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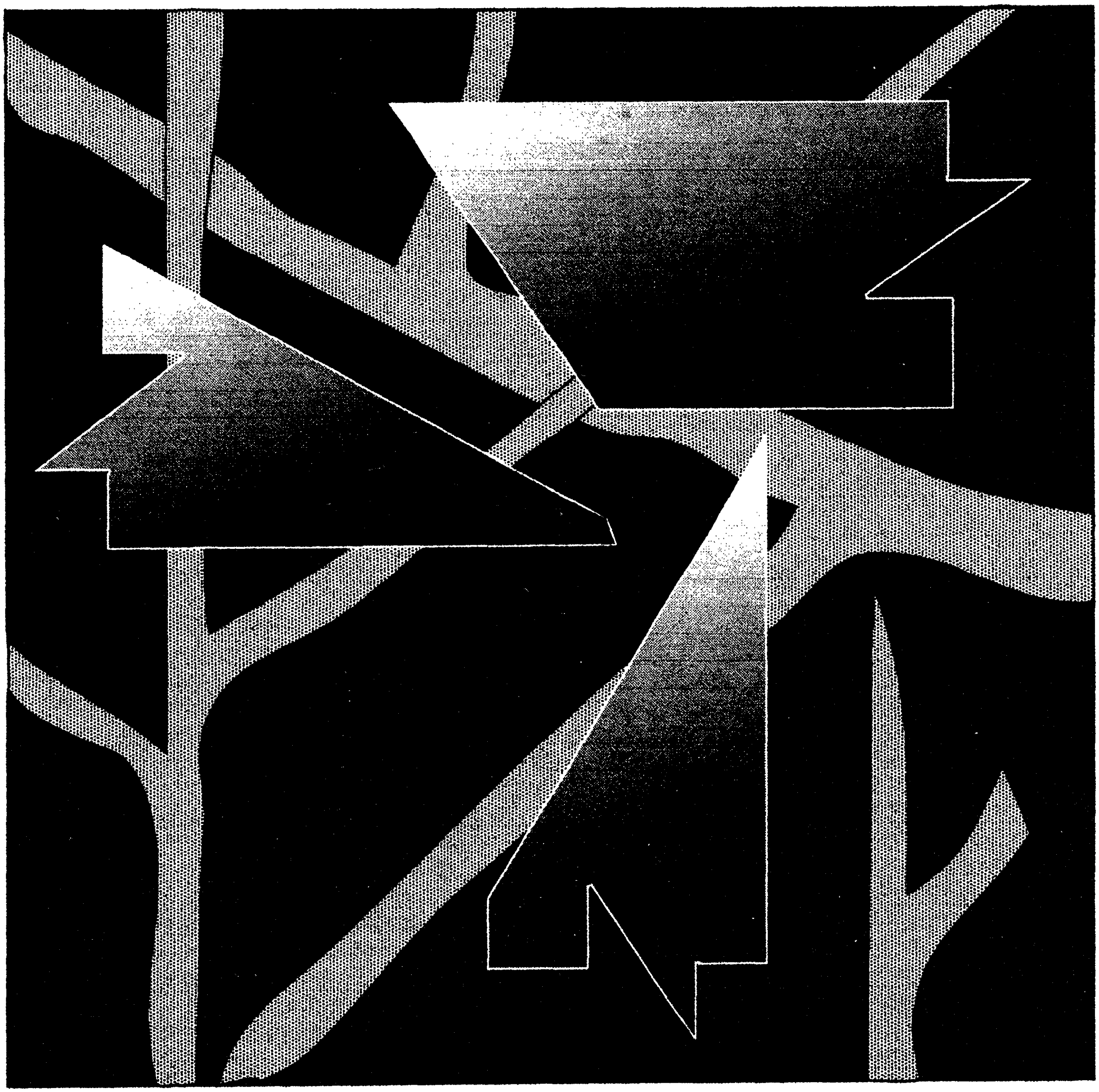

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Reducing The Forces Required To Delimb Hardwoods

James A. Mattson and Joseph B. Sturos

Society is creating additional demand for commodity outputs from our forest resources. The Nation's consumption of wood products is projected to increase by 50 percent in the next 50 years (U.S. Department of Agriculture, Forest Service 1989). The demand for both wood products and noncommodity values from the forest resource, while not mutually exclusive, will undoubtedly mean that the forest lands on which timber is produced will have to be managed more carefully and efficiently.

About 80 percent of the forests in the northeast region are hardwoods, which have the potential to grow very high-value veneer and sawtimber. In addition, new technologies have been developed that make the lower quality products of these hardwood forests attractive as raw material for fiber-based products and composite wood materials.

