PREDICTION OF FIBER ORIENTATION IN NORWAY SPRUCE LOGS USING AN X-RAY LOG SCANNER: A PRELIMINARY STUDY

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ABSTRACT

Previous studies have shown that a CT scanner can be used to accurately measure spiral grain in logs. However, the application of such a CT scanning system is of limited use in an industrial application because of the cost and processing time associated with CT scanning. The aim of this study was a preliminary assessment of predicting fiber orientation, an indication of spiral grain, in centerboards from Norway spruce (*Picea abies*) saw logs using an X-ray log scanner. The scanner is a high-speed commercial log-scanning device used to grade and sort logs based on internal quality characteristics.

In this study, nineteen logs were first scanned with a CT scanner. Afterwards, the CT images were used to simulate X-ray log scanner images, with which measurements of different variables such as diameter, taper, percentage of heartwood, density, and density variations could be calculated. Depending on the log diameter, two to four centerboards were then sawn from each log, and the fiber orientations of the boards were measured for observed spiral grain for each log. A statistical model for predicting fiber orientation was then developed using partial least squares (PLS) regression. The PLS-model was developed to predict the fiber orientation of a log at a distance of 50 mm from the pith based on different variables that are measurable with the industrial X-ray log scanner. The resulting PLS-model was shown to produce an $R^2 = 0.45$ for the training set and $R^2 = 0.55$ for the test set. The statistically significant variables used to predict spiral grain were green heartwood density, knot volume, and a measure of the unsymmetrical distribution of knot volume. Significant correlation of these variables warrants further research and development with the X-ray log scanner to nondestructively sort out logs with excessive spiral grain.

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Keywords: Spiral grain, X-ray log scanner, partial least squares (PLS) regression, nondestructive measurement.

INTRODUCTION

The successful running of a sawmill is dependent on its ability to achieve the highest possible value recovery from saw logs. Spiral grain is one example of a growth feature in logs that decreases the desirable properties and thereby the value of the timber. Therefore, it would be of interest to find a nondestructive method of measuring spiral grain and sorting logs with excessive spiral grain before they are sawn.

Spiral grain occurs when the cells are not aligned parallel to the axis of the tree; they have grown in a helical structure around the pith (Harris 1969). Spiral grain is a well-known phenomenon that has been studied by many scientists (Harris 1969). An important observation (Skatter and Kucera 1998) is that spiral grain varies depending on its degree of inclination from the pith to the bark (see Fig. 1). It has been shown that spiral grain leads to a reduction of mechanical properties of the timber (Bodig and Jayne 1993). An even greater problem is that sawn lumber from timber with extreme spiral grain has a marked tendency to twist during drying (Harris 1969). Traditionally, fiber direction has been measured using different destructive methods (Harris 1969). While these destructive methods are useful for providing baseline information about spiral grain in logs and lumber, they are of little use in practice. Sepúlveda et al. (2003) found that spiral grain is strongly correlated to fiber orientation and can be quantified by measuring fiber direction in lumber. Nondestructive techniques have been successfully used for measuring wood fiber and grain orientation including electrical capacitance, laser, and computed tomography (CT) scanning (McDonald and Bendtsen 1986; Nyström 2000; Sepúlveda 2001). Nyström and Grundberg (2002) showed that it is possible to predict the spiral grain within a log based on measurements on the surface of debarked logs. For research purposes, it has been shown that CT scanning is a possible method of measuring the spiral grain in logs nondestructively (Sepúlveda 2001). But, the fastest CT scanners have a speed of approximately 1 image/second, which corresponds to a scanning speed of 1 cm/s with a resolution of 1 cm/pixel in the longitudinal direction. This speed is much too slow for most softwood sawmills.

An industrial X-ray log scanner has been developed and tested for high-speed log sorting and grading applications (Grundberg and Grönlund 1997; Oja et al. 1998, 2001). The X-ray log scanner can scan logs at 3 m/s and uses two X-ray sources to generate two orthogonal X-ray images of the log (Fig. 2). With these images, it is possible to measure several important variables that relate to log quality including green density, knot volume, and percentage of heartwood and sapwood. Furthermore, by utilizing different halves of

