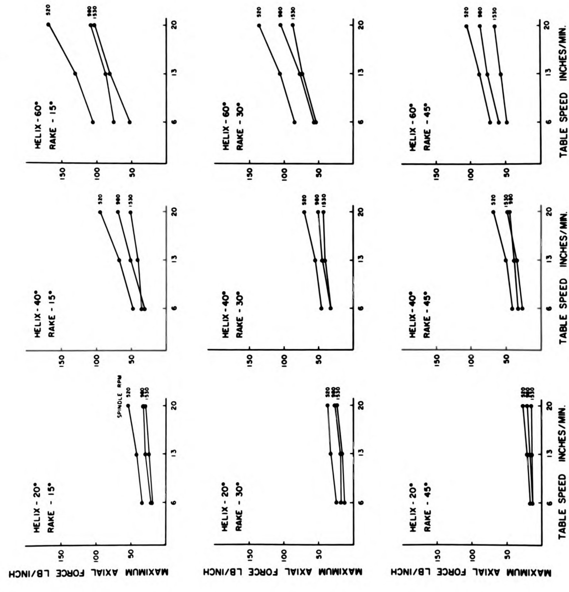
Figure 12

Table 10. Maximum axial force vs. helix angle for green and frozen wood by species.

	Maximum axial force*, Lb/in. Helix angle			
Species	0	20	40	60
Aspen				
Green	0	17	36	60
Frozen	0	19	39	71
Maple				
Green	0	25	48	87
Frozen	0	29	60	112
Pine				
Green	0	14	33	55
Frozen	0	21	38	75

*Averaged over all feed settings and rake angles.

Figure 13 Maximum axial force vs. spindle rotational speed and table feed speed by rake and helix angle combinations for sugar maple cut green.



MAXIMUM AXIAL FORCE LB/INCH
HELIX - 20° RAKE - 15°
HELIX - 40° RAKE - 15°
HELIX - 60° RAKE - 15°
HELIX - 20° RAKE - 30°
HELIX - 40° RAKE - 30°
HELIX - 60° RAKE - 30°
HELIX - 20° RAKE - 45°
HELIX - 40° RAKE - 45°
HELIX - 60° RAKE - 45°
SPINDLE RPM
520
980
1530
150
100
50
6
13
20
TABLE SPEED INCHES/MIN.

Figure 13

The effects of species and temperature are consistent throughout the data and follow expected patterns, the frozen wood increased T_{max} by an average of 20 percent over the green material, and the results by species showed maple to be higher than red pine and aspen, following the differences in specific gravity.

The effect of helix angle on T_{max} shows decreasing values of T_{max} with increasing values of helix angle from 0 to 40 degrees with a leveling out or increase in T_{max} from 40^{o} to 60^{o} (Table 11).

Increasing rake angle has the effect of decreasing T_{max}, the average reduction from a 15^{o} rake angle to 45^{o} rake angle being 38 percent (Figures 14 and 15).

The effect of table speed and spindle r.p.m. are consistent over the three species considered, green and frozen wood and the twelve cutters, or twelve combinations of rake and helix angle. Increasing values of spindle speed tend to decrease the value of T_{max} while increasing values of table speed increase the resultant torque. The general effects of these variables are illustrated in Figure 16 for maple cut in the green condition. They will again be considered in more detail in the next section.

The overall results of T_{max} and F_x versus rake and helix angles are shown in Figure 17. Using the selection criterion for the optimum cutter of the combination of rake and helix angles which produces the lowest T_{max} and simultaneously the lowest F_x, it can be seen that a compromise between the criteria must be made. The lowest T_{max} occurs at a 60^{o} helix angle while the highest axial force also occurs at the 60^{o} helix angle. The combination of the lowest T_{max} and lowest F_x occur at the 20^{o} helix angle and the 45^{o} rake angle. However, a third consideration should be

Table 11. Maximum torque vs. helix angle for green and frozen wood by species.

	Maximum torque* in-lb/in. Helix angle			
Species	0	20	40	60
Aspen				
Green	90	76	68	64
Frozen	104	86	75	74
Maple				
Green	124	103	88	89
Frozen	145	121	112	110
Pine				
Green	83	70	64	63
Frozen	104	91	75	80

*Averaged over all feed settings and rake angles

Figure 14 Maximum torque vs. helix and rake angles for green wood by species.

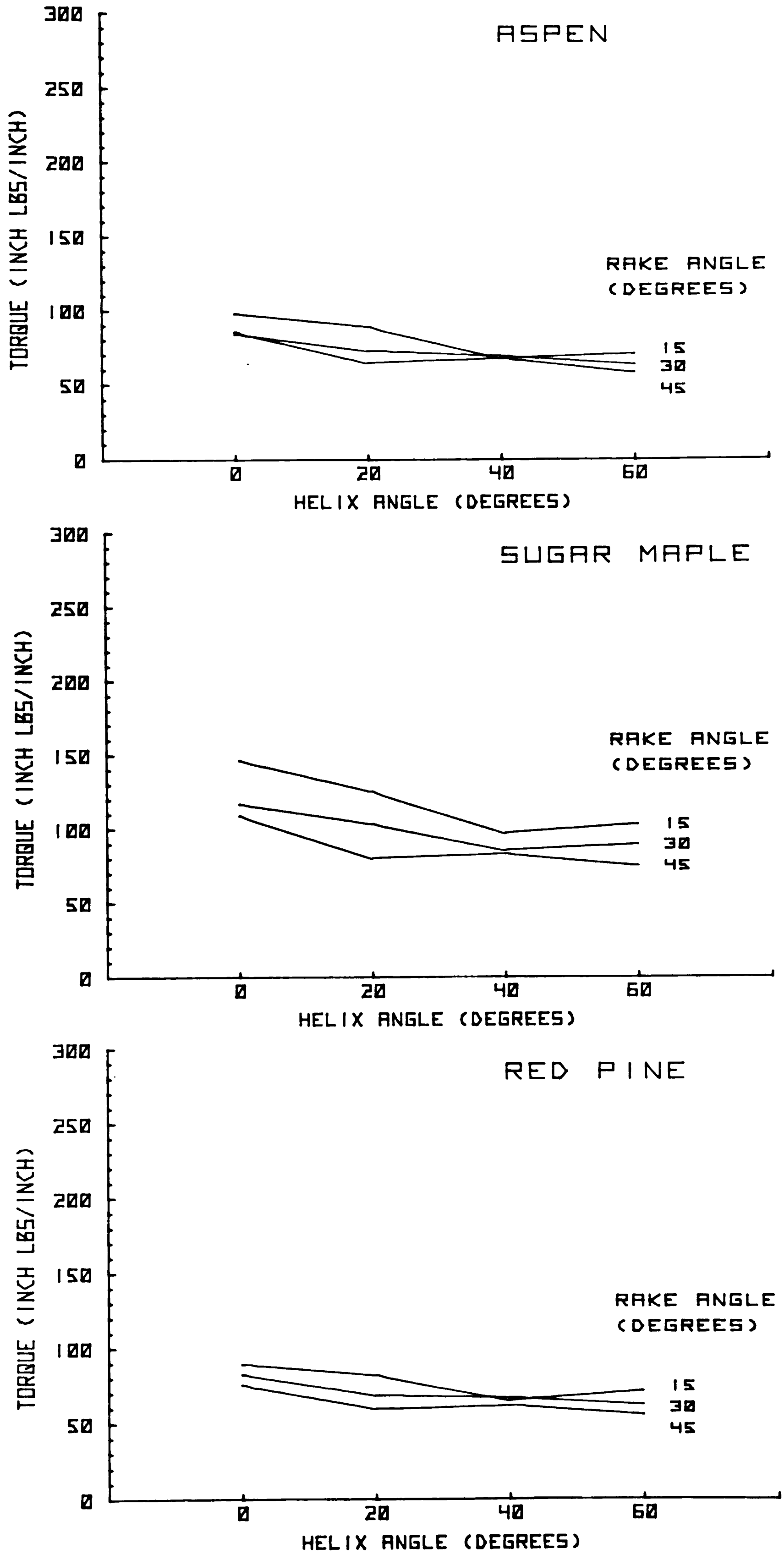

ASPEN
TORQUE (INCH LBS/INCH)
300
250
200
150
100
50
0
RAKE ANGLE (DEGREES)
15
30
45
0
20
40
60
HELIX ANGLE (DEGREES)
SUGAR MAPLE
TORQUE (INCH LBS/INCH)
300
250
200
150
100
50
0
RAKE ANGLE (DEGREES)
15
30
45
0
20
40
60
HELIX ANGLE (DEGREES)
RED PINE
TORQUE (INCH LBS/INCH)
300
250
200
150
100
50
0
RAKE ANGLE (DEGREES)
15
30
45
0
20
40
60
HELIX ANGLE (DEGREES)

Figure 14

Figure 15 Maximum torque vs. helix and rake angles for frozen wood by species.

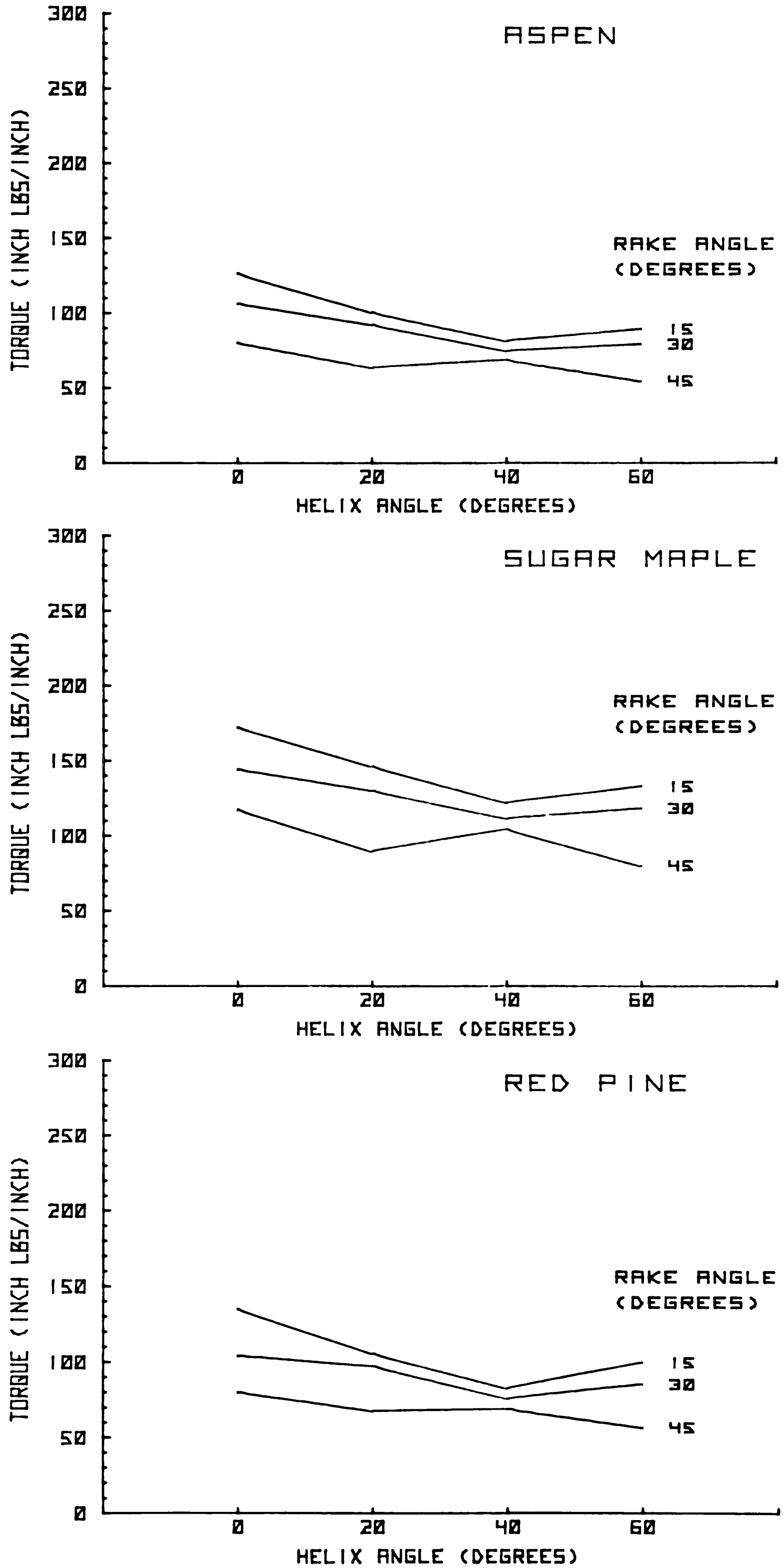
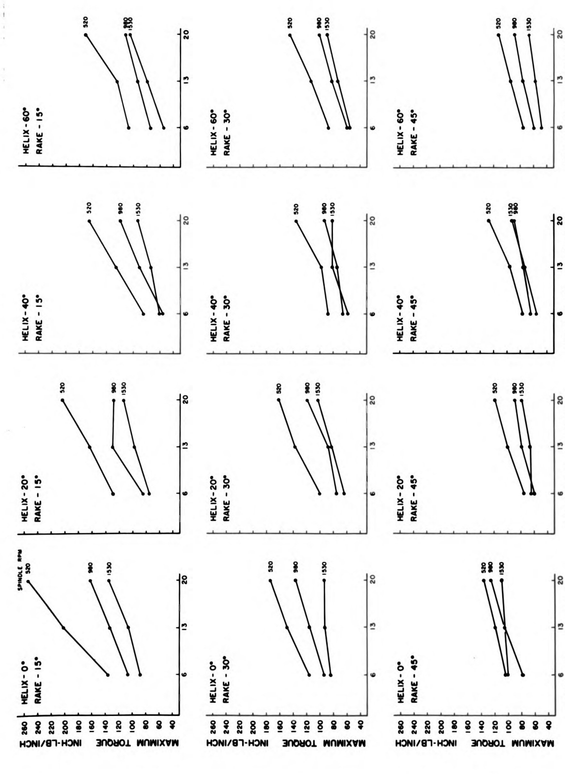

ASPEN
TORQUE (INCH LBS/INCH)
300
250
200
150
100
50
0
RAKE ANGLE (DEGREES)
15
30
45
0
20
40
60
HELIX ANGLE (DEGREES)
SUGAR MAPLE
TORQUE (INCH LBS/INCH)
300
250
200
150
100
50
0
RAKE ANGLE (DEGREES)
15
30
45
0
20
40
60
HELIX ANGLE (DEGREES)
RED PINE
TORQUE (INCH LBS/INCH)
300
250
200
150
100
50
0
RAKE ANGLE (DEGREES)
15
30
45
0
20
40
60
HELIX ANGLE (DEGREES)

Figure 15

Figure 16 Maximum torque vs. spindle rotational speed and table feed speed by rake and helix angle combinations for sugar maple cut green.