Hardwood forests that are managed for timber production require periodic timber harvest (Erdmann 1986). Uneven-age silvicultural systems prescribe periodic selection harvests, designating the removal of a variety of tree sizes and products. Even-age silvicultural systems prescribe a series of thinnings designed to remove poor-quality trees, undesirable species, and the excess basal area, typically as pulpwood.

In either management system, the quality and productivity of the remaining trees and site must be protected. The need to protect the site and residual stand, low harvest volumes per acre, and typically low product values in thinning operations increase the difficulty of these intermediate cuts in hardwood stands for the logging industry (Winsauer and Mattson 1987). The need to maintain recreational, wildlife, aesthetic, and cultural values of the stands will complicate the harvest of these stands.

The logging industry has undergone radical changes in recent years. Historically, logging has been labor-intensive, using large numbers of semiskilled workers to do most of the work involved in producing timber products. Felling the trees, removing the limbs, and cutting the boles into the desired products have typically been done manually. Only the removal of trees from the stand was accomplished with animal or machine power.

In the last 20 years, much of this manual labor has been replaced with mechanized operations for two reasons. First, the labor force has been decreasing as potential workers choose to take jobs in other industries, often for higher pay and benefits. Second, hazardous working conditions and high accident rates have made workmen's compensation rates for logging businesses among the highest. These high costs have forced the logging industry to shift toward more mechanized operations that require fewer employees.

Currently available mechanized harvesting equipment is not ideally suited for hardwood thinning operations. Most currently available tree harvesting machines use some form of delimbing knives to cut off the branches. This technique has been shown to work well with the branches found on softwoods, but is still questionable with hardwoods. Many of the available harvesters can, in fact, delimb hardwoods to varying degrees, but they may not be able to hold up mechanically over the long term if subjected continuously to high-density hardwood trees with large branches. Because most forestry machines are initially developed by small companies with limited resources, the industry has

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little capability to systematically pursue possible solutions to the delimbing problem.

Current scientific literature is nearly devoid of information pertinent to the delimbing of hardwoods. An exploratory study of delimbing typical northern forest species using a rotary cutter was reported by Christopherson (1984). In Sweden, a study of possible improvements to delimbing technology for hardwood species common to Scandinavia was found to be inconclusive (Scherman 1989). Koch (1985) also found little in the research literature about using shears to fell and/or delimb southern hardwoods. Citing other works involving knives to shear other species (mainly softwoods), Koch made the following generalizations: the shearing forces are less for unfrozen wood, clear wood, low-density wood, perpendicular to annual rings (parallel to grain), a Teflon-coated blade, a thin blade, a vibrating blade, negative blade taper, and oblique cutting angle; the shearing forces are not significantly affected by shearing velocity, a greased blade, or a V-notched blade.

We conducted a study to determine which machine parameters can be varied to reduce the force and power required to delimb hardwoods.

METHODS

The basic approach of our study was to use an instrumented test fixture to measure the force required to push a knife blade through a stationary branch. Controlled laboratory testing was used to determine the effects of various blade, branch, and machine variables.

To establish a realistic range of values for the study, we surveyed users of several different commercially available tree harvesting machines. Blade cutting edge angles were found to range from about 35° to 60° included angle; blade thickness ranged from three-eighths to one-half inch; and delimbing speed ranged from about 1,500 inches/minute to 3,000 inches/minute. In addition, 3 inches was about the largest diameter of sugar maple branch that most operators recommended removing by delimbing knife.

The test fixture consists of two main parts, a stationary base and a moving blade carriage assembly (fig. 1). The base is designed to hold either a 6-foot-long bole segment with an attached branch segment, or a sapling or small bole section as a simulated branch. The moving blade carriage assembly glides on four linear ball

