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Abstract

The 20h International Nondestructive Testing and Evaluation of Wood Symposium was hosted by the USDA Forest Service Forest Products Laboratory in Madison, Wisconsin, USA, on September 12–15, 2017. This Symposium was a forum for those involved in nondestructive testing and evaluation (NDT/NDE) of wood and brought together many NDT/NDE users, suppliers, international researchers, representatives from various government agencies, and other groups to share research results, products, and technology for evaluating a wide range of wood products, including standing trees, logs, lumber, and wood structures. Networking among participants encouraged international collaborative efforts and fostered the implementation of NDT/NDE technologies around the world. The technical content of the 20th Symposium is captured in these proceedings.

Keywords: International Nondestructive Testing and Evaluation of Wood Symposium, nondestructive testing, nondestructive evaluation, wood, wood products

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Drill Bit Friction and Its Effect on Resistance Drilling Measurements in Logs

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Abstract

The objectives of this study were to determine the effect of drill bit shaft friction on resistance drilling measurements on green logs and assess the potential of using drilling resistance and feeding force to predict density and hardness of wood in logs, and ultimately in standing trees. Two freshly-cut yellow birch (*Betula alleghaniensis*) logs, one with internal decay and the other of decay free, were used as test specimens. Drilling measurements were conducted on the logs using an IML-RESI PD 400 tool equipped with a standard spade-type drill bit. Following drilling measurements, nine 5.1-cm-thick disks were cut from the decayed log, one at each drilling location, and then a 5.1-cm-wide strip was cut from each disk. A series of hardness tests were conducted on each strip based on a procedure modified from ASTM D 143-2012. Then each strip was cut into 1.8-cm segments to determine wood density using a volumetric method. In addition, 195 drilling measurements were conducted on the decay-free log to characterize shaft friction variations and its relationship with drilling depth. The mean shaft friction observed on the defect-free yellow birch log was 19.2% with a coefficient of variation of 17.5%. A linear relationship was found between shaft friction and drilling depth in the defect-free log. Linear models were used to make a correction to the original drilling resistance profiles by subtracting the shaft friction along the entire drilling path. The adjusted resistance profiles showed better contrast between decayed zone and intact wood than the original resistance profile, which could be an advantage in tree inspection. The results also indicated that removing shaft friction from the original resistance profiles increased the prediction power of the drilling resistance as a nondestructive measure of wood density and hardness. Feeding force exhibited similar patterns with drilling resistance which is useful in decay detection, but it has limited prediction power if it is used to assess wood density and hardness.

Keywords: Drilling resistance, resistance profile, wood density, feeding force, hardness, logs

Introduction

Since introduction of the first prototype of resistance-based drilling machine in Germany in the 1980's, resistance drilling technique has quickly evolved into sophisticated electronic tools that simultaneously measure, display, and record relative resistance profile as a long drilling needle is driven into wood. The relative resistance profile (hereafter refers to resistance profile) is obtained through direct measurement of the electric power consumption (EPC) of a direct-current needle-rotation motor. So far, the resistance drilling method has been successfully used in various applications such as tree ring analysis (Rinn et al. 1996; Chantre and Rozenberg 1997; Wang and Lin 2001; Wang et al. 2003; Guller et al. 2012), tree decay detection (Wang and Allison 2008; Allison and Wang 2015), and structural timber condition assessment (Rinn 1990, 2012; Ceraldi et al. 2001; Ross et al. 2004). Research has progressed to evaluate the potential of resistance drilling as an indirect method to measure density or specific gravity of dry wood. Some early studies demonstrated that there was a strong linear correlation between the mean drilling resistance and gross density of dry wood (Görlacher and Hättich 1990; Rinn et al. 1996). More recent studies on structural wood members also showed moderate to strong relationships between measured resistance values and wood density (Ceradi et al. 2001; Park et al. 2006; Bouffier et al. 2008; Zhang et al. 2009; Sharapov and Chernov 2014).