MAXIMUM TORQUE INCH-LB/INCH
SPINDLE RPM
HELIX - 0° RAKE - 15°
HELIX - 20° RAKE - 15°
HELIX - 40° RAKE - 15°
HELIX - 60° RAKE - 15°
HELIX - 0° RAKE - 30°
HELIX - 20° RAKE - 30°
HELIX - 40° RAKE - 30°
HELIX - 60° RAKE - 30°
HELIX - 0° RAKE - 45°
HELIX - 20° RAKE - 45°
HELIX - 40° RAKE - 45°
HELIX - 60° RAKE - 45°
520
980
1530
TABLE SPEED INCHES/MIN

Figure 16

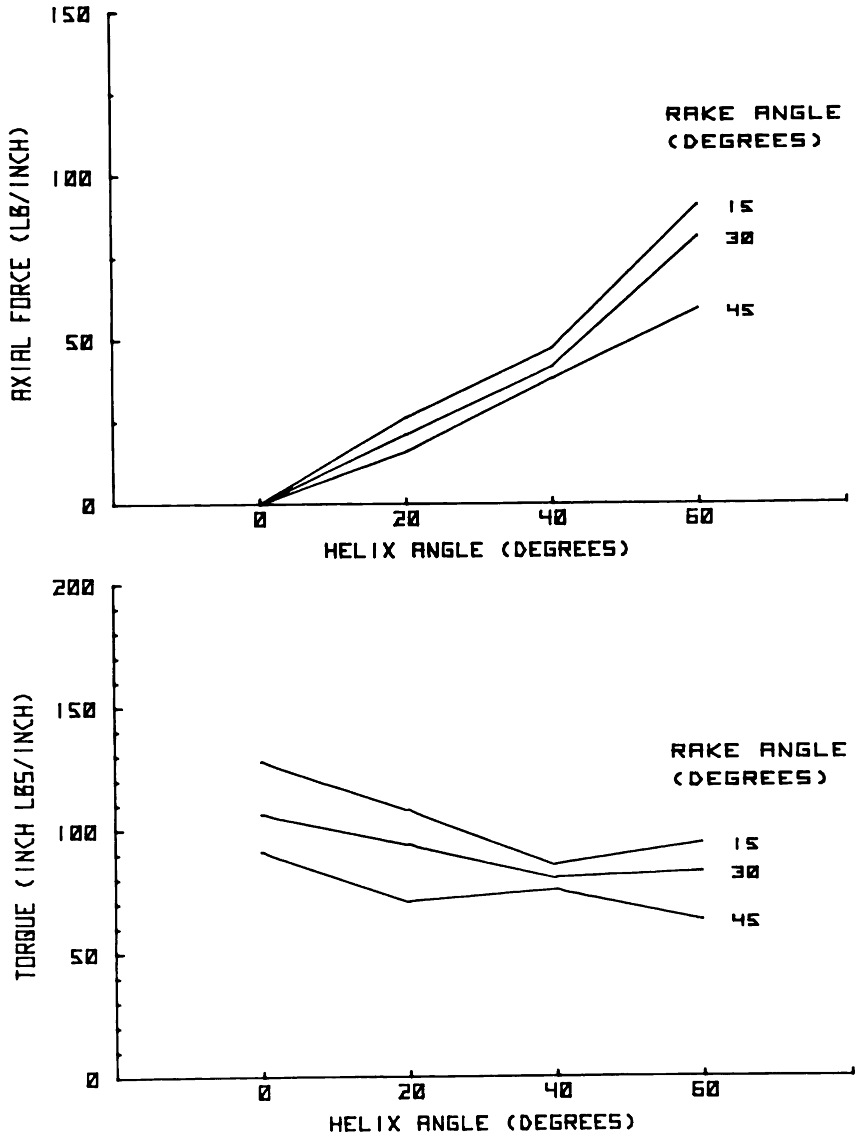


Figure 17 Maximum axial force and maximum torque vs. helix and rake angles averaged over all tests.

included at this point. The combination of a 20^{o} helix angle and a 45^{o} rake angle gives a normal sharpness angle of 35 degrees (Table 2). For practical cutting situations where the auger cutter would be employed, experience in wood working has shown that this sharpness angle and the implied fine edge, would create a significant problem in maintaining the sharpness of the cutter, and also in providing enough mass in the tooth to minimize damage due to hitting obstructions during the cutting process (13). For this reason, a cutter with a 30^{o} rake angle, 40^{o} helix angle and a sharpness angle of 50 degrees is believed to be a better combination. The average T_{max} found for this combination is only 14 percent higher than for the 20^{o} helix, 45^{o} rake combination, while the sharpness angle is about 40 percent greater.

Cutting Rate

Any cutting process that has as its eventual application the commercial felling of timber requires an analysis of the rate at which the device can cut the wood, and the effect of the cutting rate on the forces and power requirements for the device. This portion of the experimental program was designed to develop the data needed to evaluate the effects of cutting rate on the performance of the cutter and the resulting forces and power requirements.

The experimental design used in this study was complete in that the effect of cutting rate could be evaluated for any of the combinations of cutter geometry, i.e., rake and helix angle, that were used in the test program. However, since the combination of a 40^{o} helix angle and 30^{o} rake angle has been selected as an optimum combination of cutter parameters, the following analysis of the effect of cutting rate will be limited to that combination only. For identification purposes, the cutter with the combination of the 40° helix angle and 30° rake angle was labeled cutter number 8, and that identification will be used in the discussion which follows.

The basis for the analysis of the effect of cutting rate on the cutter performance was the 9 cutter feed rates built into the experimental design. Within the limitations of the milling machine used for the test setup, 3 nominal spindle speeds, or cutter rotational speeds, of 520, 980 and 1530 r.p.m., and 3 nominal table feed speeds of 6, 13 and 20 inches per minute were used in a factorial combination to provide 9 feed rates for the experimental design. This combination gave a range of feed rates from 22 x 10^{-4} to 200 x 10^{-4} inches/tooth. The following tabulation gives the values of feed rate for each combination of rotational speed and table feed speed.

Feed rates (inches/tooth x 10^{-4})

		Nominal cutter rotational speed (r.p.m.)		
		520	980	1530
Nominal table speed (in/min)	6	66	35	22
	13	130	67	43
	20	200	100	67

The values of cutter rotational speed and table speed used were specifically selected from those available so that a full range of values was included, and also so that the values of feed rate on the diagonal of the above matrix were as nearly equal as possible. A hypothesis of this study was that the forces on the cutter and the power requirements of the cutting operation were dependent upon the feed rate rather than independently upon the cutter rotational speed or the table speed. Thus, if the hypothesis is true, the values of the forces and power requirements observed for the three equivalent feed rates on the diagonal of the above matrix should be equal. This hypothesis is partially borne out in the following discussion of the experimental results of the effect of cutting rate on the performance of the auger cutter.

The effect of cutter rotational speed and table feed speed on the resulting torque and axial force are consistent for the three species of wood considered and for green and frozen wood. Increasing values of cutter rotational speed tend to reduce both the torque and the axial force, while increasing values of table feed speed tend to increase both the torque and axial force. In all cases, the axial force and torque are higher for frozen wood than green wood. These results are illustrated in Figures 18 and 19 for the three species of wood, both green and frozen. The results by species follow the difference in specific gravity between the three species, sugar maple being highest, with aspen and red pine lower, but quite close.

Examination of the data in Figures 18 and 19 shows that for those combinations of cutter rotational speed and table feed speed that create the same feed rate of 66 x 10^{-4} inches/tooth, the resultant values of axial force and torque are quite similar. The data in Figures 18 and 19 are taken from Tables 12, 13 and 14 where this trend can be seen in numerical form. As previously stated, a hypothesis of this work was that the resultant forces and power requirements for the auger cutter were dependent on the feed rate of the cutting operation rather than independently on the cutter rotational speed or the table feed speed. The effect this has is that it allows the significant loadings on the cutter to be documented in terms of one variable instead of two, and greatly simplifies

Figure 18 Maximum axial force vs. spindle rotational speed and table feed speed for green and frozen wood by species.

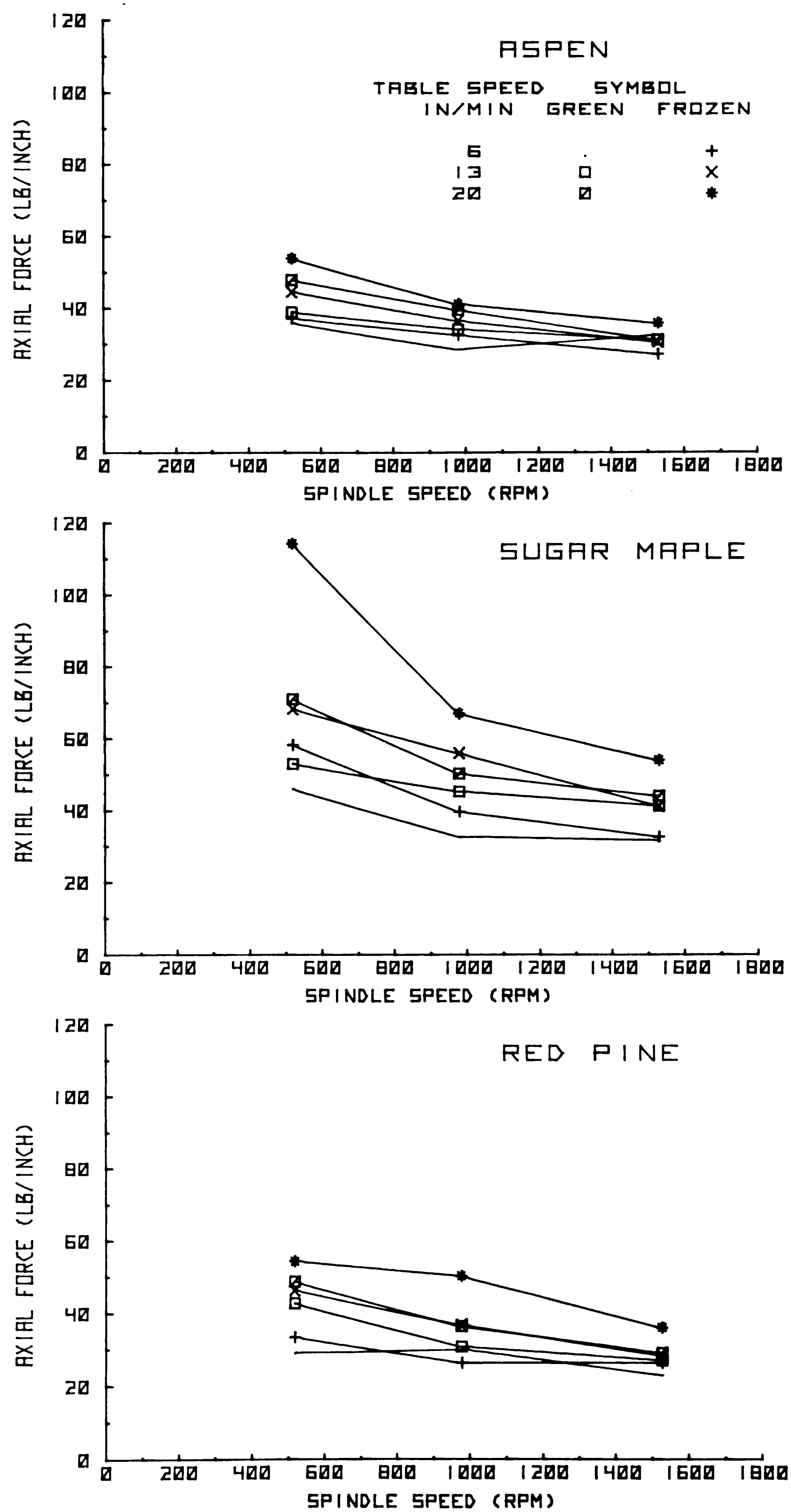

ASPEN
TABLE SPEED SYMBOL
IN/MIN GREEN FROZEN
6 . +
13 □ X
20 Ø *
AXIAL FORCE (LB/INCH)
SPINDLE SPEED (RPM)
SUGAR MAPLE
AXIAL FORCE (LB/INCH)
SPINDLE SPEED (RPM)
RED PINE
AXIAL FORCE (LB/INCH)
SPINDLE SPEED (RPM)

Figure 18

Figure 19 Maximum torque vs. spindle rotational speed and table feed speed for green and frozen wood by species.