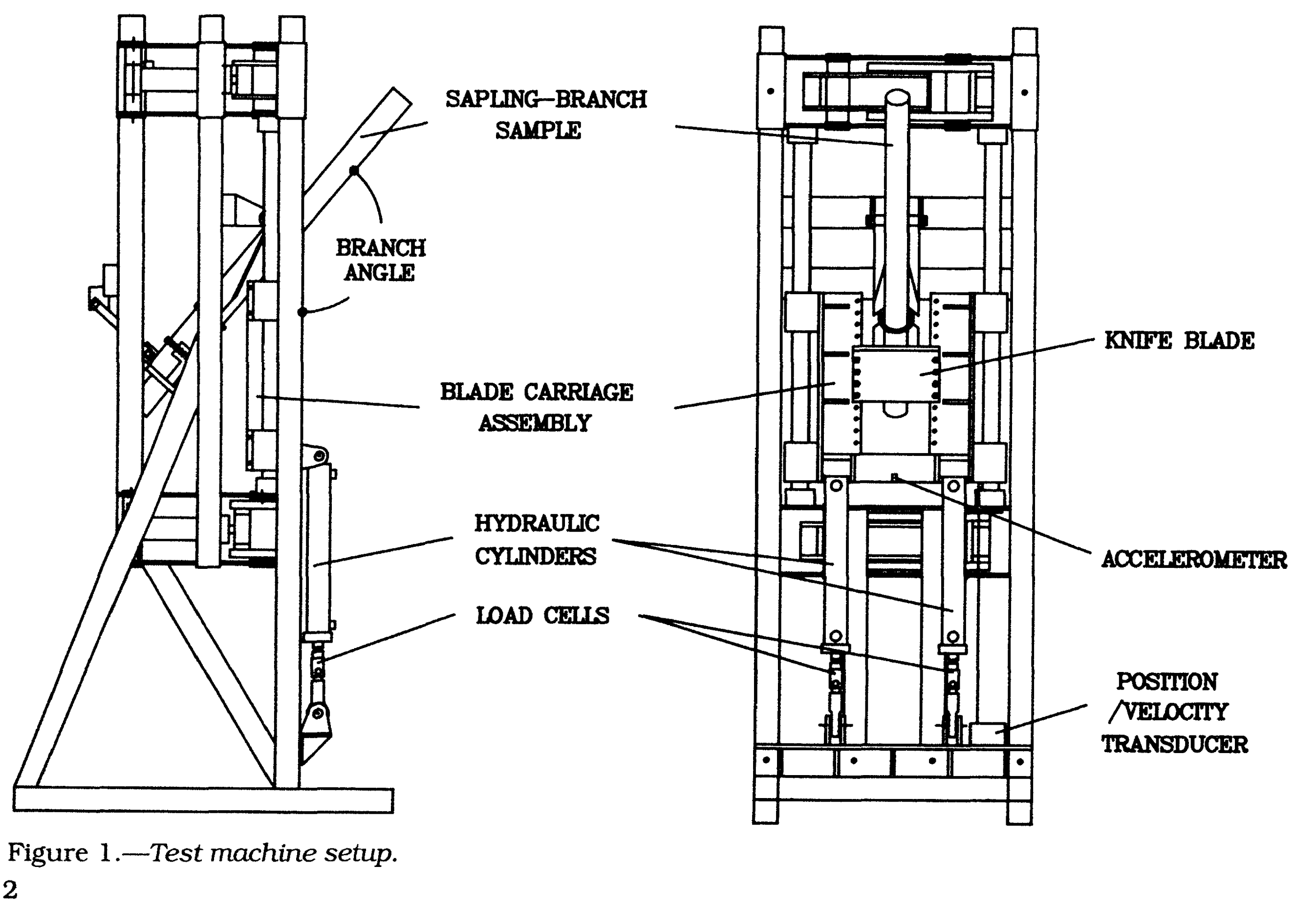

Figure 1.—*Test machine setup.*

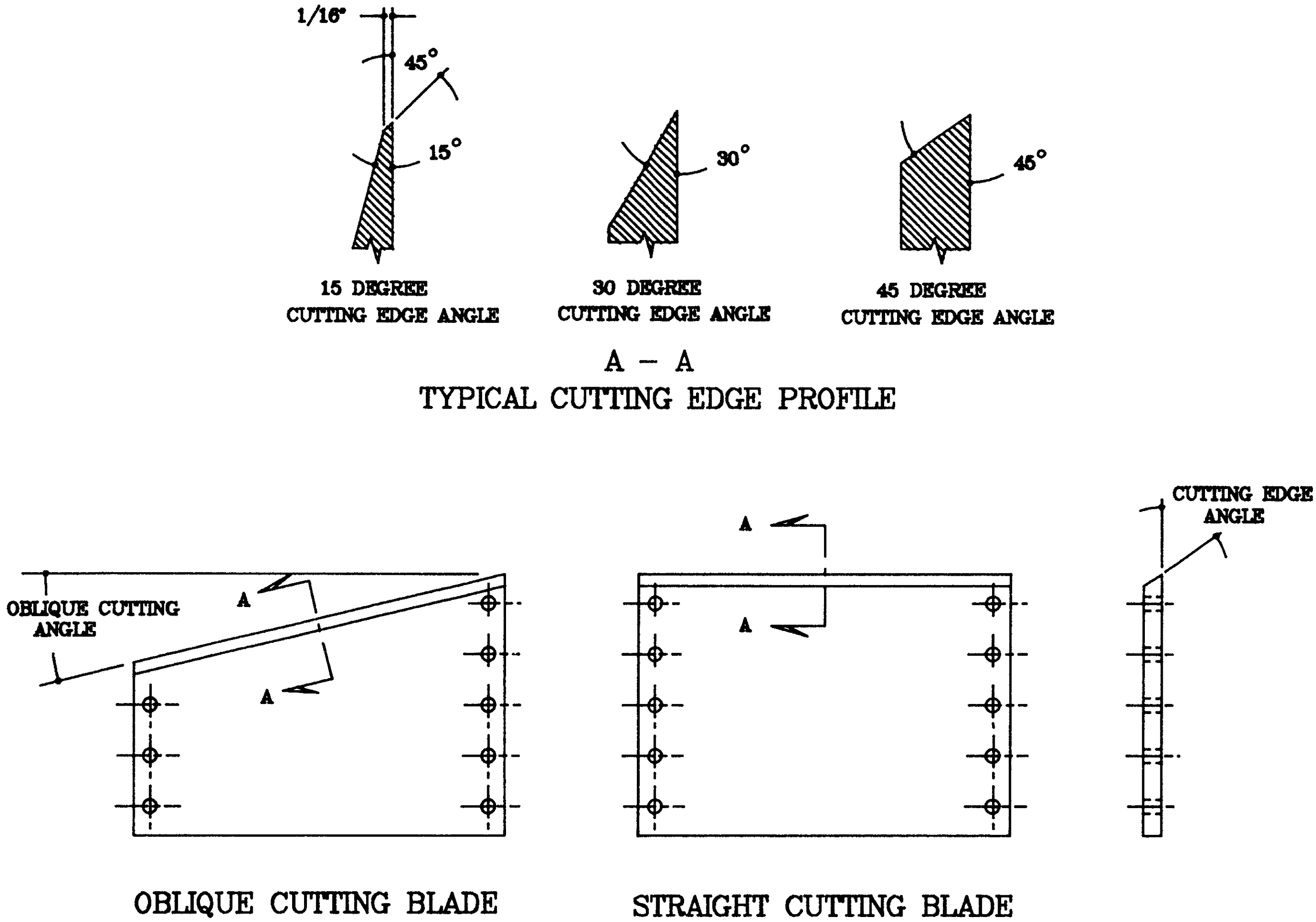

Figure 2.—*Test blades used.*

bearings. The bearings minimize the energy losses due to side loads. The blade assembly is driven by two 2.5-inch-diameter hydraulic cylinders and a 95-gpm, 3,000-psi hydraulic power supply. This configuration can generate 29,000 pounds of delimbing force at a maximum speed of about 2,800 inches/minute. For this study, three speeds of 1,500, 2,000, and 2,700 inches per minute were used. This choice of speeds covers the range typically found in commercial units.

Although most commercial delimbing knives have some curvature to them, we used flat blades in this study to facilitate blade fabrication and consistent resharpening. The basic blade is 7 inches long and 11 inches wide. Three blade thicknesses were used in the study, one-fourth, three-eighths, and one-half inch; three cutting edge angles, 15°, 30°, and 45°; and four oblique cutting angles of 0°, 15°, 30°, and 45°. Figure 2 illustrates the typical blade geometry. Note that the 15° cutting edge is actually a double bevel. Prior experience has shown that a 15° single bevel clear to the cutting edge will not hold up. The leading edge will either bend or break. To provide adequate support to the leading edge, we added a 1/16 inch x 45° secondary bevel. The test blades were made of 4140 alloy steel heat treated and tempered to approximately 45 Rc hardness.

Blade dulling is an uncontrollable variable. McKenzie and Cowling (1971) reported that minute fracturing or dulling occurs rapidly during the first few cuts and then slows as an equilibrium is reached. To minimize the effects of knife dulling, we took two measures. First, a newly sharpened blade was used for each new test sequence. Secondly, sample selection was randomized to distribute any effects of wear throughout the sample group.

The force developed during the delimbing was measured by two T-HYDRONICS[1] Model TC-S 20,000-pound load cells attached to the hydraulic cylinder rod ends. Knife position and velocity were measured using a MagneTek Model PV-30A-100G position/velocity transducer. A Kistler Model 818 piezoelectric accelerometer coupled to a Kistler Type 5002 dual charge amplifier was used to measure blade assembly acceleration.