There has also been a growing interest in using resistance drilling method to obtain wood density information from standing trees, particularly in tree genetic improvement and wood quality survey programs where hundreds or even thousands of trees must be sampled (Gao et al. 2017). One of the concerns on the use of resistance drilling tool on trees is the accuracy of measured resistance (amplitude in resistance profile, %) as an indirect measure of the wood density (Sharapov et al. 2015; Gao et al. 2017). Isik and Li (2003) evaluated the use of Resistograph tool for rapid assessment of relative wood density of live loblolly pine trees in progeny trials. They reported strong correlations among average drilling resistance value and wood density and strong genetic control at the family level. However, individual phenotypic correlations were found to be weak. Similar results have also been reported by Gants (2002), Charette et al (2008), Gwaze and Stevenson (2008), and Eckard et al. (2010).

In principle, resistance drilling in wood is a wood cutting process (Bershadskii and Tsvetkova 1975). The cutting forces are typically measured by the total power consumption. Friction is an important parameter that affects the measurement precision. The boring drill bits employed in the existing commercial drilling tools are thin needle, spade-type drill bits with a triangular-shape cutting head, which includes a tip and two symmetrical cutting edges that are perpendicular to the rotating axis. Similar to other wood cutting tools, friction force in a resistance drilling process can be generally resolved into chip friction with the rake face of the cutting edges, clearance-face friction with the wood cutting surface, side surfaces of the drill bit cutting part with the drilling hole surface, and shaft friction with wood chips and the drilling hole surface. Generally, friction is influenced by wood species, moisture content, cutting speed parameters, and angle and blunting parameters of the cutting edges. While most of the friction forces remain constant during a single drilling, the drill bit shaft friction increases with increased drilling depth. Rinn (2012) reported that the systematic errors in the profiles caused by shaft friction tend to increase for specimens with a wood density higher than 600 kg/m^3. Nutto and Biechele (2015) conducted resistance drilling measurements on six different tropical wood species and found that drill bit shaft friction ranged from 4% to 70%. There is little knowledge on how the drilling bit friction will affect sensitivity of resistance profiles in terms of decay detection and wood property prediction.

The research reported herein was a continuation of the previous study on investigating the wear behavior and blunt effect on resistance drilling measurements on wood (Sharapov et al. 2015). The objectives of this paper were to characterize the drilling friction in drilling green yellow birch logs, determine the effect of shaft friction on resistance drilling measurement, and evaluate the potential of using resistance drilling tools to assess wood density in green logs, and ultimately in standing trees.

Materials and Methods

Two freshly-cut yellow birch (*Betula alleghaniensis*) logs were obtained for resistance drilling experiments, one contained internal rot and the other was defect free. The decayed log was 2.53-meter long with a diameter of 32 cm at the large end and 30 cm at the small end, and had an average moisture content (MC) of 39.8% and average density of 589 kg/m^3. The defect-free log was 2.58-meter long with a diameter of 35 cm at the large end and 29 cm at the small end, and had an average MC of 55.5% and an average wood density of 710 kg/m^3.

An IML-RESI PD 400 tool (IML System GmbH, Wiesloch, Germany) was used to conduct resistance drilling measurement on two log samples. This Resistograph tool was equipped with standard spade-type drill bits. The drilling profiles obtained from each measurement include a relative resistance curve reflecting the torsion force on the drill bit and a feeding force curve reflecting the pressure put on the tool, both recorded in percentage of the amplitude. The drilling force parameters were measured and recorded once every 0.1 mm of drilling depth. The Resistograph data was saved and processed using the PD-Tools PRO software (IML System GmbH, Wiesloch, Germany).

Resistance drilling experiments included two parts: 1. Conduct extensive drilling tests on the defect-free log to study the wear behavior and shaft friction of the drill bit. The wear behavior of the drill bit in wood resistance drilling was reported in a previous presentation (Sharapov et al. 2015). In this paper, we analyzed the resistance profiles obtained through this extensive drilling experiment to determine the shaft friction and its relationship with drilling depth. 2. Conduct drilling tests at selected locations on the decayed log to study the sensitivity of measured drilling parameters (drilling resistance and feeding force) to wood property changes (wood density and hardness). All resistance drilling measurements were conducted at a room temperature of about 20 ºC.

