Rapid Detection of Knot Defects on Wood Surface by Near Infrared Spectroscopy Coupled with Partial Least Squares Discriminant Analysis

Zhong Yang,* Maomao Zhang, Kang Li, and Ling Chen

Natural defects, especially knots, on the surface of veneers have a great influence on the sorting and degradation of veneers. To realize rapid and accurate knot detection, a study on the possibility of detecting knots was carried out. Samples of poplar, eucalypt, and masson pine were used. The experiments mainly focused on the ability of using the models built with samples from one type of knot and normal wood to predict samples from a different type of knot and normal wood within the same wood species; and when only the samples from middle-sized knots and normal wood were used, whether or not the model based on one species could predict the samples from another species. The results showed that using the model built with small knots and normal wood to predict the larger knots and normal wood was not satisfactory, but the model based on large knots and normal wood can predict the samples from smaller knots and normal wood under a certain condition. When only the middle-sized knots and normal wood from the three species were used, the model built with eucalypt samples could predict the samples from poplar, and *vice versa*; however, the model built with masson pine samples could not predict the other two sample species, and *vice versa*.

Keywords: Rapid detection; Knot defects; Wood surface; Near infrared spectroscopy; Partial least squares discriminant analysis (PLS-DA)

*Contact information: Research Institute of Wood Industry, Chinese Academy of Forestry, Beijing 100091, China; *Corresponding author: zyang@caf.ac.cn*

INTRODUCTION

Poplar, eucalypt, and masson pine are the main kinds of plantation trees that are rich in quantity and distributed most widely in China. These plantation trees present many advantages, such as fast growth and straight stem form, which make them suitable for plywood production. Production of plywood in China has increased rapidly over the last 20 years from 2.1 million m^3 in 1993 to more than 50 million m^3 in 2010 (Luo *et al*. 2013). Such high productivity makes it necessary to evaluate the quality of veneer. Some defects that result from manufacturing processes and natural wood variability have a great impact on veneers' performance. Natural defects are hard to avoid, especially knots, which is the most common natural defect that degrades veneers. There is some tannin and other chromophoric compounds present in knots, which degrade into colored substances with UV light and ultimately seriously influence the aesthetic property of the wood products (Suttie *et al*. 2004). Further, the presence of knots is also an important strength-diminishing factor; for example, the negative influence of margin knots on the bending strength of wood (Boatright and Garrett 1979), the influence of knots on the tensile strength of Japanese larch lumber (Takeda and Hashizume 1999), and the effect of knots on the modulus of elasticity and damping correlation (Hossein *et al*. 2011). In addition, some knowledge of the influence of knots on the stiffness, bending strength, and bending modulus of elasticity has also been reported (Frank *et al*. 2005; Todoroki *et al*. 2010; Zhong *et al*. 2012). Thus, it is very important to detect knots rapidly and accurately to ensure the quality of wood products.

Several nondestructive testing methods have been shown to be feasible for the detection of knots, such as microwave detection technology and ultrasonic methods, which utilize the principle of the difference in dielectrical properties and acoustic properties between knots and normal wood (Machado *et al*. 2004; Baradit *et al*. 2006). Charge-coupled device (CCD) cameras have been utilized to exclusively detect knots on the surface of sugi laminae, which not only can detect the existence of a knot but also measure the ratio of the knot diameter (Ohuchi *et al*. 2006). This method is limited, however, in that it is only suitable for the cases in which the color between knot area and the area around the knot has a greater contrast. As another means of detecting knots, X-ray methods have been used. Some researchers have achieved excellent results by making use of X-ray methods to detect and measure all kinds of knots in softwood (Rinnhofer and Deutschl 1997). Furthermore, laser scattering has been used to detect knots on veneer surfaces (Tormanen and Makynen 2009). Thermography and computed tomography (CT) technology also make contributions to the detection of knots (Bhandarkar *et al*. 2008). Despite the above methods applied, there is still no method that has the advantages of being simple to operate, rapid and accurate, while also providing high efficiency, no harmful radiation, and a wide application scope.