A high-speed, computerized data acquisition system was used to record the transducer signals. The system consisted of an IBM-AT computer with an internal Keithley Model DAS-16G high-speed 16 channel multiplexed data acquisition board, and an external Keithley Model EXP-GP 8 channel resistance measurement accessory board. The EXP-GP board was used to excite, signal condition, and multiplex the transducer signals to the DAS-16G data acquisition board. Cylinder thrust forces, blade position, blade velocity, blade assembly acceleration, and moment of contact were recorded at a sampling rate of 1,000 samples per second.

To keep the total number of tests within practical limits, we tested only sugar maple (*Acer sacharum*). Sugar maple is the most common northern hardwood and is one of the higher density, more difficult species to delimb. Fresh, green sample material was used for the testing.

Ideally, actual tree branches would be used for testing, but two problems are associated with using actual tree branches. First, the angle between the branch and the trunk is an uncontrolled variable that would tend to confound the results. Secondly, a large number of tests and the need for replication make sample procurement difficult and wasteful, particularly in the larger branch sizes where relatively large trees would have to be sacrificed. To solve these problems, we used saplings and pole-size trees to simulate test branches.

Saplings and pole-size trees are readily available and, because of their symmetrical shape, probably have less locked-in growth stresses than cantilevered branch wood. Easy-to-obtain samples permit more replications, and more uniform specimens should reduce the random variability in the test results. Statistically, more replications and less variability will help to strengthen any conclusions about differences between the various designs (a key objective of the study).

To explore the advisability of substituting saplings for actual branches, we made a series of comparative tests. Eighteen branches (still attached to a 6-foot section of trunk) were sheared using the test machine described above. Then, 15 saplings were selected to match 15 of the branch diameters and sheared at identical angles, using a special adjustable holder. The branch diameters ranged from 2.5 to 4.7 inches, and the branch angles (the angle between the branch centerline and the lower trunk) ranged from 137° to 167°. The tests were all conducted using a 1/2-inch-thick blade sharpened to a 45° cutting edge angle and run at a speed of 2,000 inches/minute.

A plot and regression analysis of the 34 tests revealed that branches and saplings exhibit similar, though not identical, average cutting force characteristics (fig. 3). For branch angles from 137° to 153°, both branches and saplings require decreasing average cutting force for increasing branch angle, with saplings generally requiring less force. From 155° to 168°, both branches and saplings appear to be minimally affected by increasing branch angle. A paired difference t-test on these 15 pairs confirmed that there is a significant difference (at the 0.05 alpha level) between branches and saplings with respect to both average cutting force and average cutting force per inch of diameter.

Nonetheless, we felt that over the range of interest for this study, namely, 3 to 5 inches for branch diameters and 130° to 150° branch angle, there was sufficient similarity in the shearing force plots to support the use of saplings for the study.

MAIN TEST PLAN

We chose five independent variables to study: blade thickness, blade cutting edge angle, oblique cutting angle, cutting speed, and branch diameter. However, it would be too expensive and time consuming to test these variables in a full factorial design with replication. Therefore

[1]*Mention of trade names does not constitute endorsement by the USDA Forest Service.*

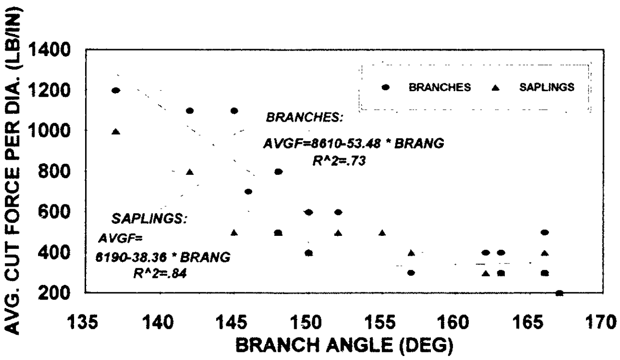

Figure 3.—*Test results and regression lines for exploratory tests comparing average cutting forces for actual tree branches and for sapling-simulated branches. Tests were run using 1/2-inch-thick blade with a 45° cutting edge angle, 0° oblique cutting angle, and 2,000 inches/minute cutting speed.*

we decided to limit the factorial experimentation to two variables—blade thickness and cutting edge angle—because they are important in terms of knife strength and durability and can be interrelated. The other three variables—oblique cutting angle, cutting speed, and branch diameter—were investigated independently by varying the parameter of interest while holding the other parameters fixed. For all tests, the branch angle was held constant.