Resistance Drilling Procedures

Drilling Experiment —Part 1: A total of 195 resistance drilling measurements were conducted on the defect-free yellow birch log using a new drill bit, with a feed rate of 0.508 m/min and a rotational speed of 2500 rpm (nominal feed rate per cutting edge was about 0.1 mm). These speed parameters were selected based on several preliminary drilling tests with different feed rate and rotational speed combinations so that the amplitudes of the drilling resistance and feeding force were not very low and within the measurement scale. All drillings were made across the log diameter in the radial-longitudinal section, with a 1-1.5 cm spacing between any neighboring drillings.

Drilling Experiment —Part 2: Nine resistance drilling measurements were conducted on the decayed log with a feed rate of 0.99 m/min and a rotational speed of 2500 rpm (nominal feed rate per cutting edge was about 0.2 mm). The large end appeared solid, but a significant central rot was observed on the small end. The drilling measurement was started at a location 12.7 cm (5 in.) from the small end, followed by the second drilling 5.1 cm (2 in.) apart from the first one, then the remaining seven drillings were made with a 30.5 cm increment. Figure 1 shows the locations of resistance drilling measurements.

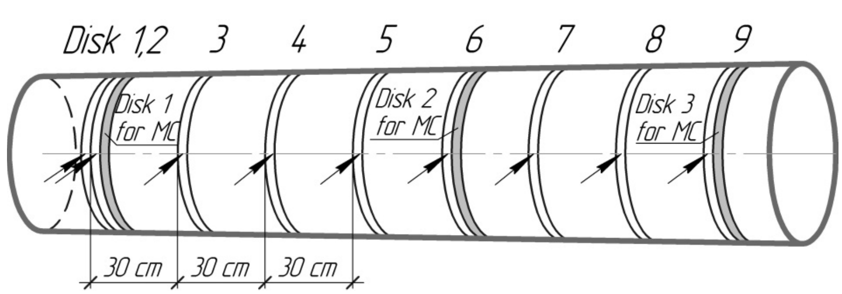


Figure 1—Schematic diagram of the decayed yellow birch *(Betula alleghaniensis)* log showing the locations of a series of resistance drilling measurements (arrows on the figure) and the disk sample at each location. Three moisture content disks are shown in gray color.

Janka Hardness Test and Wood Density Measurements

Upon completion of the resistance drilling measurements, the decayed log was dissected and a 5.1-cm-thick disk was obtained at each drilling location for further laboratory evaluation (Figure 1). For each disk, a 5.1-cm-wide strip was cut through the center of the disk along the drilling path. All strips were placed at the conditioning room of 20 °C and 65% relative humidity (RH) till the equilibrium moisture content (EMC) of 12% was reached.

To map the hardness along the drilling path, we conducted a series of Janka ball hardness tests on each strip sample based on a procedure modified from ASTM D 143-2012 (ASTM 2012). The hardness test was conducted on the end-grain face (TR plane) of the strip. On each strip sample, 2-cm grid lines were drew on the end-grain face with the pith located in the center grid. Hardness test was then conducted on each grid using an Instron universal testing machine (Model 5566, Instron Corporation, Norwood, MA, USA) with a 10 kN load cell and a loading rate of 5.08 mm/min. A total of 13 Janka hardness tests were performed on each wood strip. The hardness value obtained from this specialized test was defined as end-hardness. After Janka ball hardness tests, each strip was cut into 1.8-cm segments for determining basic wood density using volumetric method (ASTM 2012).

Wood Moisture Content Determination

For decayed log, three additional disks were obtained next to drilling location no.1, no.5 (middle of the log), and no.9 respectively. A 5.1-cm-wide strip was cut from each of these disks and used as moisture content sample. The moisture contents of the strips were then determined based on the initial (green) weight and the oven-dry weight (ASTM 2007). The same procedure was used to determine the average MC of the defect-free log.