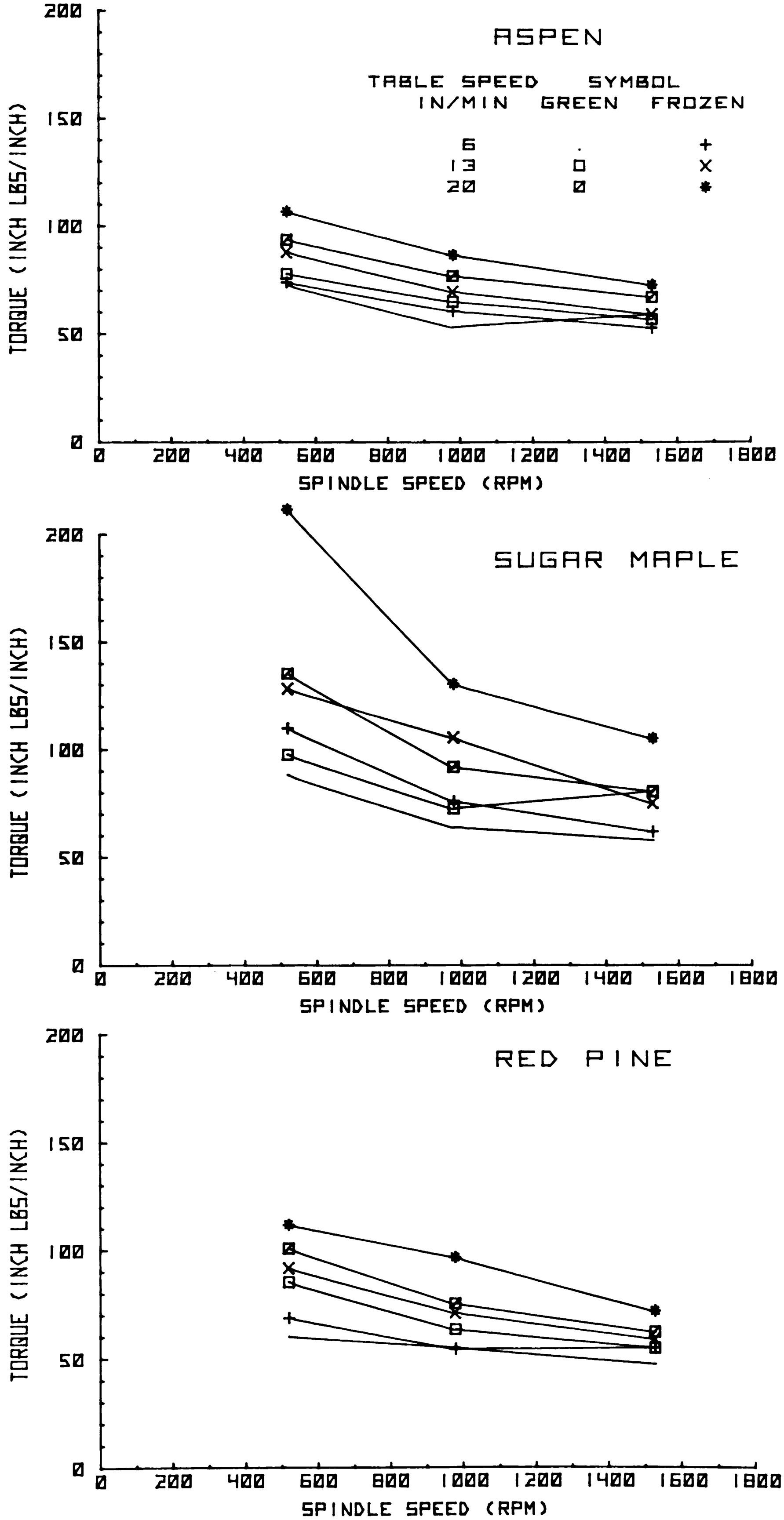

ASPEN
TABLE SPEED SYMBOL
IN/MIN GREEN FROZEN
6 . +
13 □ X
20 ⊠ ✱
TORQUE (INCH LBS/INCH)
0
50
100
150
200
0 200 400 600 800 1000 1200 1400 1600 1800
SPINDLE SPEED (RPM)
SUGAR MAPLE
TORQUE (INCH LBS/INCH)
0
50
100
150
200
0 200 400 600 800 1000 1200 1400 1600 1800
SPINDLE SPEED (RPM)
RED PINE
TORQUE (INCH LBS/INCH)
0
50
100
150
200
0 200 400 600 800 1000 1200 1400 1600 1800
SPINDLE SPEED (RPM)

Figure 19

Table 12. Summary of forces and power requirements for cutting aspen with a 40^{o} helix angle 30^{o} rake angle auger cutter.

Condition	Feed rate in/tooth x 10^{-4}	Spindle rpm	Table speed in/min	Moisture Content	Spec. gravity	Maximum axial force/lb/in	Maximum torque in-lb/in	Maximum horsepower hp/in
Green	66	520	6	43.42	.415	36.0	72.7	.62
	130	520	13	42.41	.418	39.0	78.0	.66
	200	520	20	42.54	.409	48.0	93.7	.79
	35	980	6	47.22	.403	28.7	53.3	.87
	67	980	13	43.98	.417	34.3	65.0	1.05
	100	980	20	47.91	.405	39.7	77.0	1.24
	22	1530	6	43.22	.407	32.7	59.3	1.47
	43	1530	13	48.23	.399	31.3	57.0	1.45
	67	1530	20	45.13	.411	31.3	67.3	1.70
Frozen	66	520	6	47.67	.377	37.3	74.0	.63
	130	520	13	49.64	.384	44.7	88.0	.74
	200	520	20	48.85	.384	54.0	106.7	.90
	35	980	6	48.42	.375	32.7	60.7	.96
	67	980	13	48.69	.379	36.7	69.7	1.11
	100	980	20	49.18	.360	41.3	86.7	1.38
	22	1530	6	46.80	.369	27.3	53.0	1.31
	43	1530	13	48.84	.390	30.7	59.3	1.49
	67	1530	20	48.03	.376	36.0	73.0	1.83

Table 13. Summary of forces and power requirements for cutting sugar maple with a 40° helix angle 30° rake angle auger cutter.

Condition	Feed rate in/tooth x 10^{-4}	Spindle rpm	Table speed in/min	Moisture Content	Spec. gravity	Maximum axial force/lb/in	Maximum torque in-lb/in	Maximum horsepower hp/in
Green	66	520	6	35.01	.615	46.0	88.3	.75
	130	520	13	35.31	.617	54.0	97.7	.83
	200	520	20	32.82	.603	71.0	135.3	1.15
	35	980	6	34.32	.623	32.7	64.0	1.02
	67	980	13	35.14	.617	45.3	72.7	1.15
	100	980	20	36.30	.592	50.3	92.0	1.45
	22	1530	6	34.68	.605	31.7	58.0	1.46
	43	1530	13	34.24	.632	41.2	80.7	2.02
	67	1530	20	33.59	.600	44.0	80.7	1.98
Frozen	66	520	6	37.90	.610	58.3	110.0	.93
	130	520	13	38.35	.587	68.3	128.3	1.09
	200	520	20	36.58	.620	114.3	211.7	1.78
	35	980	6	38.16	.597	39.7	76.3	1.21
	67	980	13	37.55	.603	56.0	105.7	1.68
	100	980	20	37.61	.609	67.0	130.7	2.05
	22	1530	6	37.37	.611	32.7	62.3	1.56
	43	1530	13	38.25	.594	41.3	75.3	1.87
	67	1530	20	39.07	.605	54.0	105.3	2.65

Table 14. Summary of forces and power requirements for cutting red pine with a 40° helix angle 30° rake angle auger cutter.

Condition	Feed rate in/tooth x 10^{-4}	Spindle rpm	Table speed in/min	Moisture Content	Spec. gravity	Maximum axial force lb/in	Maximum torque in-lb/in	Maximum horsepower hp/in
Green	66	520	6	54.90	.387	29.0	60.0	.51
	130	520	13	54.38	.423	42.7	85.3	.73
	200	520	20	52.70	.417	48.7	100.7	.85
	35	980	6	54.46	.408	30.0	55.0	.87
	67	980	13	51.01	.390	30.7	63.3	1.01
	100	980	20	55.05	.395	36.3	75.3	1.22
	22	1530	6	55.14	.397	23.0	47.3	1.18
	43	1530	13	54.41	.401	27.0	54.7	1.35
	67	1530	20	59.85	.419	29.0	62.0	1.55
Frozen	66	520	6	55.33	.404	33.3	68.7	.58
	130	520	13	58.56	.401	46.3	91.7	.78
	200	520	20	53.73	.398	54.3	111.7	.94
	35	980	6	48.47	.422	26.3	54.3	.86
	67	980	13	55.34	.411	36.7	71.0	1.13
	100	980	20	54.95	.420	50.3	96.7	1.53
	22	1530	6	53.27	.426	26.3	54.7	1.35
	43	1530	13	55.77	.407	28.3	58.7	1.48
	67	1530	20	55.01	.420	36.0	71.7	1.81

the explanation of the effect of cutting rate on the force and power requirements of the cutting process.

The relationships between the axial force and torque and the feed rate were found to be linear. Figures 20 and 21 show this linear relationship by plotting the data for the axial force and torque versus feed rate. Linear regressions of the form $Y = AX + B$ were fitted to this data, and the results are tabulated in Tables 15 and 16. The multiple correlation coefficient, or degree of linear association between the independent and dependent variables, varies between .70 and .94 for these regressions, and the standard error of estimate is 8 lb/in or less for the regression on the axial force, and 15 in lb/in or less for the regression on the torque. The regressions plus 95 percent confidence limits on the mean are plotted for these relationships in Figures 22, 23, 24, and 25. The closeness of the confidence limit curves to the regression lines indicate the good fit of the experimental data to these curves.

In addition to the loading on the cutter, the power requirement of the cutting is of practical importance. The effect of cutter rotational speed and table feed speed on the horsepower are illustrated in Figure 26. Slightly different than the effect found on the axial force and the torque, increasing values of both cutter rotational speed and table feed speed increase the power requirement. The axial force and torque were found to increase with increasing table speed but decreased with increasing cutter rotational speed. The power requirement of the cutting is thus found not to be dependent only on the feed rate, but dependent on both the cutter rotational speed and table feed speed.

The relationships between the power requirement, feed rate, cutter rotational speed and table feed speed are illustrated in Figure 27.

Figure 20 Maximum axial force vs. feed rate for green and frozen wood by species and spindle rotational speed.