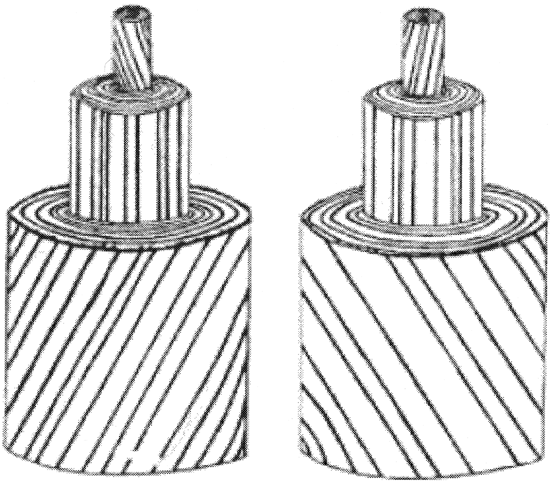

FIG. 1. Spiral grain is seen internally. (1) LR model: in the innermost parts of the tree the spiral grain is left-handed, deviating to an angle of zero in the middle of the tree and becoming right-handed in the outermost part. (2) RL model: in the innermost parts of the tree the spiral grain is right-handed, deviating to an angle of zero in the middle of the tree and becoming left-handed in the outermost part.

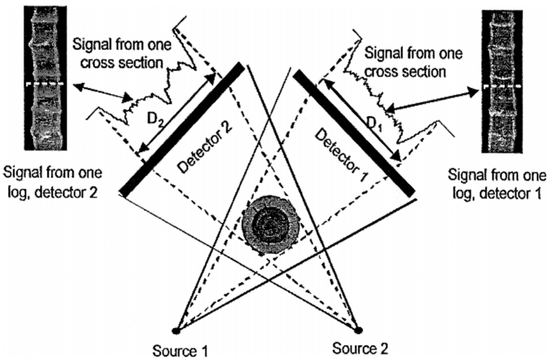

FIG. 2. Schematic description of the X-ray log scanner.

each of the log scanner images, these variables can be measured in separate log quadrants and compared to make assessments regarding internal feature irregularities. Also by utilizing the method described by Nyström and Grundberg (2002), the X-ray log scanner has the advantage of being able to scan logs before debarking. The fact that various growth irregularities, such as density and crown asymmetry, are indications of spiral grain (Nicholls et al. 1977; Eklund and Säll 2000; Eklund et al. 2003; Sepúlveda et al. 2002), leads to the possibility of predicting spiral grain based on X-ray log scanner measurements.

The objective of this study was to predict the magnitude of fiber orientation based on X-ray log scanner measurements. Since the magnitude of fiber orientation is correlated to the magnitude of spiral grain, the results of this study provide a preliminary assessment to the feasibility of industrial sorting of logs with excessive spiral grain.

MATERIALS AND METHODS

This study was based on 19 Norway spruce (*Picea abies* L. Karst) logs from Sweden. These logs were randomly selected from a sawmill in northern Sweden and intended for both this study and a separate study described by Johansson et al. (2002). The logs were collected in the winter, and little change was observed in log moisture content (MC) during the data collection phase of the study.

After felling and cross-cutting, the logs were scanned every 30 mm along the log in a medical CT scanner (Siemens SOMATOM AR.T).[1] The logs were fixed at both ends and adjusted to three laser lines so all the logs from a tree followed the same coordinate system during the scanning. The X-ray beam width was 5 mm. All images were stored as a 16-bit gray-scale image with a resolution of 512×512 pixels. The linear representation of CT-numbers from −1,000 to +700 was calibrated such that a pixel with CT-number −1,000 corresponds to a material with the same X-ray attenuation as air, while a pixel with CT-number 0 corresponds to a material with the same X-ray attenuation as water.

Because the X-ray log scanner is a commercial device, it is not readily available as a tool for research experimentation. As such, a simulated X-ray log scanner has been developed and validated and is available to test proof-of-concept for different log scanning applications (Grundberg and Grönlund 1997). Utilizing the raw CT scanner data as input, X-ray log scanner images were simulated as described by Grundberg and Grönlund (1997). The output from the simulated X-ray log scanner includes two longitudinal X-ray images of the log (Fig. 2). From these images, proprietary software has been developed to calculate up to 152 measurements that can be used to evaluate log quality (Anon. 2002). These measurements include several important log quality features related to knot volume, knot frequency, green heartwood density. Because the X-ray log scanner can measure and compare knot characteristics in four different halves of the log (two halves for each X-ray log scanner image in Fig. 2), the standard deviation of knot volume between the four halves is also included as a key measurement related to knot distribution in the log (Oja et al. 2000). An uneven spatial distribution of knots is an indication of growth variations (e.g., crown asymmetry) that can be correlated to fiber an-

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[1] Further information on Siemens SOMATOM class medical CT scanners is available at http://www.siemensmedical.com.