Data Processing and Analysis

During each resistance drilling measurement, two cutting-force parameters were measured and recorded: drilling resistance (torque moment acting on the drill bit cutting-head) and feeding force (external force acting on the Resistograph tool by the operator). It is hypothesized that variations in the output amplitudes of both drilling resistance and feeding force are directly related to the changes in wood density and mechanical properties along the drilling path. The exact unit of resistance amplitude is not specified by the tool manufacturer and expressed as a relative value in percentage (%). For regression analysis with the wood density and hardness data, the resistance amplitude data was averaged over each wood segment where the actual wood density and end hardness value were obtained. The amplitude of feeding force curves was calibrated to actual feeding force in Newton (N) based on the calibration data obtained in a universal testing machine (MTS 810, MTS Systems Corporation, Eden Prairie, MN USA) with a 1-kN load sell. The feeding force data obtained from each drilling measurement was then converted into actual force.

Results and Discussion

Drilling Friction

Figure 2 shows the last portion (drilling depth beyond 280 mm) of a typical drilling profile obtained from the birch logs, with drilling resistance displayed with higher amplitude (in grey shade) and the feeding force displayed in lower amplitude (in dark shade). It was observed that a residual drilling-resistance existed after the drill bit cutting-head exited the log at 305 mm. This residual resistance remained relatively constant as the drill bit continued feeding through and it is caused by the friction between the drill bit shaft and the wood chips remained within the drilling hole. During a drilling process, wood chips remain inside the drilling hole and can be compacted and cause friction along the shaft. The magnitude of this friction theoretically depends on wood species, basic wood density, moisture content, size and forms of the chips, as well as drilling parameters such as cutting speed and feed rate. In Figure 2, the drill bit shaft friction is characterized by the residual amplitude of the resistance profile, which is 15%. The feeding force, on the other hand, reduced significantly after the cutting-head exited the log and fluctuated between 0 and 3% like a sine wave. This fluctuation in residual feeding force is believed to be related to the feeding mechanism of the screw gear in the drilling tool.

Table 1 summarizes the statistical data of the residual drilling-resistance (shaft friction) and the residual feeding-force for both decayed and defect-free birch logs. The mean residual drilling-resistance observed on decayed log is 16.8 (amplitude in %), which is 12 percent lower than the mean shaft friction observed on defect-free log (19.2). Based on wood density data obtained from the disks, the density of decayed log is 17% lower than the decayed log. It is apparent that the lower wood density of the decayed log contributed to the decrease in shaft friction during the resistance drilling. The mean residual feeding-force for both decayed and defect-free logs is below 3%. This translates into a direct feeding force of less than 2.5 N. Coefficient of variation for normalized (COV_N) residual drilling resistance (shaft friction) in relation to the drilling depth (log diameter) is less than the standard COV which is consistent with the interaction between shaft friction and drilling depth. At the same time decreasing of COV_N for the residual feeding force is negligible.

Figure 3 shows the linear relationship observed between the drill bit shaft friction and the drilling depth for the defect-free yellow birch log, with a coefficient of determination (R^2) of 0.45. The empirical regression model indicates a 1.5% increase in friction for every 10 mm increase in drilling depth. Nutto and Biechele (2015) examined the drilling friction in several tropical species and the observed friction ranged from about 5% for Parana pine (*Araucaria angustifolia*) (with 30 cm in diameter) to about 65% for Pau Ferro (*Caesalpinia ferrea*) (with 32 cm in diameter). Among the species investigated, the Arueira (*Lithraea molleoides*) had a wood density of 725 kg/m^3, which is close to the density of the defect-free yellow birch log in this study. When the empirical regression model for yellow birch was applied to Arueira, we obtained a friction of 19.7%, which is close to the actual friction 18% reported by Nutto and Biechele (2015). It is therefore hypothesized that the empirical friction model developed for a species can be used to predict the drilling friction at any point of the drilling path for the same species or a species with similar wood density.