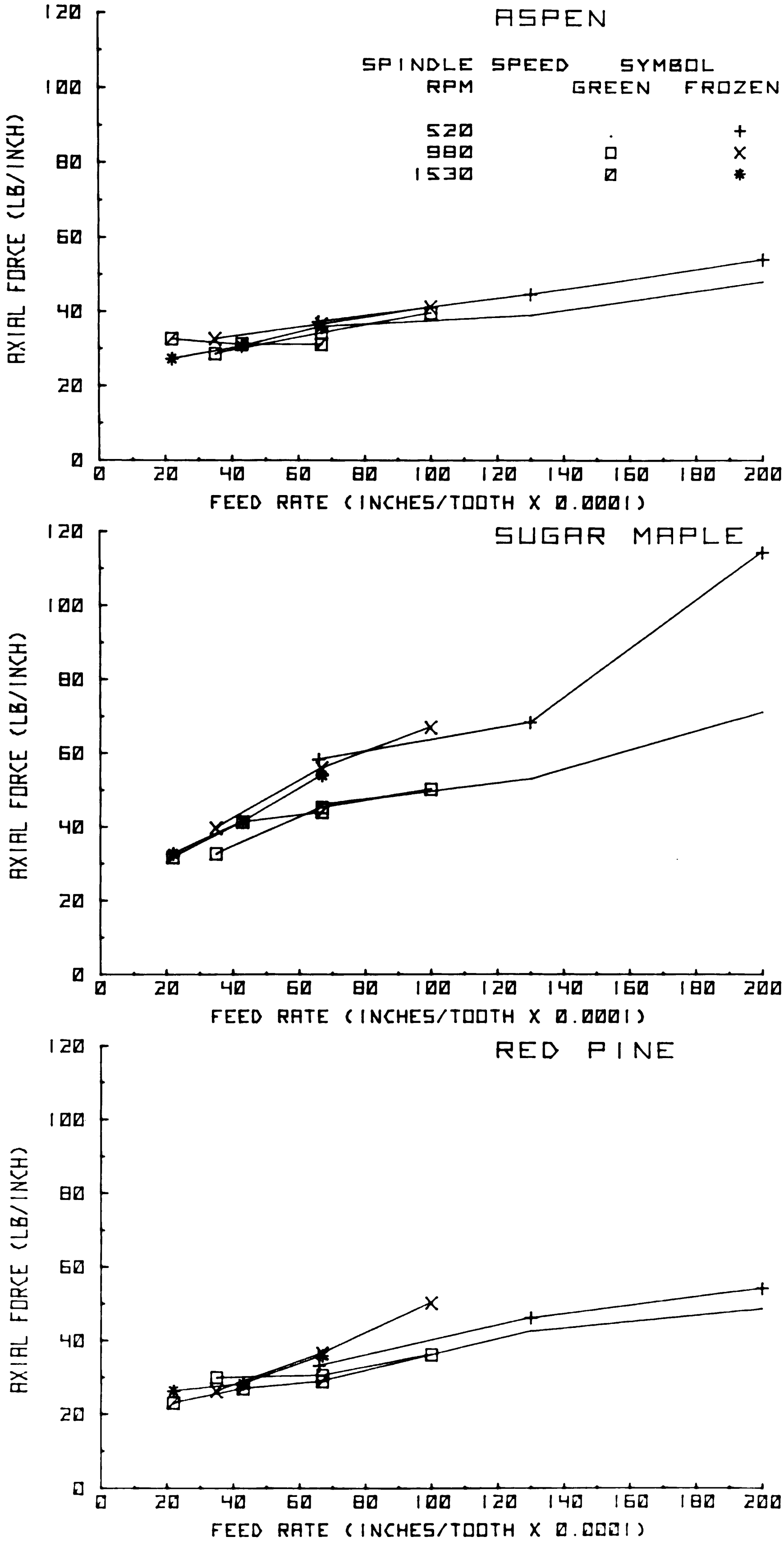

ASPEN
SPINDLE SPEED SYMBOL
RPM GREEN FROZEN
520 . +
980 □ X
1530 ⊠ *
AXIAL FORCE (LB/INCH)
FEED RATE (INCHES/TOOTH X 0.0001)
SUGAR MAPLE
RED PINE
0 20 40 60 80 100 120
0 20 40 60 80 100 120 140 160 180 200

Figure 20

Figure 21 Maximum torque vs. feed rate for green and frozen wood by species and spindle rotational speed.

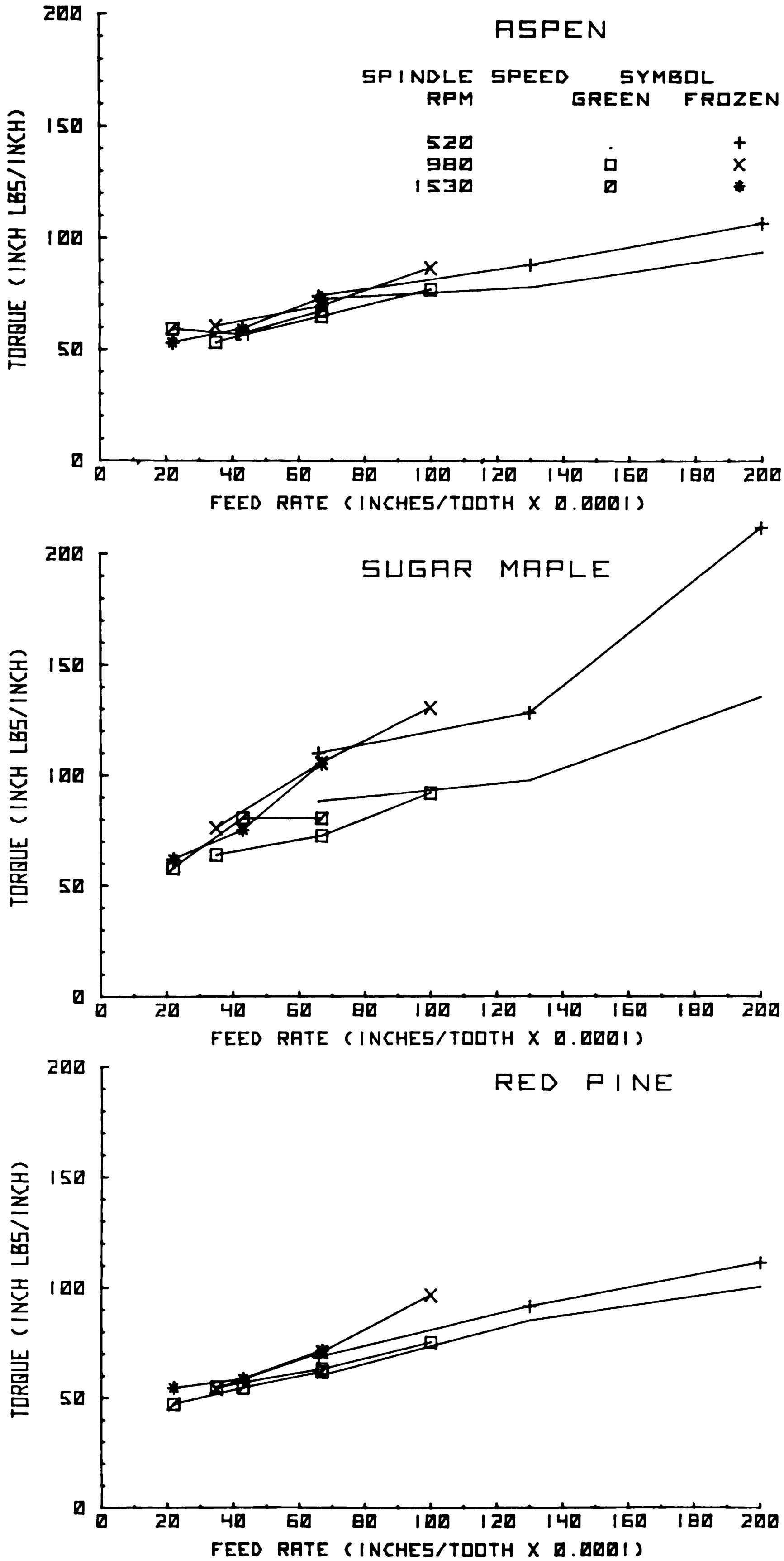

ASPEN
SPINDLE SPEED SYMBOL
RPM GREEN FROZEN
520 . +
980 □ X
1530 Ø ✱
TORQUE (INCH LBS/INCH)
FEED RATE (INCHES/TOOTH X 0.0001)
SUGAR MAPLE
TORQUE (INCH LBS/INCH)
FEED RATE (INCHES/TOOTH X 0.0001)
RED PINE
TORQUE (INCH LBS/INCH)
FEED RATE (INCHES/TOOTH X 0.0001)

Figure 21

Table 15. Regressions of maximum axial force vs. feedrate by species and green or frozen wood.

		Regression Coefficients			
Species	Condition	Constant (C_1)	Feedrate (C_2)	Multiple Correlation coefficient	Standard error of estimate
Aspen	Green	27.60	.10	.70	5.52
Aspen	Frozen	26,29	.14	.86	4.54
Sugar Maple	Green	29.36	.21	.82	7.99
Sugar Maple	Frozen	24.66	.42	.94	8.11
Red Pine	Green	21.36	.14	.81	5.51
Red Pine	Frozen	23.38	.17	.77	7.78

Form of Equations   Maximum Axial Force = $C_1 + C_2$ x Feedrate

Table 16. Regressions of maximum torque vs. feedrate by species and green or frozen wood.

		Regression Coefficients		Multiple	Standard
Species	Condition	Constant (C_1)	Feedrate (C_2)	Correlation coefficient	error of estimate
Aspen	Green	51.77	.22	.78	9.50
Aspen	Frozen	50.47	.30	.86	9.55
Sugar Maple	Green	53.64	.39	.80	15.74
Sugar Maple	Frozen	48.41	.78	.94	14.73
Red Pine	Green	42.42	.30	.83	11.01
Red Pine	Frozen	47.20	.35	.79	14.47

Form of equation Maximum Torque = $C_1 + C_2 \times$ Feedrate

Figure 22 Linear regressions and 95% confidence limits for maximum axial force as a function of feed rate for green wood by species.

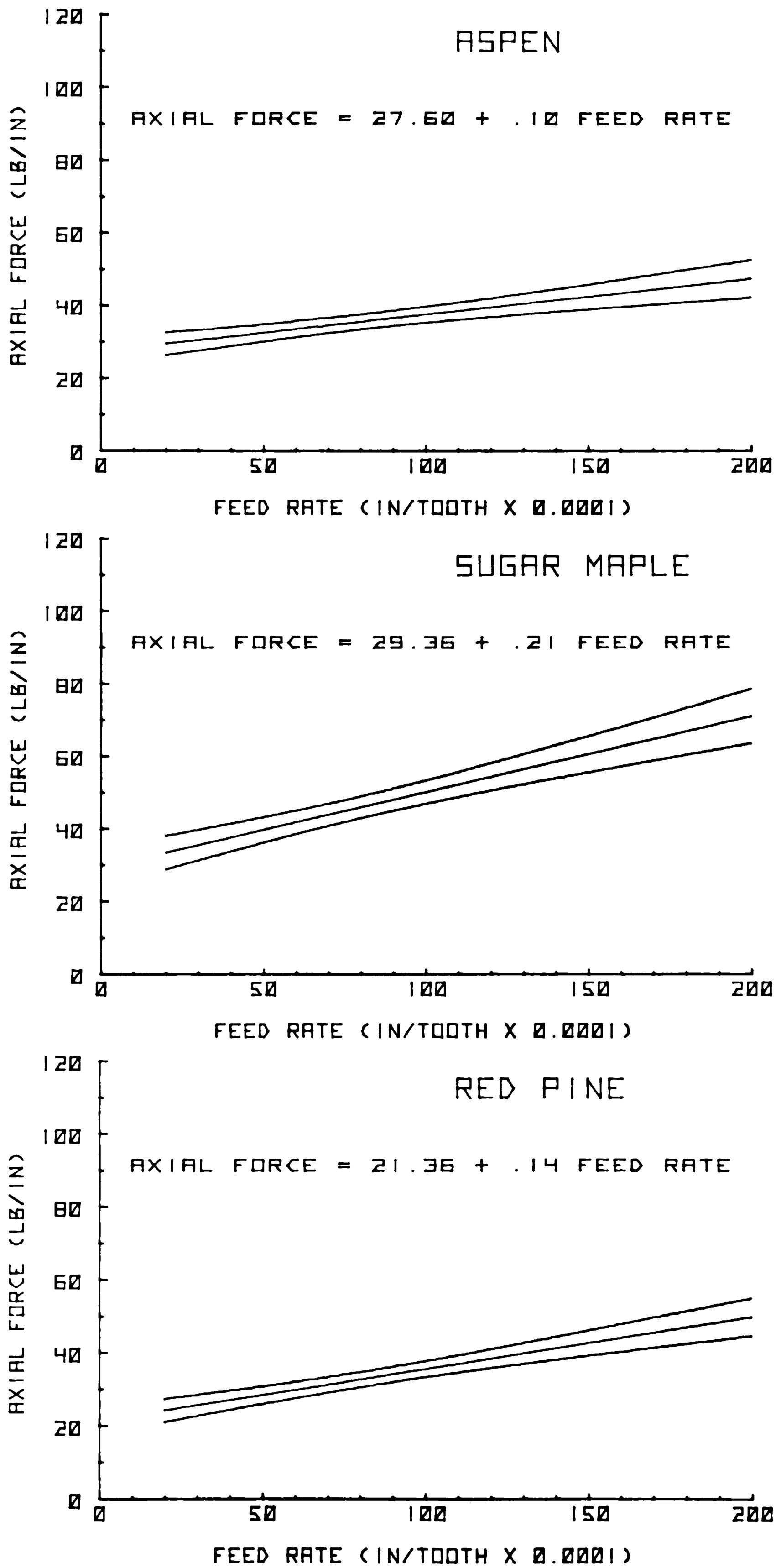

ASPEN
AXIAL FORCE = 27.60 + .10 FEED RATE
AXIAL FORCE (LB/IN)
120
100
80
60
40
20
0
0
50
100
150
200
FEED RATE (IN/TOOTH X 0.0001)
SUGAR MAPLE
AXIAL FORCE = 29.36 + .21 FEED RATE
AXIAL FORCE (LB/IN)
FEED RATE (IN/TOOTH X 0.0001)
RED PINE
AXIAL FORCE = 21.36 + .14 FEED RATE
AXIAL FORCE (LB/IN)
FEED RATE (IN/TOOTH X 0.0001)

Figure 22

Figure 23 Linear regressions and 95% confidence limits for maximum axial force as a function of feed rate for frozen wood by species.