Based in part on the informal user survey mentioned above, the following series of tests was devised:

I. Blade cutting edge angle vs blade thickness factorial
   Variables:
      Blade thickness: 1/4, 3/8, 1/2 inch
      Blade cutting edge angle: 15°, 30°, 45°
   Constants:
      Oblique cutting angle: 0°
      Cutting speed: 2,000 inches/minute
      Sapling-branch diameter: 3.0 to 3.4 inches
      Branch angle: 140°

II. Oblique cutting
   Variable:
      Oblique cutting angle: 0°, 15°, 30°, and 45°
   Constants:
      Blade thickness: 1/2 inch
      Blade cutting edge angle: 45°
      Cutting speed: 2,000 inches/minute
      Sapling-branch diameter: 3.0 to 3.4 inches
      Branch angle: 140°

III. Cutting speed
   Variable:
      Speed: 1,500, 2,000, 2,700 inches/minute
   Constants:
      Blade thickness: 1/2 inch
      Blade cutting edge angle: 45°
      Oblique cutting angle: 0°
      Sapling-branch diameter: 3.0 to 3.4 inches
      Branch angle: 140°

IV. Sapling-branch diameter
   Variable:
      Sapling-branch diameter:
         4 classes: 2.5 to 2.9, 3.0 to 3.4, 3.5 to 3.9, 4.0 to 4.4 inches
   Constants:
      Blade thickness: 1/2 inch
      Blade cutting edge angle: 45°
      Oblique cutting angle: 0°
      Cutting speed: 2,000 inches/minute
      Branch angle: 140°

RESULTS AND DISCUSSION

One of our objectives was to find ways to reduce the forces required to remove limbs from sugar maple using delimbing knives. We used analysis of variance to determine which of the factors studied caused significant differences in the average cutting force.

Because integration has a smoothing effect, average cutting force was chosen as the main measure for the study. Average cutting force was derived by dividing the area under the total cutting force vs. displacement curve by the total length of cut, where total cutting force was the sum of cylinder thrust force and the effective mass of the blade carriage assembly multiplied by its acceleration. To minimize the effect of the variation of diameters within diameter classes, we normalized the average force by dividing by the sapling-branch diameter.

We conducted a total of 68 tests (17 variable combinations times four replications). Figures 4 to 7 depict the resulting average cutting force per inch of diameter cut for the various treatments.

To help determine what factors cause significant differences in average cutting force, an Analysis of Variance (ANOVA) was done on the five variables—blade thickness, blade cutting edge angle, oblique cutting angle, cutting speed, and branch diameter plus (blade thickness)*(blade cutting edge angle) interaction. The (blade thickness)*(blade cutting edge angle) interaction was found to be not significant (P=0.47) and so was removed from the model. The ANOVA was rerun using only the five main variables.

Of the five variables tested, only blade cutting edge angle (P=0.00), oblique cutting angle (P=0.00), and branch diameter (P=0.00) were found to significantly affect average cutting force (table 1).

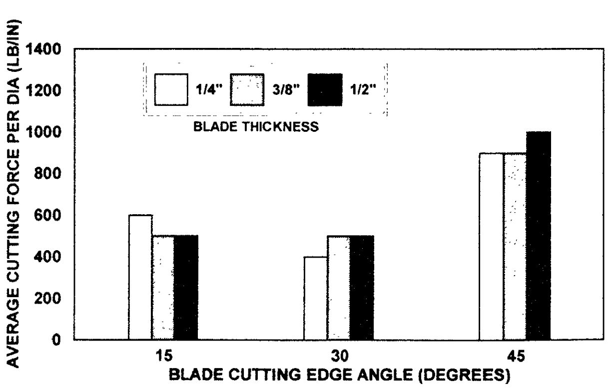

Figure 4.—*Test results for Series I, Average Cutting Force vs Blade Cutting Edge Angle and Thickness. The bars represent the mean of four tests. The tests were run using samples from the 3.0- to 3.4-inch diameter class. Cutting speed was 2,000 inches/ minute.*

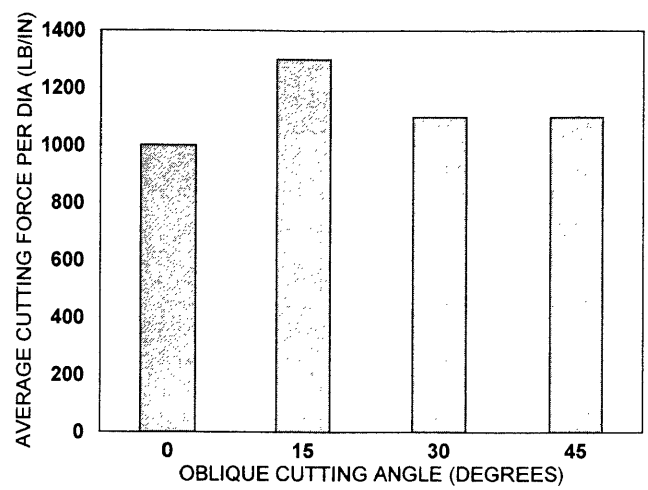

Figure 5.—*Test results for Series II, Average Cutting Force vs Oblique Cutting Angle. The bars represent the mean of four tests. The tests were run using samples from the 3.0- to 3.4-diameter class. The blade was one-half inch thick and sharpened to a 45° cutting edge angle. Cutting speed was 2,000 inches/ minute.*