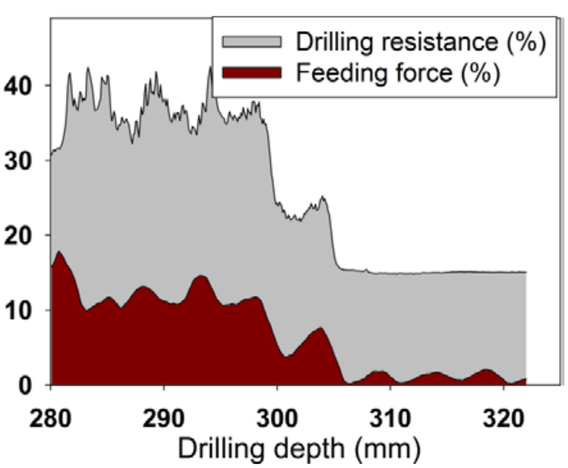


Figure 2—Typical drilling profiles obtained from the yellow birch logs (showing later portion), with drilling resistance displayed in grey shade and feeding force displayed in in dark shade.

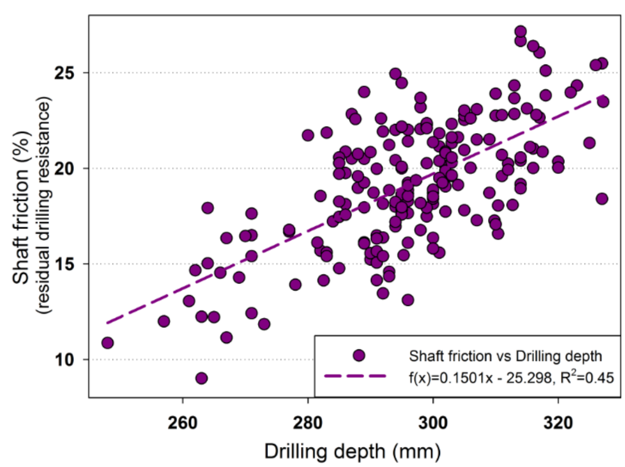


Figure 3—Relationship between shaft friction (residual drilling resistance, %) and drilling depth for the defect-free yellow birch log.

Table 1—Statistical data of residual drilling resistance (shaft friction) and residual feeding force for decayed and defect-free yellow birch logs.

Log sample	Residual drilling resistance (%) (Needle shaft friction)			Residual feeding force (%)			Basic wood density (kg/m^3)	
	Mean	COV [a]	COV_N [b]	Mean	COV	COV_N	Mean	COV
Decayed log	16.8	22.2	20	1.65	90.9	89.1	589	14.9
Defect-free log	19.2	17.5	14.9	2.43	50.5	50.1	710	5.6

[a] COV – coefficient of variation; [b] COV_N – coefficient of variation for normalized residual drilling resistance and residual feeding force

Sensitivity of Drilling Resistance Profiles to Internal Decay

Comparison of drilling-resistance profiles for decayed and defect free-logs is presented in Figure 4. The drilling resistance in defect-free log was relatively consistent within the first radius (0-150 mm), with a slight increase as the drill bit moved towards the pith; then it increased significantly in the second radius (150-300 mm). This might indicate nonlinearity of the drilling friction, but it could also be caused by the wood property differences between two halves of the log. Overall, the drilling-resistance profile in defect-free log did not show significant drops through the entire drilling path. In contrast, the drilling resistance in decayed log showed different patterns comparing to the defect-free log. The drilling-resistance profile exhibited sharp drops in the central area of the log, from 90 to 225 mm. The Janka hardness and wood density data obtained from the disk also showed significant reduction in the same central area, which indicated a good agreement with the resistance profile. With respect to direct interpretation of the resistance profile obtained from decayed log, the starting boundary of the central decay can be readily recognized by the sharp drop in drilling resistance at a drilling depth of about 90 cm. However, as the drill bit penetrated through the decay zone and reached the intact wood, the drilling resistance showed a gradual increase, not a sharp transition. Consequently, identifying the other side of the decay boundary might not be straightforward. The extent of the central decay can only be estimated approximately.