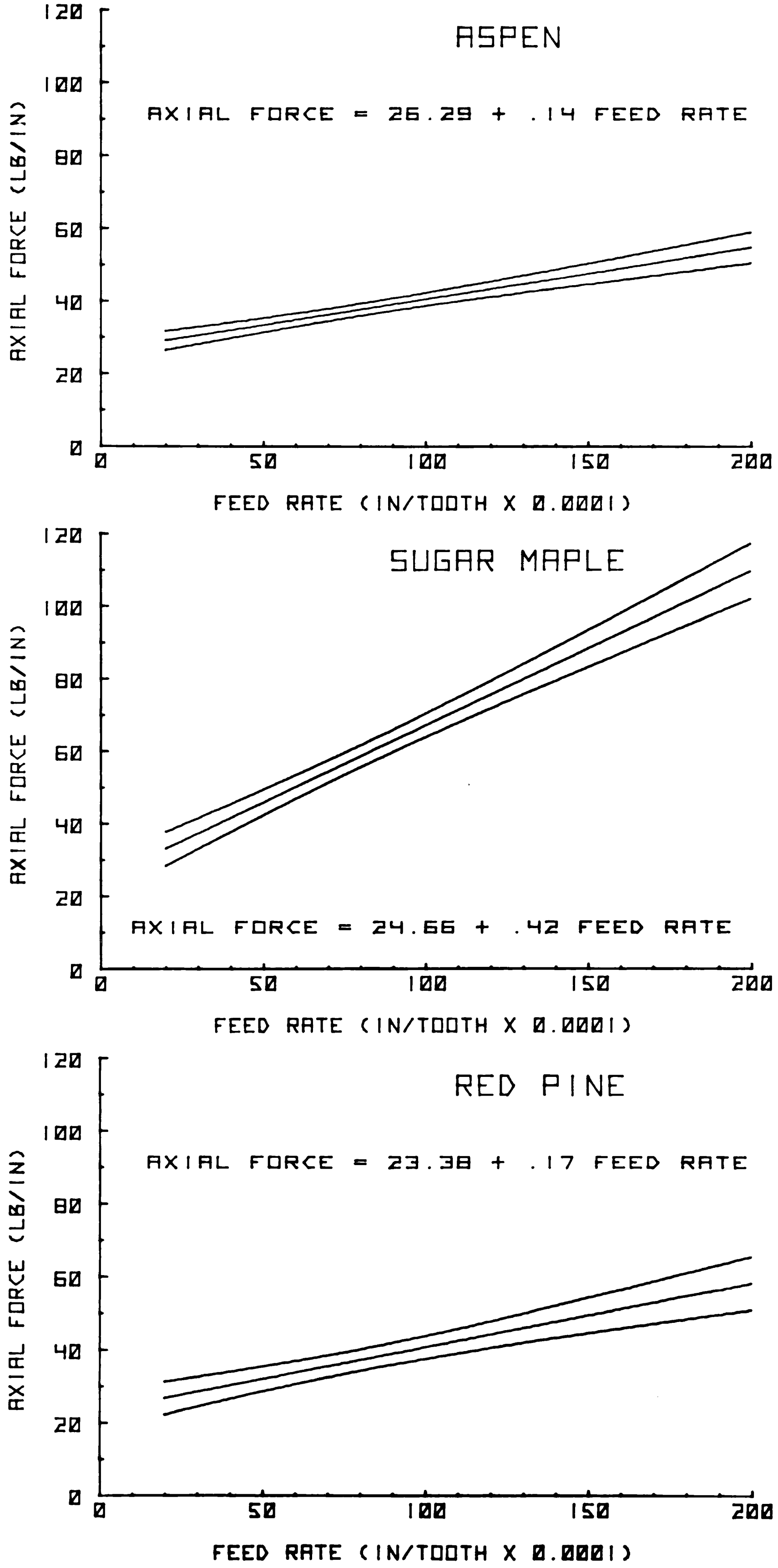

ASPEN
AXIAL FORCE = 26.29 + .14 FEED RATE
AXIAL FORCE (LB/IN)
FEED RATE (IN/TOOTH X 0.0001)
0
20
40
60
80
100
120
0
50
100
150
200
SUGAR MAPLE
AXIAL FORCE = 24.66 + .42 FEED RATE
AXIAL FORCE (LB/IN)
FEED RATE (IN/TOOTH X 0.0001)
RED PINE
AXIAL FORCE = 23.38 + .17 FEED RATE
AXIAL FORCE (LB/IN)
FEED RATE (IN/TOOTH X 0.0001)

Figure 23

Figure 24 Linear regressions and 95% confidence limits for maximum torque as a function of feed rate for green wood by species.

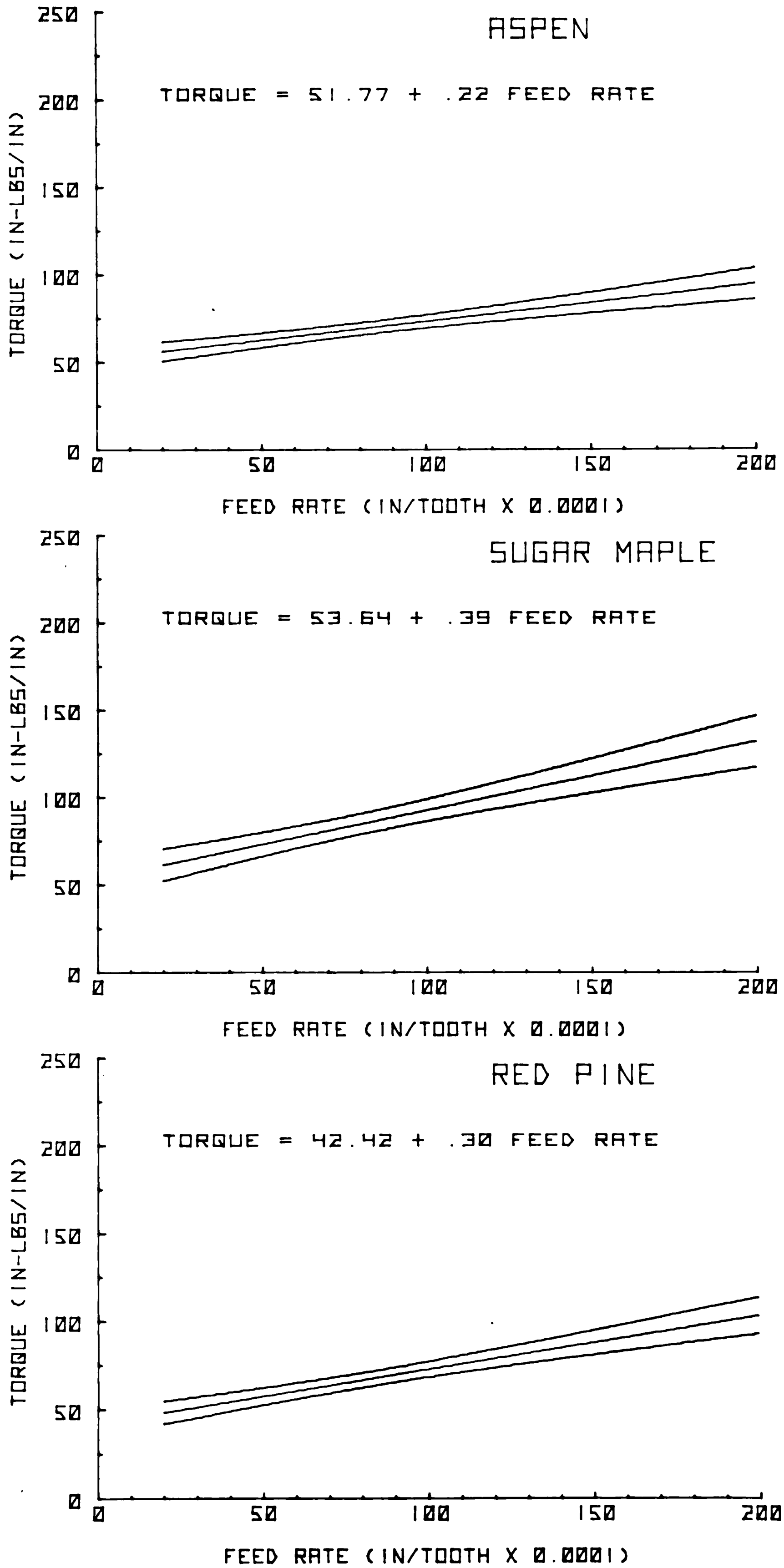

ASPEN
TORQUE = 51.77 + .22 FEED RATE
TORQUE (IN-LBS/IN)
FEED RATE (IN/TOOTH X 0.0001)
SUGAR MAPLE
TORQUE = 53.64 + .39 FEED RATE
TORQUE (IN-LBS/IN)
FEED RATE (IN/TOOTH X 0.0001)
RED PINE
TORQUE = 42.42 + .30 FEED RATE
TORQUE (IN-LBS/IN)
FEED RATE (IN/TOOTH X 0.0001)

Figure 24

Figure 25 Linear regressions and 95% confidence limits for maximum torque as a function of feed rate for frozen wood by species.

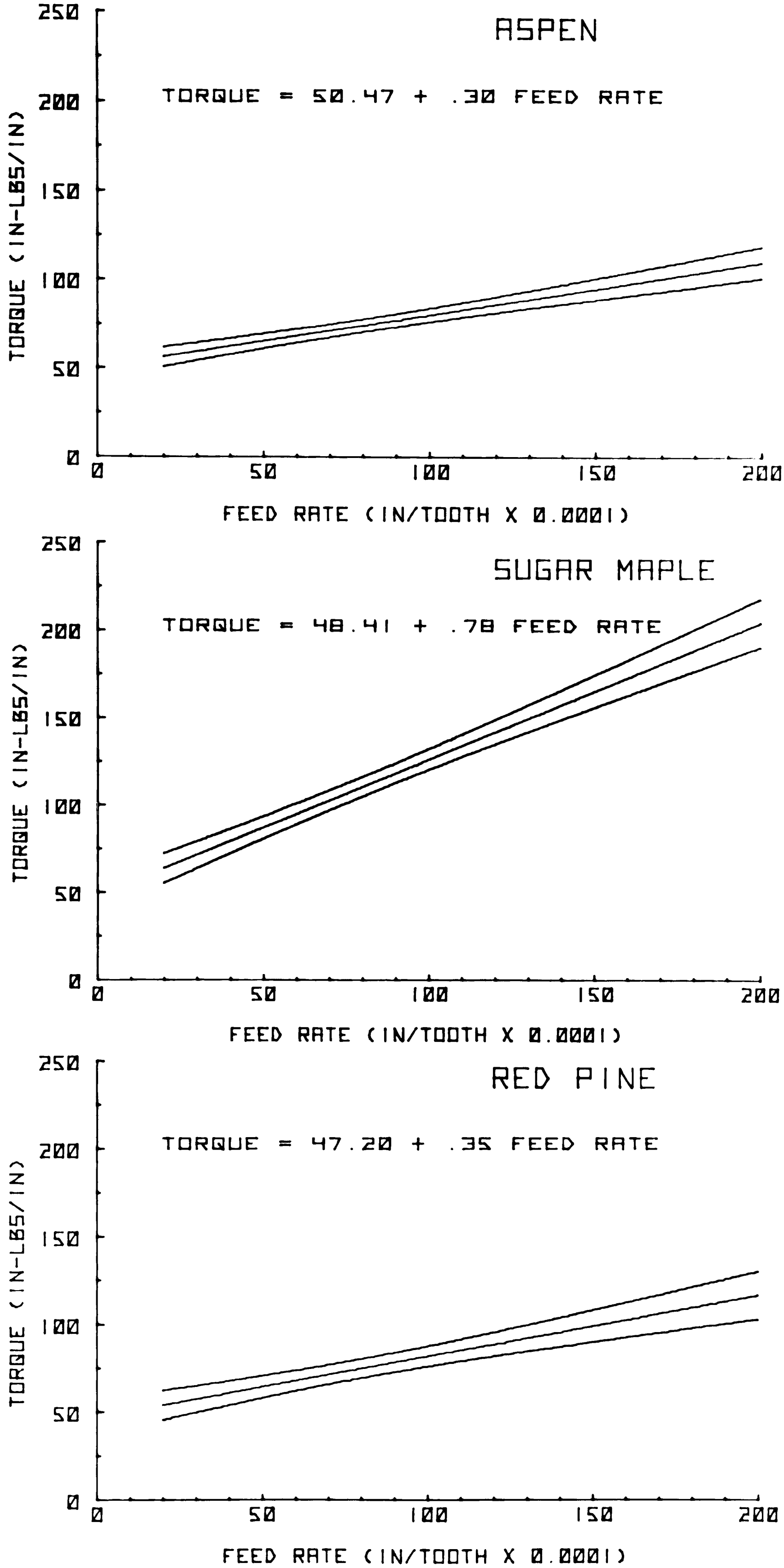

ASPEN
TORQUE = 50.47 + .30 FEED RATE
TORQUE (IN-LBS/IN)
0
50
100
150
200
250
FEED RATE (IN/TOOTH X 0.0001)
SUGAR MAPLE
TORQUE = 48.41 + .78 FEED RATE
RED PINE
TORQUE = 47.20 + .35 FEED RATE

Figure 25

Figure 26 Maximum horsepower vs. spindle rotational speed and table feed speed for green and frozen wood by species.