TABLE 1. *Each of the nineteen Norway spruce logs were sawn to obtain centerboards with dimensions of 50* 100* 2,500 mm.*

Log number	Diameter (mm)	Number of boards	Fiber direction (degree)
1*	255	4	−0.56
2*	262	4	2.04
3*	302	3	3.58
4*	298	4	−0.36
5**	259	4	0.90
6*	220	2	1.07
7*	210	2	2.60
8*	204	2	1.37
9**	200	2	−0.84
10*	213	2	−0.42
11**	302	3	−1.58
12*	278	3	4.01
13*	312	4	2.11
14*	278	3	−0.36
15*	306	4	−0.40
16**	255	2	0.84
17*	302	3	−1.58
18*	306	4	−2.70
19**	310	4	1.68

* Logs used for training-set.
** Logs used for test-set.

gle in logs (Eklund and Säll 2000; Skatter and Kucera 1998).

The simulated log scanner images were also analyzed using Fast Fourier Transforms (FFT) and Radon Transforms (MathWorks 2001) to measure predominant directional vectors, which also can be related to fiber angle in the logs. For this study, 191 total measurements (X-variables) were derived from the simulated log scanner images (152 from log scanner software and 39 additional variables possibly related to fiber angle) and initially tested for their importance in predicting spiral grain. The aim when choosing these variables was to find variables that correlated strongly with fiber direction.

All of the nineteen Norway spruce logs were then sawn to obtain 50-mm-thick boards. This thickness was chosen because it is a common thickness for structural lumber in Sweden. Thickness of sawing kerf was approximately 3 mm. The number of boards attained from each log varied depending on the diameter and shape of the log (see Table 1). Each board was then kiln-dried to approximately 8% MC. The fiber orientation was measured on the board surfaces corresponding to 50 mm from the log pith using the tracheid-effect method. The tracheid-effect is a phenomenon that can be observed when a narrow beam of light is projected on a wood surface (Nyström 2000). The softwood fibers (tracheids) conduct light better along the longitudinal fiber direction. This phenomenon can readily be observed when a wood surface is illuminated with a small circular spot of structured light. This light is eventually reflected back as an elliptical shape that is oriented in the direction of the fibers. The tracheid measurements were performed as described by Nyström (2000). The light source was delivered using a focused laser beam with a wavelength of 677 nm and output power of 26.3 mW. The camera used for these experiments was a Soliton GPC fitted with a MAPP 2200 Smart Image Sensor with a spatial resolution of 256×256 pixels and an 8-bit gray-scale resolution (see Fig. 3).

The fiber orientation measurements in this study correspond to the fiber direction on a tangential surface approximately 50 mm from the pith. Depending on the number of boards recovered from sawing (see Table 1), at least two and up to four different tangential surfaces were available from which fiber direction measurements could be made for each log. Twenty fiber direction measurements were sampled on each surface. Some of these measurements resulted in extreme outliers when a sample was taken in a defect area (e.g., near a knot or pitch pocket). To minimize the impact of these unrepresentative outliers, the median of the 20 measurements was calculated. Finally, the fiber direction corresponding to 50 mm from the log pith (Y-variable) was estimated using the arithmetic mean of these median values for each tangential surface. Note that due to sawing kerf and exact positioning of the centerboards in relation to the log center, attained measures of fiber direction are an approximate estimate of 50 mm from the log center. The measured fiber direction is also