The accuracy of drilling-resistance profiles recorded in the resistance drilling tool is affected by the shaft friction. Although shaft friction are dependent of many factors as we discussed early, for green yellow birch logs/trees, a linear model of shaft friction in relation to drilling depth can be used to make a correction in original resistance profiles by subtracting the friction along the entire drilling path. Figure 5 shows the original resistance profile (1) superimposed with the adjusted resistance profile (2), as well as the original feeding-force curve for the decayed log. The adjusted resistance profile essentially had a pattern very similar to the original resistance profile. But from visual appearance, adjusted resistance profile had better contrast between decayed zone and intact wood. This may be an advantage in tree inspection. The feeding force curve for the decayed log also exhibited a similar pattern comparing to the resistance profiles (original and adjusted), but the contrast in amplitude between intact wood and decay zone is much smaller than those seen in the resistance profiles.

Both 3D surface and 2D contour graphs of the drilling resistance for the entire decayed log were created through approximation and interpolation of eight sets of the measured resistance profile (drilling no. 2 to no. 9) (Figure 6). In the graphs, low resistance values are highlighted by red colour, and high resistance values are highlighted by green colour. These graphs provide an overall assessment of the log condition and demonstrate resistance/wood density variations through the RL plane of the log.

Relationships between Drilling Parameters and Wood Properties

Figure 7 is the data plot of Janka hardness measured in the wood strips of the decayed log and wood density of the corresponding small segments cut from the strips. Regression analysis indicated a strong linear relationship between hardness and wood density (R^2=0.79), which is in agreement with the results reported in Forest Products Laboratory (2010).

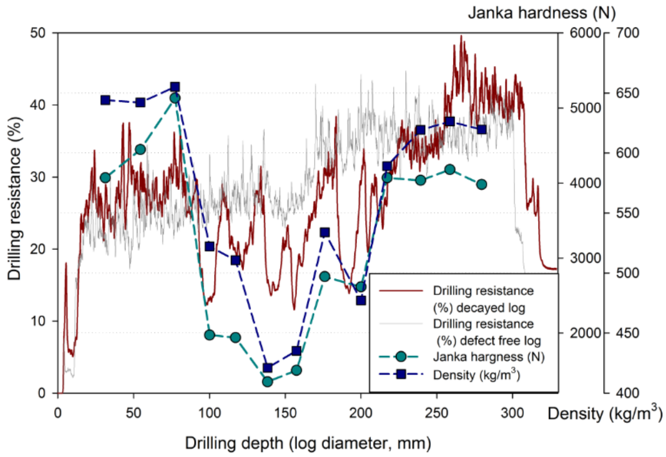


Figure 4—Comparison of the drilling resistance profiles for decayed and defect free yellow birch logs. Data points shows the distribution of Janka hardness and wood density along the drilling path for the decayed log.

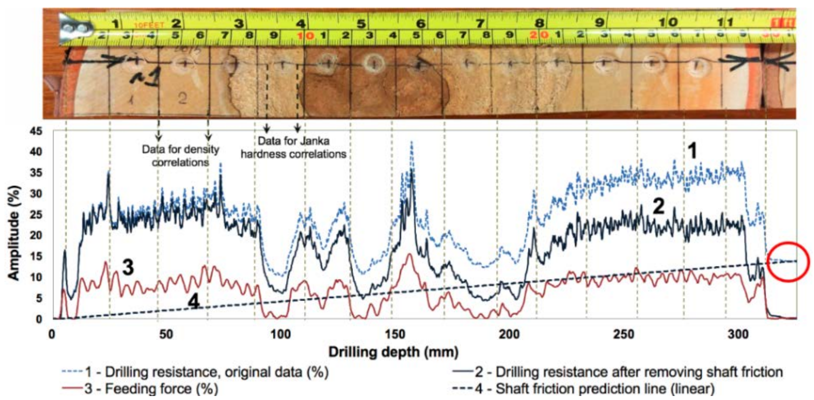
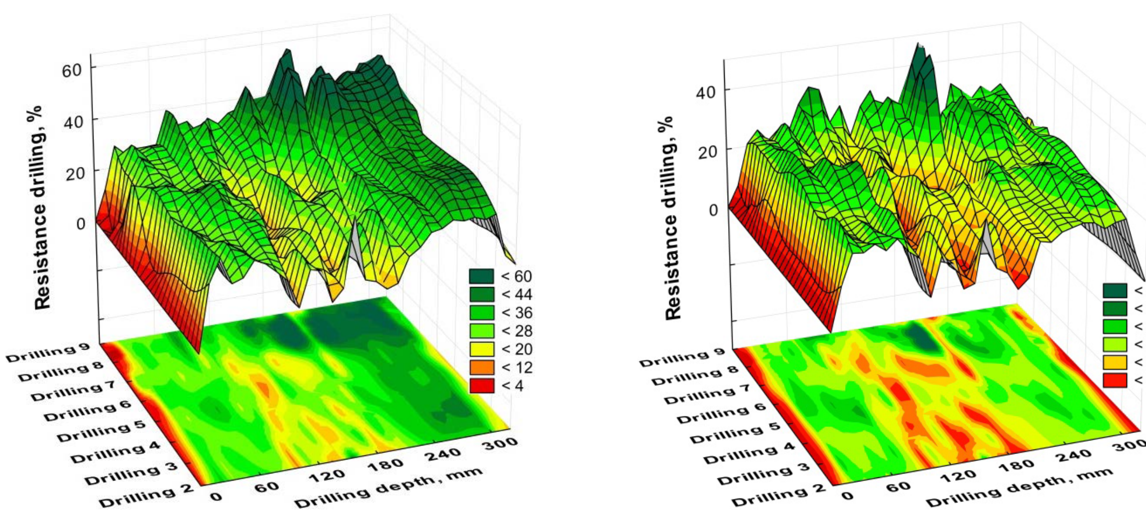