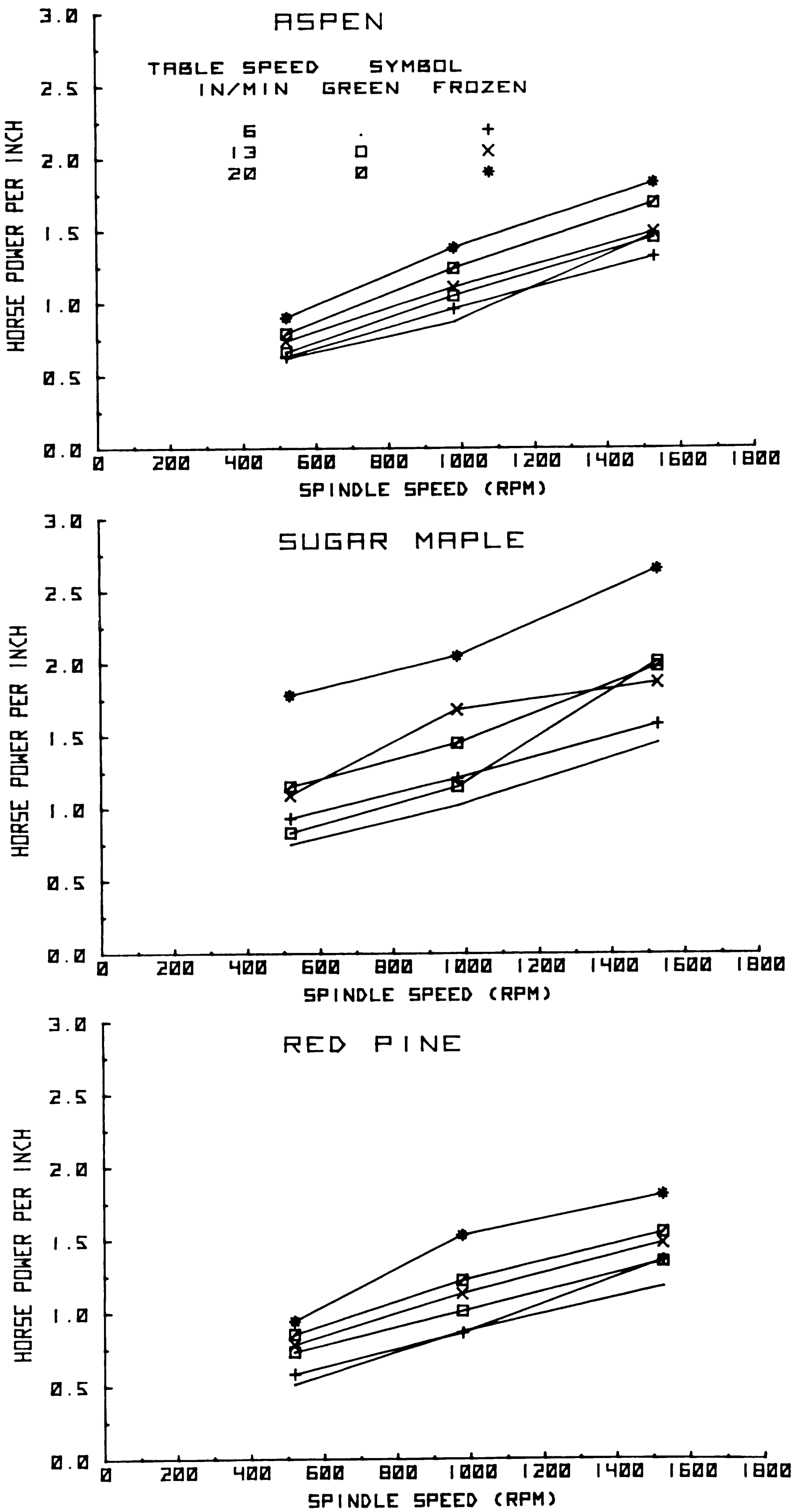

ASPEN
TABLE SPEED IN/MIN
SYMBOL GREEN FROZEN
6 . +
13 □ X
20 Ø *
HORSE POWER PER INCH
3.0 2.5 2.0 1.5 1.0 0.5 0.0
0 200 400 600 800 1000 1200 1400 1600 1800
SPINDLE SPEED (RPM)
SUGAR MAPLE
HORSE POWER PER INCH
3.0 2.5 2.0 1.5 1.0 0.5 0.0
0 200 400 600 800 1000 1200 1400 1600 1800
SPINDLE SPEED (RPM)
RED PINE
HORSE POWER PER INCH
3.0 2.5 2.0 1.5 1.0 0.5 0.0
0 200 400 600 800 1000 1200 1400 1600 1800
SPINDLE SPEED (RPM)

Figure 26

Figure 27 Maximum horsepower vs. feed rate by spindle rotational speed and table feed speed for green and frozen wood by species.

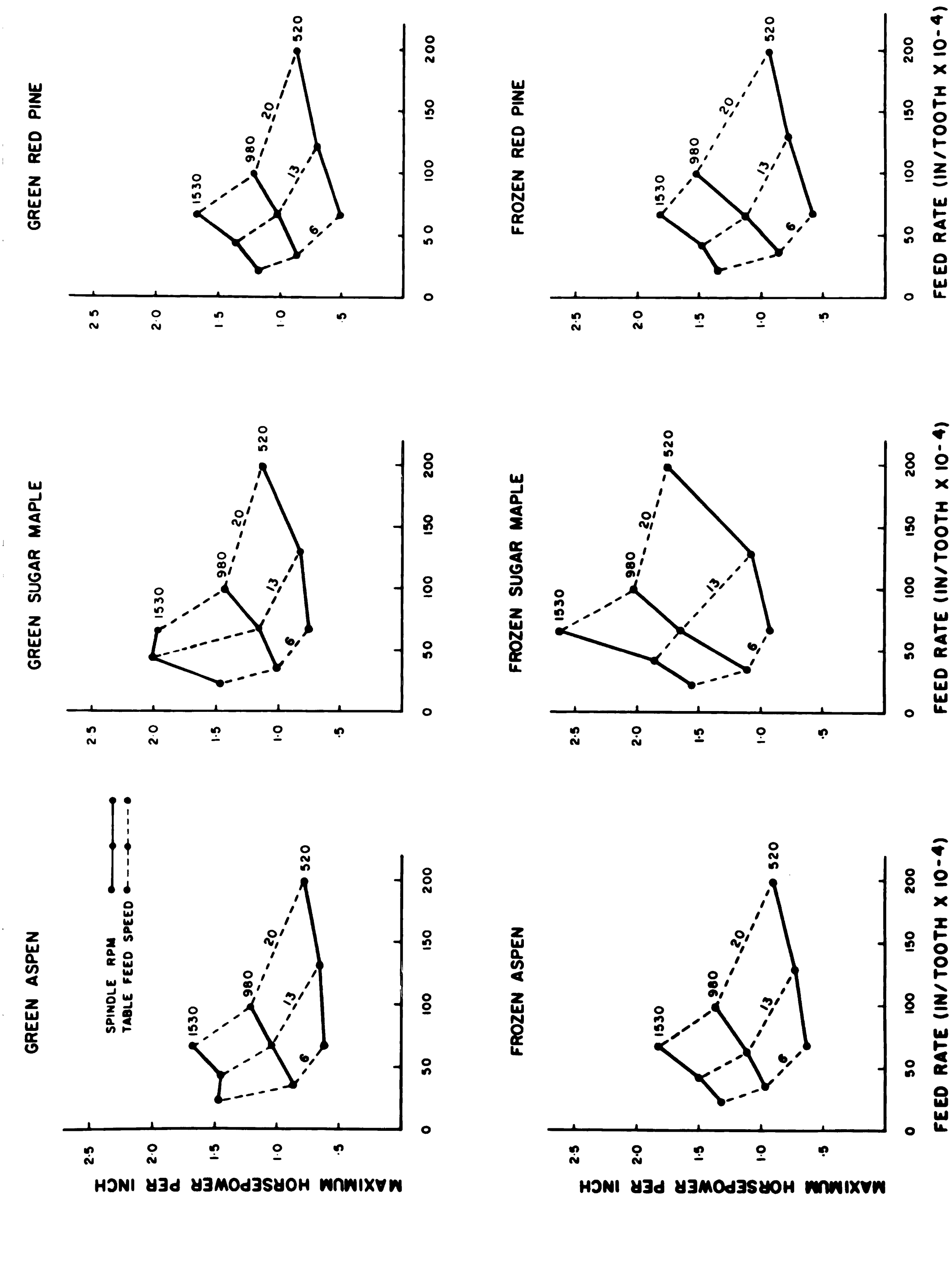

GREEN ASPEN
GREEN SUGAR MAPLE
GREEN RED PINE
FROZEN ASPEN
FROZEN SUGAR MAPLE
FROZEN RED PINE
SPINDLE RPM
TABLE FEED SPEED
MAXIMUM HORSEPOWER PER INCH
FEED RATE (IN/TOOTH X 10-4)
1530
980
520
20
13
6

Figure 27

A significant observation that can be made from this data is that at a given table feed speed, which is the speed at which the cutter is actually moving through the wood, the power requirement goes down significantly with increasing feed rate or decreasing cutter rotational speed. Associated with the increase in feed rate is an increase in the force loading on the cutter as seen in previous results, but a significant reduction in the horsepower requirement may have important implications for the total design of a felling device utilizing an auger cutter. Quite often, the total horsepower available for a given machine is the critical constraint around which the processing functions of the machine need to be designed. For instance, in the case of a swath harvester as discussed in the background section of this paper, the power source of the machine would have to power the cutting device and associated material processing equipment, as well as provide the motive power for the machine. The actual cutting of the wood would be a major consumer of the available horsepower, and thus any significant reduction in the power requirement of the cutter itself could have major impact on the total design.

ANALYSIS

Analytic analysis of wood machining processes has trailed the analysis of metal cutting operations, and has usually attempted to apply the basic techniques developed for metal cutting operations to the more complex problem of predicting the action of a tool penetrating wood. The major factor complicating the analysis of wood cutting is the anisotropic nature of wood which results in any analysis being specific to a particular orientation between the cutting device and the principal directions of the workpiece. Additionally, all previous analyses of wood machining operations have been directed at finishing operations such as planing where the primary variable of interest is the quality of the surface produced. This limits the applicability of previous works to the case at hand where surface finish is of little significance to the process.

Most wood machining operations can be considered as variations of two basic processes, orthogonal cutting and peripheral milling (13). Orthogonal cutting is that machining situation where the cutting edge of a straight tool is perpendicular to the direction of relative motion between the tool and work piece, and the surface generated is a plane parallel to the original work surface. Illustrative of this type of process is the carpenter's hand plane. Specification of the relationship between the cutting edge and the principal directions of the workpiece in orthogonal cutting is commonly based on a system devised by

McKenzie (14) where a two number system is employed (Figure 28). The first number gives the angle between the cutting edge and the grain direction of the wood, and the second number gives the angle between the velocity vector of the cutting edge and the grain direction of the wood. Thus, crosscut shearing of wood would be classified as a 90° - 90° cutting situation, planing with a hand plane is typically done in the 90° - 0° orientation, and rotary veneer peeling is done in the 0° - 90° orientation. Franz (7) investigated the 90° - 0° cutting situation extensively, while McKenzie (14) has done an extensive investigation of the 90° - 90° cutting situation.

The second basic cutting process, peripheral milling, is a rotary cutting process in which wood is removed in the form of single chips. These single chips are formed by the intermittent engagement with the workpiece of knives carried on the periphery of a rotating cutter head. The single surface rotary planer is illustrative of this type of process. Koch (12) has investigated this cutting process and has also compiled a thorough review of the information available on the basic cutting processes (13).

It is not the intent of this work to do a comprehensive review and analysis of the work which has been done in the area of wood machining. Rather, the findings and conclusions of several investigators will be related to the findings of this study, and their results used to explain and expand the work done here.