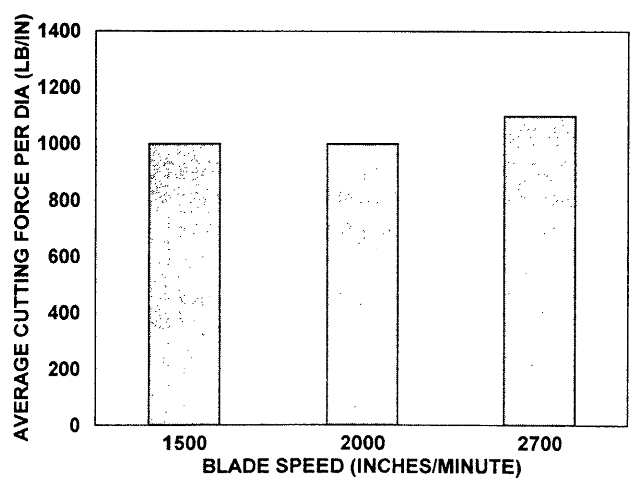

Figure 6.—*Test results for Series III, Average Cutting Force vs Cutting Speed. The bars represent the mean of four tests. The tests were run using samples from the 3.0- to 3.4-inch diameter class. The blade was one-half inch thick and sharpened to a 45° cutting edge angle and 0° oblique cutting angle.*

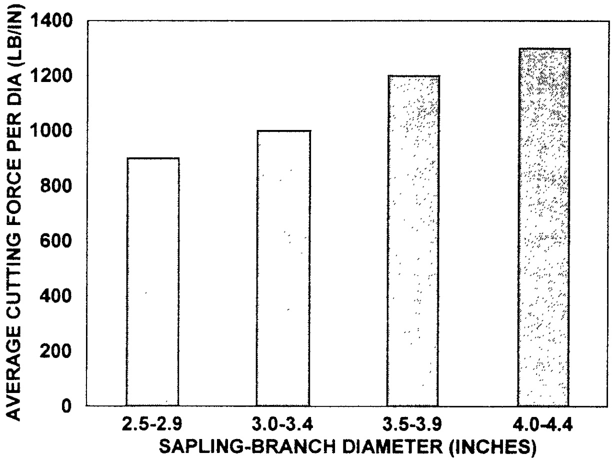

Figure 7.—*Test results for Series IV, Average Cutting Force vs Sapling-Branch Diameter. The bars represent the mean of four tests. The blade was one-half inch thick and sharpened to a 45° cutting edge angle with 0° oblique cutting angle. Speed was 2,000 inches/ minute.*

Both figure 4 and table 1 show cutting edge angle as the most important factor in explaining variability in the cutting force. Fisher's LSD test revealed significant differences between 15° and 45° (P=0.00) and between 30° and 45° (P=0.00) but not between 15° and 30° (P=0.24).

The results on oblique cutting angle were mixed. Figure 5 shows that increasing the oblique angle increased rather than reduced average cutting force. Fisher's LSD test revealed that the average cutting force for 0° oblique cutting angle was significantly different from 15° (P=0.00), 30° (P=.002), or 45° (P=0.02). The 15° angle was significantly different from 30° (P=0.03) and 45° angles (P=0.03), but there was no significant difference between 30° and 45° angles. The 15° angle appears to be abnormally high, probably because of the variability and small size (four replications) of the sample.

Even though the average cutting force has been normalized for diameter, branch diameter exhibits a significant effect on the cutting force. The normalized average cutting force increases with increasing branch diameter (fig. 7). The Fisher's LSD test indicated significant differences between some, but not all, diameter classes. There was no significant difference between the 2.5- to 2.9-inch and 3.0- to 3.4-inch size classes (P=0.61) or the 3.5- to 3.9-inch and 4.0- to 4.4-inch size classes (P=.015). An analysis of this diameter effect is beyond the scope of this study, but the cross-cutting of wood with a blade such as that used in this study is known to be a complex process of cutting individual wood fibers, compressing the wood ahead of the blade, and relieving the compression by splitting the sample material (Persson 1987). Based on this knowledge, diameter and depth of penetration, which is related to diameter, could be expected to significantly affect the cutting force.