Figure 5— Resistance drilling profiles of the decayed yellow birch log and image of the wood strip cut along the drilling path (Disc no. 2).



a) Based on original resistance profiles b) Based on adjusted resistance profiles

Figure 6— 3D surface map and 2D contour map of drilling resistance for the decayed yellow bitch log. a) Developed from the original resistance profiles; b) developed from the adjusted resistance profile.

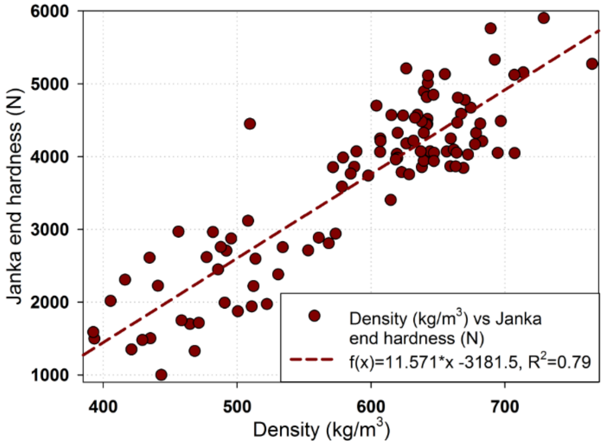


Figure 7— Relationship between hardness measured in the wood strips of the decayed yellow birch log and wood density of the corresponding segments cut from the strips.

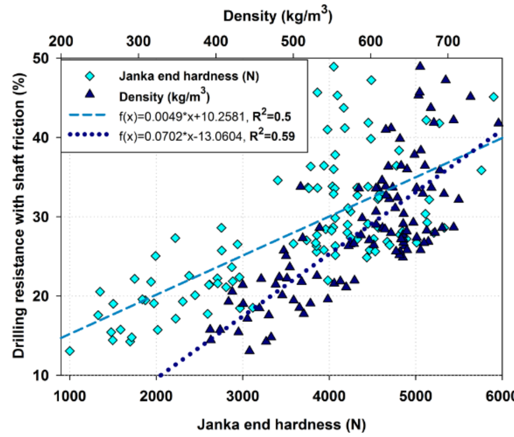


Figure 8—Relationships between the original drilling resistance (shaft friction included) measured in decayed log and hardness and wood density of the corresponding segments in the drilling path.