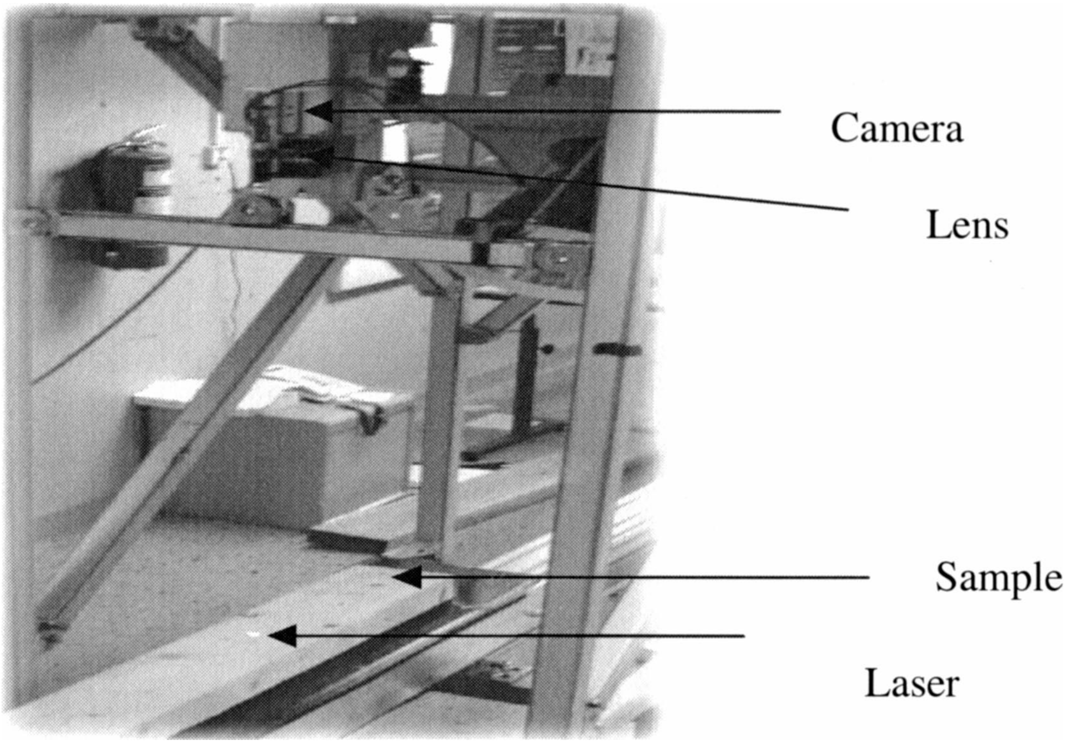

FIG. 3. Setup of the tracheid-effect scanner.

shown in Table 1. Positive values refer to a LR fiber direction model (see Fig. 1).

A multivariate model was developed to predict the fiber direction using partial least squares (PLS) regression (Eriksson et al. 2001). PLS finds the best functional relationship between a matrix Y (dependent variables) and matrix X (predictor variables) and is expressed as:

$$Y = f(X) + E \qquad (1)$$

The function relationship, f (X), can be a linear or polynomial function of the variables that best fit observed values of Y such that the model error, E, is minimized. PLS is a multivariate technique that is designed to statistically analyze data matrices with more variables than observations. PLS can efficiently process and scale data that are noisy and highly collinear (Eriksson et al., 2001).

The logs were randomly separated into two groups: a training set (14 logs) and a test set (5 logs) for model validation (see Table 1). The training set was used to fit the PLS-model. The test set was used to independently validate the accuracy of the PLS-model fit. PLS-modeling and analyses were performed using the statistical software program SIMCA 9.0 (Anon. 2001).

RESULTS

As mentioned in the previous section, 191 possible measurements (X-variables) were available to choose from in the development of the best predictor of fiber direction. Sepúlveda et al. (2002) describes a variable selection procedure to determine which variables were best suited for an accurate model. The result of this procedure found 3 highly significant variables: 1) green heartwood density (BY), 2) total knot volume (BX), and 3) a measure of the uneven spatial distribution of knot volume (EK). Findings from the literature

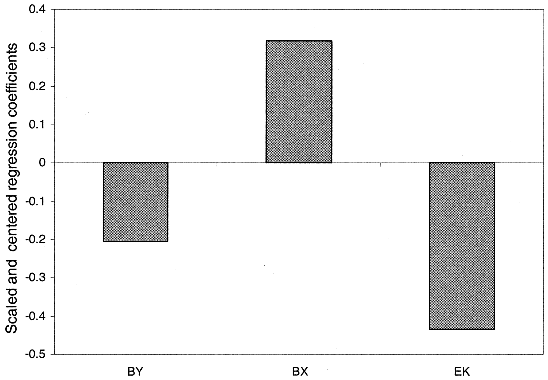

FIG. 4. Scaled and centered regression coefficients, the PLS-model. The variables are measured for each log by the simulated X-ray log scanner and the model includes three variables. The three variables are: BY = green heartwood density, BX = total knot volume; EK = a measure of the unsymmetrical distribution of knot volume.

support the significance of these variables. Lower wood densities (BY) have been associated with spiral grain (Nicholls et al. 1977). A high knot volume (BX) can be an indication of fast growth, which has also been correlated to spiral grain (Eklund et al. 2003). As mentioned in the Methods section, EK is the standard deviation of knot volume between the four halves of the log scanner X-ray images and can be an indication of asymmetric crown growth (e.g., longer or more branches on one side of the tree). Crown asymmetry has been correlated to spiral grain in regions with prevailing winds (Skatter and Kucera 1998). No significance was found using any of the 39 variables based on predominant directional vectors derived from X-ray image FFT and Radon Transforms.