CONCLUSIONS

These results indicate considerable potential for improvement in the operational efficiency and productivity of delimbing machines. Several commercially available harvesting machines were observed during the initial development of this

Table 1.—*Analysis of variance for effect of cutting edge angle, blade thickness, oblique cutting angle, cutting speed, and branch angle on average cutting force*

Source	Sum-of-squares	df	Mean-square	F-ratio	P-value
Edge angle	143.72222	2	71.86111	50.17102	0.00000
Blade thickness	0.38889	2	0.19444	0.13575	.87335
Oblique angle	39.42014	3	13.14005	9.17394	.00005
Speed	6.67836	2	3.33918	2.33130	.10670
Diameter	42.08681	3	14.02894	9.79453	.00003
Error	78.77778	55	1.43232		

project. Most of them were found to be using delimbing knives with approximately 45° cutting edge angles and operating at a speed of 1,800 to 2,200 inches/minute. Our tests showed that a 30° cutting edge angle would significantly reduce the forces encountered, by almost 50 percent in this study. Going below 30° to 15° was not found to be beneficial. Strength and durability considerations might preclude smaller cutting edge angles in any event.

The insignificance of blade thickness is a positive result in that the blade can be kept heavy enough to provide adequate strength without increasing the cutting forces.

Similarly, the insignificance of shearing speed on the cutting force, at least in the range of values tested, indicates that potential exists for increasing the delimbing speed and productivity.

The increase in average cutting forces in oblique cutting edges suggests that knife designs can be simplified by not employing an oblique or inclined cutting edge. Because most delimbing blades are curved and not straight, an oblique cutting edge becomes a helix, or worse, an irregular three-dimensional curve, a complicating factor for both manufacturing and maintenance.

Finally, although cutting force increases with diameter, it appears that force reductions from smaller cutting edge angles would more than compensate for the slight increases caused by larger diameters. If 3- to 4-inch branches could be routinely removed without having to abandon a top prematurely or drop the top and lop the branch off using the felling head saw, production could be improved.

LITERATURE CITED

Christopherson, Nels S. 1984. **Removing single limbs using a rotary auger cutter**. Res. Note NC-311. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 5 p.

Erdmann, Gayne G. [1986]. **Developing quality in second-growth stands**. In: Mroz, Glenn D.; Reed, David D., comps. The northern hardwood resource: management and potential: Proceedings of a conference; 1986 August 18-20; [Houghton, MI]. Houghton, MI: Michigan Technological University: 206-222.

Koch, Peter. 1985. **Utilization of hardwoods growing on southern pine sites**. Agric. Handb. 605. [Washington, DC]: U.S. Department of Agriculture, Forest Service. 2: 1794-1795.

McKenzie, W.M.; Cowling, R.L. 1971. **A factorial experiment in transverse-plane (90/90) cutting of wood**. Part I. Cutting force and edge wear. Wood Science. 3(4): 204-213.

Persson, Sverker. 1987. **Mechanics of cutting plant material**. Chapter 4, The cutting process. Number 7: 74-91. ASAE Monograph.

Scherman, Svante. 1989. **Modified limbing knives for hardwoods**. In: News No. 1. Kista, SE: Forskningsstiftelsen Skogsarbeten: 2. Abstract.

U.S. Department of Agriculture, Forest Service. 1989. **RPA assessment of the forest and rangeland situation in the United States, 1989**. For. Resour. Rep. 26. Washington, DC: U.S. Department of Agriculture, Forest Service. 72 p.

Winsauer, Sharon A.; Mattson, James A. 1987. **Harvesting alternatives for thinning northern hardwoods**. In: Nyland, Ralph D., ed. Managing northern hardwoods: Proceedings of a silvicultural symposium; 1986 June 23-25; Syracuse, NY. Misc. Publ. 13 (ESF 87-002): SAF Publ. 87-03. [Syracuse, NY: State University of New York, College of Environmental Science and Forestry]: 223-240.

Mattson, James A.; Sturos, Joseph B.
1996. **Reducing the forces required to delimb hardwoods**. Res. Pap. NC-327. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 8 p.

Documents the forces required to delimb hardwoods as a function of knife parameters, and identifies opportunities to reduce forces and increase productivity of machines using delimbing knives.

KEY WORDS: Harvesters, processors, mechanization, cutting forces, delimbing knives.