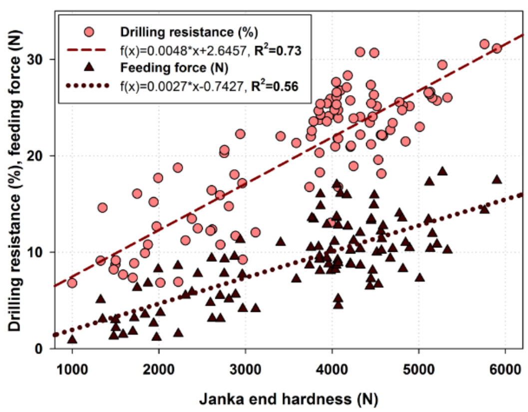


Figure 9—Relationships between drilling parameters (adjusted drilling resistance and feeding force) of the decayed log and the corresponding hardness.

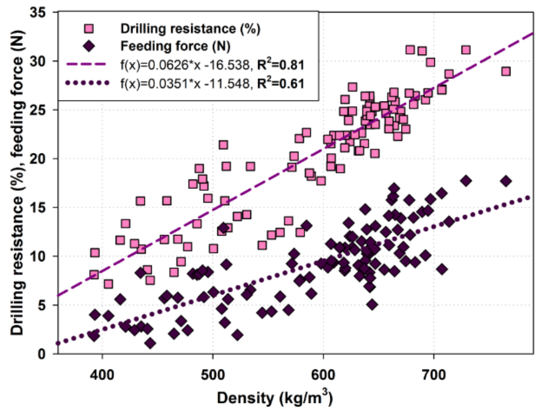


Figure 10—Relationships between drilling parameters (adjusted drilling resistance and feeding force) of the decayed log and the corresponding wood density.

Figure 8 shows the relationships between the original drilling-resistance (shaft friction included) measured in the decayed log and hardness and wood density of the corresponding segments in the drilling path. Regression analysis indicated positive linear relationships with a moderate strength (R^2 =0.5 for hardness, R^2 =0.59 for density).

Figure 9 shows the relationships between drilling parameters (adjusted drilling-resistance and feeding force) of the decayed log and the corresponding hardness. The adjusted drilling-resistance had a relatively strong correlation with hardness with a R^2 of 0.73, which is a significant improvement comparing to the original drilling resistance (R^2 = 0.5). Feeding force showed a moderate correlation with hardness (R^2 =0.56).

Figure 10 shows the plots of the drilling parameters (adjusted drilling-resistance and feeding force) and the corresponding wood density for the decayed log. The adjusted drilling-resistance had a strong linear relationship with wood density with a R^2 of 0.81, which is a significant improvement comparing to the original drilling resistance ($R^2 = 0.59$). Again, feeding force showed a moderate correlation with wood density ($R^2 = 0.61$).

Conclusion

In this study we characterized the drill bit shaft friction in resistance drilling green yellow birch logs through extensive laboratory experiments. It was found that a residual drilling-resistance existed after the drill bit cutting head exited the log. This residual resistance was caused by the friction between the drill bit shaft and the wood chips within the drilling hole and remained relatively constant as the drill bit continued feeding through. The mean shaft friction observed on the defect-free yellow birch log was 19.2% with a coefficient of variation of 17.5%. A linear relationship was found between shaft friction and drilling depth in the defect-free yellow birch log. The empirical regression model indicates a 1.5% increase in shaft friction for every 10 mm increase in drilling depth. The mean residual feeding force for both decayed and defect-free logs was below 3% (or less than 2.5 N).

The accuracy of drilling-resistance profiles recorded in the resistance drilling tool is affected by drill bit shaft friction. For green yellow birch logs, a linear model of shaft friction in relation to drilling depth can be used to make a correction to the original resistance profiles by subtracting the friction along the entire drilling path. The adjusted resistance profiles showed better contrast between decayed zone and intact wood than the original resistance profile, which could be an advantage in tree inspection.

The results also indicated that removing shaft friction from the original resistance profiles increased the prediction power of the drilling resistance as a nondestructive measure of wood density and hardness. Resistance data adjustment can be carried out directly on the resistance drilling tool by adding a data correction module or accomplished during post data processing. Feeding force parameter, although exhibited similar patterns with drilling resistance, has limited prediction power if it is used to assess wood density and hardness.

Acknowledgments

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