Analytic Methods

Because of the extreme anisotropy of wood, it is generally conceded that a general analysis of the process of chip formation in wood cutting is impossible. The common technique employed in most work has been to experimentally observe the mechanism by which individual chips are formed

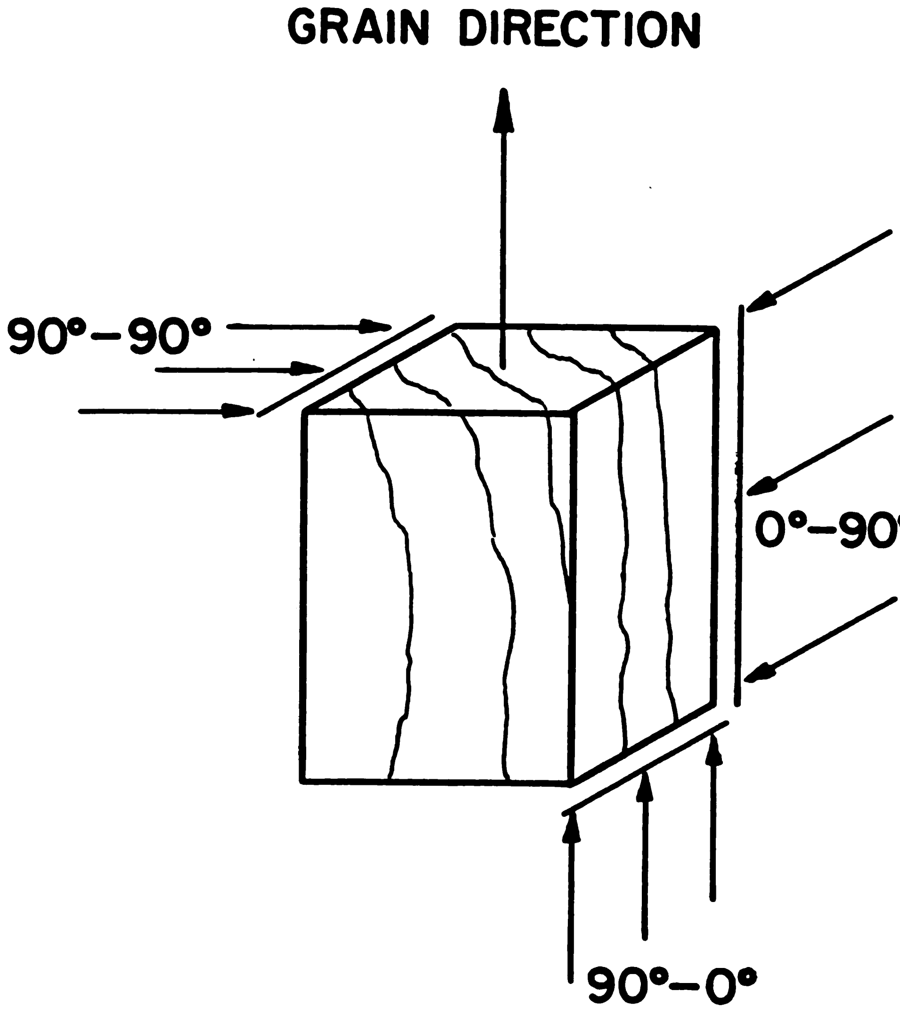


Figure 28 Principal configurations for orthogonal cutting of wood.

during the cutting operation and then through the use of an appropriate model, relate the resultant loadings on the cutter to the properties of the workpiece. This approach has also been useful in that the mechanism of chip formation also determines the quality of the resultant surface, and as previously stated, most wood machining operations previously analyzed have dealt with finishing operations where the quality of the surface finish is the primary variable of importance. Franz (7), McKenzie (14), and Stewart (20) have reported good results with this approach.

Application of this approach to this study was considered impractical for the following reasons. The cutting action involved in the auger cutting process is very complex compared to any analysis that have been previously made. Franz's analysis was on the 90° - 0°, or plane milling configuration, while McKenzie analyzed the 90° - 90°, or crosscutting configuration. The auger cutting operation is closer to the peripheral milling work of Koch, but because of the cutting direction being through the workpiece, it involves cutter contact throughout a 180° cycle of the cutter and a complex combination of orientations between the helical shaped cutter and the grain orientation, plus a continuously varying chip thickness which is not found in the orthogonal cutting situations.

The observation of the actual mechanism of chip formation is critical to this type of analysis of the wood machining process. In the studies done previously, the geometry of the cutting permitted the placement of a clear plastic plate adjacent to the workpiece through which the chip formation process could be viewed, and which served to contain the edge of the workpiece. The auger cutter with the helical knife configuration is not conductive to this type of visual observation. Restraining the edge is not practical because of the flow of chips in an oblique direction, and if the edge is not constrained, extraneous modes of chip formation can occur.

Chip Formation with the Auger Cutter

A detailed analysis of the mechanism of chip formation was not thought to be practical for the auger cutting process for the reasons listed above, but an overview of the process can help to explain the results obtained experimentally. Samples of the chips formed by the cutting process were collected during the test program for selected combinations of cutter rotational speed and table feed speed, and also for the twelve cutters studied. The sample blocks cut were also saved for later observation of the appearance of the cut surface.

Examination of the chips formed under the various cutting conditions showed very little change in the character of the resulting chips. Within an individual test there was a variety of sizes and shapes of the resultant chips but this would be due to the fact that the chip thickness varies continuously from zero to a maximum halfway thru the cutter cycle, and back to zero as each cutter flute completes a cycle. For comparison purposes a representative sample of the major chip type formed was sorted out for each test. Figure 29 illustrates the chip formation observed for aspen cut by the twelve cutters at the same feed rate conditions. It is seen that the basic form of the chips is very similar, and it can be concluded that the rake and helix angle combinations have little effect on the basic form of chip formation. The observation of the chips formed for the other species and the other feed rate conditions showed a similar effect of rake and helix angle.

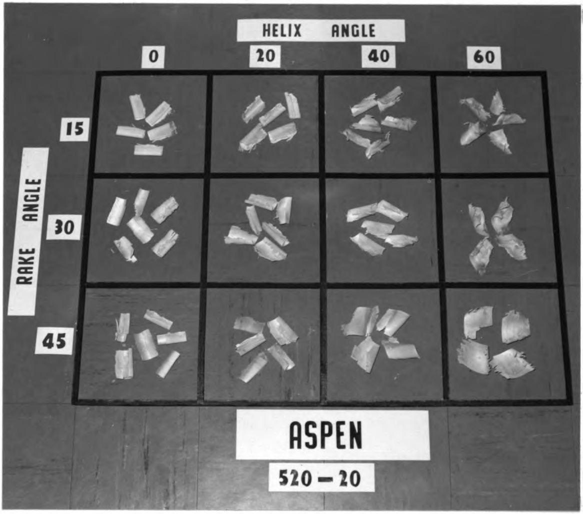


Figure 29 Chips formed when cutting aspen at a constant feed rate by rake and helix angles.

The effect of the feed rate combinations of table feed speed and cutter rotational speed on chip type are illustrated in Figure 30 for aspen cut with cutter 8. Again the basic chip form is similar but the size varies due to the difference in feed rate and thus the difference in chip thickness. The results again for other cutters and species were similar. From these results it may be concluded that for the range of conditions investigated in this work the basic chip form encountered does not change on the macroscopic level. Microscopic examination of the mechanism of chip formation may lead to other conclusions but was not investigated here.

Examination of the sample blocks saved showed a very similar pattern of cut surface over the test conditions. Referring to Figure 31 to identify zones on the cut surface of the sample blocks, zones 1 and 4 generally showed a smooth resultant surface due to the repeated action of shaving off very thin chips. These zones are not of particular interest because the primary cutting was done in zones 2 and 3. Zone 2 invariably showed a smooth cut surface while the resultant surface in zone 3 showed varying degrees of what might be referred to as torn grain. Figure 32 illustrates the appearance of the torn grain surface in a sample block.

On the suspicion that the marked difference in cut surface observed could be related to the force and power requirements of the cutting process, the strip chart recordings of all the test runs were analyzed to determine the locations where the maximum values of the loading occurred. Analyzing the maximum torque and coding the peak locations within the cutter cycle between 0 and 1, 0 being the initial point of zone 2, and 1 being the final point of zone 3, the results in Table 17 were obtained. This data shows that invariably the maximum torque values occurred in zone 3

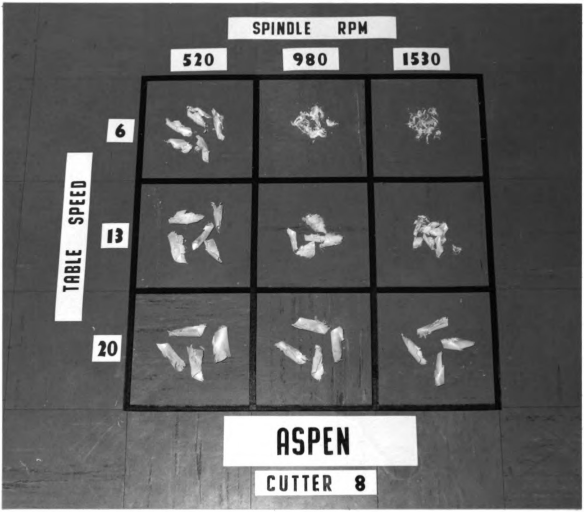


Figure 30 Chips formed when cutting aspen with cutter 8 by spindle RPM and table feed speed.

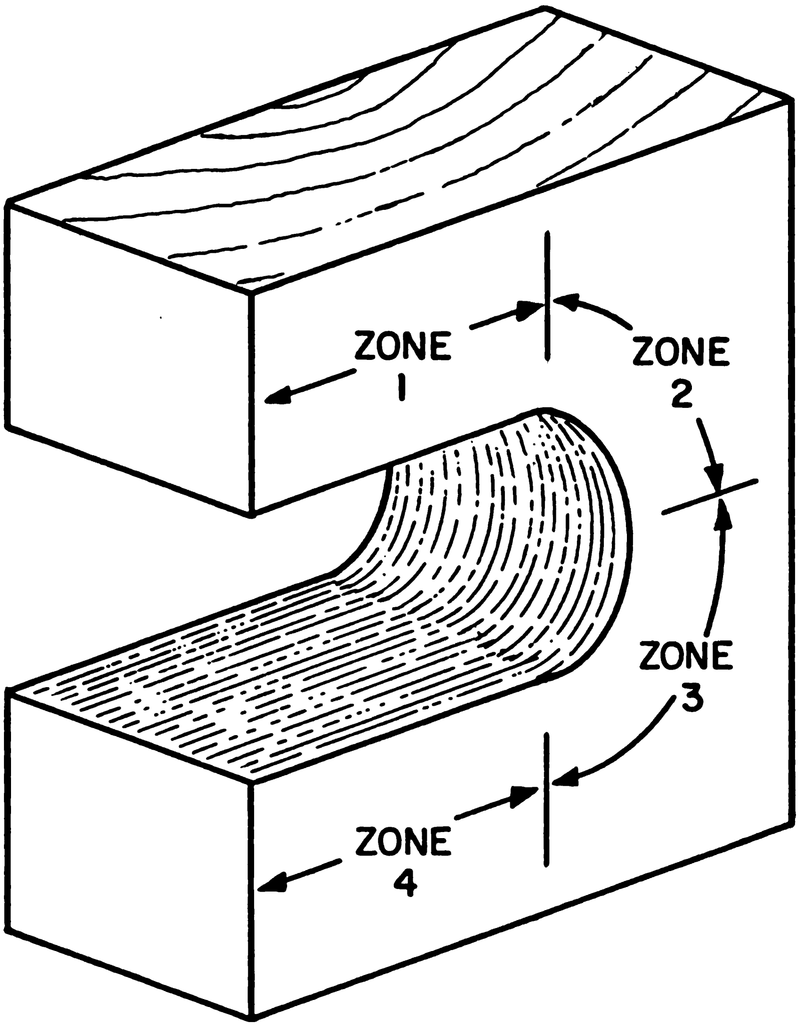


Figure 31 Identification of zones on cut surface of sample blocks.

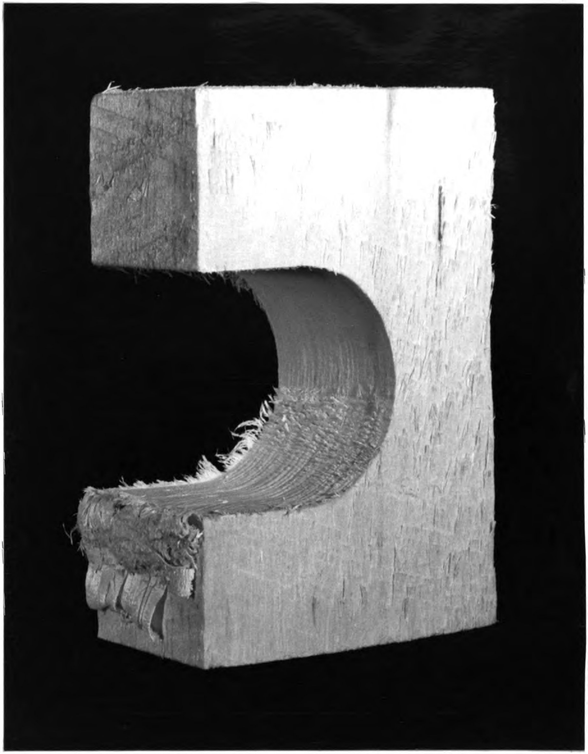


Figure 32 Appearance of torn grain in zone 3 of sample block.

Table 17. Location within cutter cycle of maximum recorded torque by spindle speed, table feed speed, and cutter.