The regression coefficients of the fitted PLS-model are shown in Fig. 4. These coefficients have been scaled and centered to a common scale. Figure 5 shows the prediction results of the fitted model. The fit is evaluated based on 1) the training set used to develop the model, and 2) the independent test set (see Table 1). The result when using the model to predict the spiral grain was $R^2 = 0.45$ when compared to the training set and $R^2 = 0.55$ for the independent test set (Fig. 5). The prediction error (Root Mean Squared Error, RMSE) of the model was +1.398° and +0.945° for the training and test data, respectively. The bias of the test set was −0.297°.

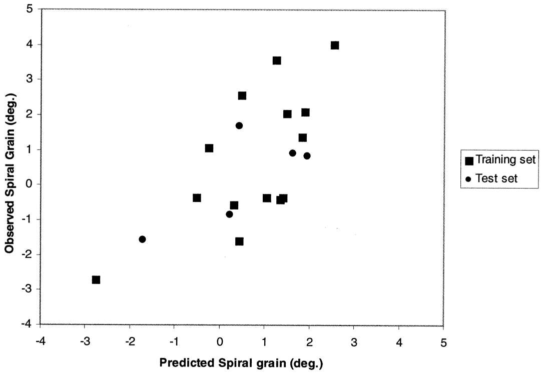

FIG. 5. Predicted and observed spiral grain for each log. Statistics for the fitted models are: Training set (■)—$R^2 = 0.45$; RMSE = 1.398° and Test set (●)—$R^2 = 0.55$; RMSE = 0.945°; Bias = −0.297°.

DISCUSSION

The results indicate that it is possible to predict the magnitude of fiber orientation of a log based on variables measured by an industrial X-ray log scanner. While the unexplained variation in the PLS-model is high ($R^2 = 0.45$ to 0.55), the results show a statistically significant relationship between the measured indicators BY, BX, and EK and fiber direction. These results warrant further and more comprehensive studies to develop a practical scanning system for sorting logs with critically high spiral grain. Recall that the prediction corresponds to fiber direction at 50 mm from the pith. It is important to note that this technique can be extended to predicting fiber direction at any other location (e.g., 20, 50, 100, 150, etc . . . mm). The reason for choosing 50 mm in this study was that it corresponds to the tangential surface of a 50-mm-thick centerboard, which is a common lumber cutting for Swedish structural lumber. Once the fiber direction is identified at a specified location in the log, logs with excessive or problematic spiral grain can be sorted. This sorting would prevent logs from being used in high value products such as furniture or building components where they may cause further quality problems.

A limitation of this study was the small log sample size. Nineteen logs represent a very minute fraction of the total variation that can be possible. Recall that the fiber direction observed in this study (see Table 1) ranged from +4.0° to −2.7°. In similar species, reported values in the literature range from +9° to −5° (Noskowiak 1963; Danborg 1994) for a similar distance of 50 mm from the log pith. Developing and calibrating a PLS-model that applies for the entire range of variability in fiber direction can be significantly different from the one tested in this study. Another limitation is that the results are based on simulations of an X-ray log scanner. Even though the simulated X-ray log scanner produces realistic theoretical results (Grundberg and Grönlund 1997), the commercial version of the scanner will generate image data that can be influenced by the industrial environment such as electrical noise and mechanical vibrations.

Despite the study limitations, the results show a significant correlation and motivate future studies on the subject. Future studies should not only address the aforementioned limitations, but should also determine more precisely what fiber direction is considered excessive whereby lumber produced from such logs will have unacceptable quality. Once a critical fiber direction is established, a metric can then be used to assess the performance of an X-ray log scanner system for sorting out logs with excessive spiral grain.

CONCLUSIONS

The results from this study indicate that it is possible to predict the fiber direction in logs based on variables measured by an industrial X-ray log scanner. The variables used to predict spiral grain were green heartwood density, knot volume, and a measure of the unsymmetrical distribution of knot volume. These results motivate work in further developing nondestructive evaluation technologies to identify and sort logs with excessive or problematic spiral grain.

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