		Table feed speed in/min.								
		6			13			20		
		Spindle rpm			Spindle rpm			Spindle rpm		
		520	980	1530	520	980	1530	520	980	1530
	1	.74 (.097)	.61 (.264)	.49 (.393)	.70 (.075)	.74 (.113)	.74 (.178)	.71 (.102)	.67 (.099)	.60 (.266)
	2	.65 (.213)	.47 (.322)	.38 (.324)	.67 (.223)	.64 (.216)	.64 (.310)	.74 (.091)	.67 (.154)	.54 (.272)
	3	.65 (.165)	.58 (.287)	.43 (.357)	.71 (.103)	.71 (.083)	.53 (.296)	.70 (.118)	.68 (.095)	.70 (.175)
	4	.72 (.086)	.73 (.071)	.64 (.265)	.68 (.134)	.67 (.098)	.72 (.117)	.72 (.077)	.67 (.074)	.72 (.107)
	5	.72 (.049)	.65 (.199)	.60 (.283)	.76 (.070)	.72 (.071)	.68 (.216)	.74 (.057)	.73 (.063)	.75 (.098)
Cutter	6	.67 (.111)	.64 (.230)	.65 (.272)	.72 (.141)	.64 (.166)	.64 (.243)	.74 (.048)	.72 (.071)	.71 (.172)
	7	.59 (.368)	.52 (.412)	.44 (.433)	.71 (.172)	.59 (.371)	.66 (.374)	.75 (.062)	.76 (.114)	.60 (.362)
	8	.73 (.062)	.70 (.161)	.62 (.283)	.78 (.040)	.74 (.115)	.78 (.094)	.78 (.056)	.73 (.130)	.77 (.146)
	9	.69 (.186)	.70 (.209)	.45 (.326)	.76 (.076)	.76 (.073)	.54 (.309)	.75 (.128)	.58 (.271)	.66 (.230)
	10	.77 (.170)	.72 (.181)	.72 (.145)	.69 (.207)	.75 (.171)	.78 (.149)	.66 (.156)	.75 (.201)	.72 (.157)
	11	.67 (.168)	.80 (.152)	.73 (.187)	.72 (.206)	.74 (.187)	.67 (.152)	.74 (.209)	.66 (.168)	.72 (.162)
	12	.75 (.210)	.82 (.185)	.75 (.195)	.70 (.267)	.75 (.203)	.71 (.200)	.64 (.183)	.70 (.312)	.71 (.191)

First entry is average value over species and green and frozen wood. Number in parenthesis is standard deviation.

where the occurrence of the torn grain was observed.

The relationships between the cutter and the principal directions of the workpiece are very complex in zone 3 but these results can be related to the conclusions developed by McKenzie in analyzing the 90^{o} - 90^{o} cutting configuration (15).

Microscopic examination of the action of a cutting edge by McKenzie has shown two stages in what is referred to as the "indentation" stage of cutting. In the first stage the wood is deformed or deflected before the edge without apparent rupture, and in the second, rupture occurs to separate the chips from the workpiece along the cutting plane. This second stage is referred to as the "incision" stage of the cutting. In the case of a cutter which is ideally sharp, the indentation stage would be minimal as the ideally sharp cutter would produce a stress intensity much in excess of the strength of the material and rupture of the individual fibers would be immediate. However in practical situations, ideal sharpness is never achieved and on the microscopic level a certain degree of bluntness is alway present. Thus, under normal cutting circumstances wood deflection becomes significant before fiber severance occurs. The wood immediately in front of the cutter is deflected and the bending stresses build up until the stress on the fibers is sufficient for severance to occur. The force then drops off until a new deflection stage begins and the fiber deflection begins to build up again. Figure 33 taken from McKenzie, illustrates the progression through the indentation stage of cutting.

The interaction between the parameters of the cutting edge and the properties of the workpiece then determine the mode by which failure occurs at the cutting edge. If the combination of properties is such

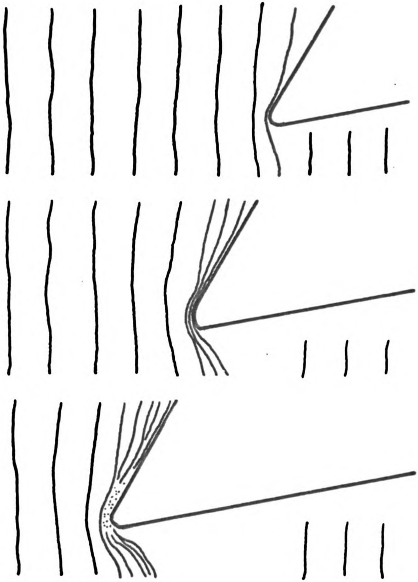


Figure 33 Schematic of indentation stage of cutting wood.

that incision occurs before the deflection proceeds far enough to build up the tensile stresses in the fibers to their limit, then the wood fails by fiber severance at the cutting edge and the resultant cut surface is uniform. This is labeled a type I failure by McKenzie. This type of failure was shown by McKenzie to be characterized by a normal stress which has the tendency to pull the cutter into the wood.

If the conditions are such that the mode of failure is by the buildup of tensile stresses in the fibers to their ultimate strength before incision severs the fibers, then the condition of torn grain appears. This is classified as a type II failure by McKenzie. This type of failure produces a very poor surface finish and is characterized by a normal stress which tends to pull the cutter away from the workpiece. The type II chip involves higher cutting forces as more energy is required to deflect the fibers and raise the bending stress to their ultimate limit.

As previously stated, the cutting configuration in zones 2 and 3 are a more complex situation than that studied by McKenzie but is partially related. At the initial point in zone 2, with a 0° helix angle cutter, the cutting would be in the 90° - 90° orientation as studied by McKenzie. As the cutting edge moves through zone 2, the configuration would move to a 90° - 0° orientation at the end of zone 2. As the cutter progresses through zone 3, the cutting configuration would shift back to 90° - 90° at the end of zone 3. Inclusion of a helix angle on the cutter would complicate the configuration, and this effect will be discussed subsequently.

Considering the geometry of the auger cutter, it can be deduced that the cutting action in zone 2 is such that the cutter is driving into the wood. This would have effect of creating a normal stress into the workpiece, and related to the findings of McKenzie should tend to create a type I chip and a good surface finish. This is the type of surface which was found in the sample blocks, and analysis of the force patterns found in the cutting cycle such as are illustrated in Figure 10 bear out this description of the force directions. The geometry would indicate that in zone 3 the cutter would be pulling out of the wood which would create a normal stress tending to pull up on the workpiece. The result would be a type II chip form and the resulting torn grain appearance. The force patterns and the observed surface again bear out this contention.

Concluding that the observations made in this study agree with the conclusions of McKenzie made on a microscopic study of cutting wood in a 90^o - 90^o orientation, several of McKenzie's deductions are significant to the analysis of the auger cutter.

As a means of promoting the type I chip with its lower force requirements and better surface finish, McKenzie tried inducing a lateral velocity component to the cutting edge by vibration. The results of this experiment and the following study by McKenzie and Franz (16) were that the addition of a lateral velocity component improved the surface finish and reduced the forces measured. These results bear out the results obtained in this work on the effect of the helix angle. Inclusion of the helix angle has the effect of creating an angle between the cutting edge and the feed direction thus effectively creating a velocity component along the cutting edge. The results shown for the maximum torque vs. helix angle in Figures 14 and 15 reflect these results. Visual observation of the sample blocks saved from the tests also support this contention, as the amount of torn grain is evidently reduced by the inclusion of the helix angle.

McKenzie's results also showed a small improvement in surface finish with higher rake angles. This is credited to the creation of a sharper edge which would facilitate the quicker incision of the wood. However, the benefits of a higher rake angle are not very significant in that it is the shape of the microscopic cutting edge that had the most bearing on the chip formation. This result is also supported by the findings of this study where increasing rake angle has the effect of lowering the resultant forces observed but not significantly. This result also supports the earlier decision to select a cutter with a 30° rake angle as preferred over one with a 45° rake angle.

McKenzie also found an improvement in the cutting was possible through lubrication of the cutting edge with SAE 30 oil. This possibility was not investigated here, but should be considered as a possibility when considering the design of a tree felling apparatus.

DISCUSSION

The objective of this study was to evaluate the major parameters which affect the auger cutting process as it may be applied to tree felling devices and document the force and power requirements of the cutting as a function of the major variables. The focus of the study was on the cutter parameters, rake and helix angle; the machine variables, cutter rotational speed and feed speed; and the workpiece parameters, species and temperature of the wood being cut.

The range of rake and helix angles studied covers the practical range for this application. It was found that increasing values of rake angle consistently decreased the forces and power requirements of the cutting. However, increasing the rake angle decreases the sharpness angle, which is the included angle of the tooth of the cutter, and it is the sharpness angle of the cutter which would become the limiting value. In practical situations experience has shown that with a sharpness angle less than 45 degrees, and the resulting fine edge, the cutter is difficult to maintain. The conclusion was that a 30 degree angle was an optimum value.

Increasing values of the helix angle produced a linear increase in the maximum axial force recorded up to a value of 40 degrees, and simultaneously produced a decrease in the maximum torque recorded. For helix angles above 40 degrees, the rate of increase in the axial force accelerated and the maximum torque leveled out or increased.

Thus helix angles above 40 degrees do not appear to be beneficial, and an optimum cutter geometry appeared to be a 40 degree helix angle and a 30 degree rake angle.

Several parameters of the auger cutter which were not studied in this work should be commented on. The cutter diameter is a significant parameter in that the torque on the cutter will be directly proportional to the diameter. Increasing the diameter will create a larger cross section to support the loading on the cutter but will also increase the resultant torque. A need exists for an analysis of the stress created on the cutter, and a determination of an optimum cutter diameter. This was not undertaken as a part of this work, but the data presented in this study would permit such an analysis to be made.

The cutters used in this study all were constructed with two flutes to minimize the confusing effect of having more than one flute cutting simultaneously. However, for a practical device, the possibility of using more than two flutes should be considered. The cutting action of this type of device creates very cyclic loading when considering the action of a single flute. The use of 3 or possibly 4 flutes on the cutter could have the effect of balancing the loading and reducing the wide fluctuation observed on a single flute. This would have significant beneficial effects regarding the fatigue strength of the cutter.

The configuration of the cutter cross section was not evaluated in this study. The shape of the cross section, particularly in the area just below the tooth, could have a significant effect on the ability of the cutter to convey the cut chips out of the cutting zone. If the auger cutter were used on a very wide material, the ability to clean the chips out of the cutting zone, and thus avoid plugging of the cutter, would be of significance. The small sample width used in this study, because of machine limitations, precludes any analysis of this problem, but it is an item which needs to be considered in any subsequent design of an auger cutting device.

The investigation of the machine variables, cutter rotational speed and feed speed, covered a range of 500 to 1500 rpm for the cutter rotational speed, and 6 to 20 inches/minute for the feed speed. The significant finding was that the cutter rotational speed and the feed speed could be combined into a single parameter, feed rate, expressed as the feed per tooth, and the loadings on the cutter related to this one parameter. The range of feed rates studied, 22×10^{-4} to 200×10^{-4} inches/tooth, is felt to cover the practical range for this type of device. The two main loadings on the cutter that were analyzed in this study, the maximum axial force, and the maximum recorded torque, were found to be linearly related to the feed rate (Figures 22, 23, 24 and 25).

The power requirement of the cutting was found to be dependent on both the cutter rotational speed and the feed speed, rather than only on the feed rate (Figure 27). It was found that at a constant feed speed, or rate at which the cutter is actually moving through the wood, the horsepower requirement decreases with increasing feed rate. That is, the power requirement can be reduced by decreasing the cutter rotational speed while still maintaining a constant feed speed through the workpiece. This finding is contrary to commonly held beliefs and could have significant implications for the design of a cutting device utilizing the auger cutting concept, since total horsepower requirement is frequently a major constraint in the total design of a felling device.

The three species of wood used for sample material in this study, sugar maple, aspen, and red pine, illustrate the range of results that will be obtained with varying species. The species selected are three that the auger cutter could be used on, and therefore, in these cases, the results would be directly applicable. If other species are of interest, then additional work would be required. As noted in the results of this study, the mechanical strength of wood, and the force requirements for cutting wood vary directly with the specific gravity of the wood. Additional study could possibly relate the variables of interest in the cutting process to the specific gravity of the wood being processed. If this type of relationship could be shown, then the required data on cutting a wide range of woods would be available by knowing only the specific gravity of the wood, which is commonly available for most species.

The effect of the temperature on the cutting results should also be expanded. The results of this work showed a 20 - 25% increase in forces from cutting at room temperature to cutting samples which were frozen and held at 30 degrees F. Additional work needs to be done to document the results at other temperature levels, particularly colder temperatures since the auger cutter could well be used in cold climates where temperatures could reach extremely low levels.

An overview of the process of chip formation in wood cutting has helped to correlate the results obtained in this study with those obtained by other investigators who have looked at the more basic aspects of wood cutting. The location of the peak forces obtained in this work can be explained by the mode of chip formation in the varying zones of the cutting process. The effect of the helix angle which was seen in this work also has basis in the literature. A needed expansion of this work is to expand the basic mathematical models of chip formation which have been developed for the basic cutting processes to the more complex case of the auger cutting process. A successful model of the basic mechanism of the auger cutting process could lead to further refinements and greater efficiency in applying the auger cutting concept to practical cutting situations.

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