As a nondestructive detection technology, near-infrared (NIR) spectroscopy coupled with discriminant analysis is an effective tool with several uses: to discriminate blue-stained wood (Via *et al.* 2008), to classify the type of fungal decay in wood (Fackler *et al*. 2007; Yang *et al*. 2008), to identify the type of preservatives in wood (So *et al*. 2004), and to identify the wood species (Schimleck *et al.* 1996; Tsuchikawa *et al.* 2003; Pastore *et al*. 2011). In many discriminant analysis methods, partial least squares discriminant analysis (PLS-DA) and soft independent modeling of class analogy (SIMCA) have been the most common methods used to analyze the data of NIR spectroscopy. For SIMCA, it is necessary to build one principal component analysis (PCA) model of each class which describes the structure of that class as well as possible, and then use these models to predict which category a new sample belongs to. It is noted, however, that the information of other classes are not included when a separate model of one class is established, which results in limited discrimination power. Partial least squares discriminant analysis is a method based on partial least squares regression, which is performed for the sake of sharpening the separation between classes of observations and then a maximum separation among classes would be obtained by hopefully rotating PCA components. Thus, a better classification result might be attained using PLS-DA. Several studies have demonstrated that PLS-DA is an excellent discriminating analysis method and it has been widely used (Yang *et al*. 2008).

In a recent study, the ability of NIR spectroscopy coupled with SIMCA was investigated to detect the surface quality of knots detected on eucalypt veneers and results showed that the method had a classification accuracy of 94.4% for knot samples and 100% accuracy for knot-free samples (Yang *et al.* 2015). In the present study, PLS-DA was selected for analyzing the data from NIR spectroscopy. The purpose of this study was to investigate the following: (1) the ability of NIR spectroscopy coupled with PLS-DA to discriminate knots on the surface of poplar, eucalypt, and masson pine veneers, (2) the effect of knots' dimension and the spectral pretreatment on the discriminant results, and (3) the feasibility of using a model built with observations from one wood species to discriminate the observations from other wood species.

EXPERIMENTAL

Sample Preparation

Three different wood species, *i.e.*, eucalypt (*Eucalyptus urophylla* × *E. grandis*), poplar (*Populus* × *euramericana* (Dode) Guineir cv. 'San Martino' (1-72/58)), and masson pine (*Pinus massoniana* Lamb.), were used in this research. Eucalypt veneers were collected from 4-year-old and 6-year-old eucalyptus logs sourced from Guangdong Province (109°39′ to 110°38′ and 20°18′ to 21°30′), and the poplar and masson pine veneers were obtained from a mill in Anhui Province, China (118°14′ to 118°21′ and 32°4′ to 32°10′). The logs were cut into many sections of 2 m in length and then were air-dried. After air drying, all the samples were cut into the veneer specimens of 2000 × 1300 × 1.7 mm. Then, the large-sized veneers were sawed into small test veneers of 400 mm × 200 mm × 1.7 mm to collect spectrum data. Three different sizes of knots including small knots (less than 5 mm in diameter), middle-sized knots (10 to 15 mm in diameter), and large knots (20 to 25 mm in diameter) were selected and sorted from the surface of the veneers. The masson pine veneers contained all three sizes of knots, but eucalypt contained just middle-sized knots and small knots. As for poplar, there was just one type of knot – middle-sized knots.

NIR Spectroscopy

Near-infrared diffuse reflectance spectrums were collected using the ASD FieldSpec® NIR spectrometer (Analytical Spectral Devices, Boulder, CO) at a resolution of 1.4 nm over the wavelength range 780 to 1050 nm and a resolution of 2 nm over the wavelength range 1000 to 2500 nm at room temperature. A 2000 mm fiber optic probe (spot diameter of 18 mm) oriented at an angle of 90° above the veneer surface was used to collect the spectra. The instrument reference was a piece of commercial microporous Teflon® white board. Thirty scans were recorded for each detection area, and the results were averaged to yield the final spectrum.

Model Development

Data pretreatment and analysis were performed by means of Unscrambler (version 9.2, CAMO, Corvallis, OR) software. The acquired spectral data obtained from the knot and knot-free samples were modelled using standard partial least squares regression with one response variable (PLS1). The model PLS1 is one of the algorithms in PLS regression, which is a statistical method that involves the simultaneous and interdependent PCA and has the ability to analyze data with massive, noisy, collinear, and even incomplete variables in both X and Y (Wold *et al.* 2001). If there is more than one response variable, then the use of PLS2 is required. The full cross-validation was used when calibration models were constructed using PLS regression. The first derivative and standard normalized variate of the data were also analyzed. The predictability of the best PLS model was identified at the maximum value of the coefficient of determination during calibration (R^2_C) and the coefficient of determination during prediction (R^2_P), the minimum value of the root mean square error of validation (RMSEV), and root mean square error of pre-diction (RMSEP). Over two-thirds of the samples were used as the calibration set, and the rest of the samples were used for testing of predictions. The number of samples for the calibration and prediction set for the different species and different knot types are presented in Table 1.

Discriminant Analysis

Samples from the prediction set were subjected to discriminant analysis using the PLS-DA models. The *Y* variables (the predicted category variable) of the knot-free samples were assigned with a dummy number '1', and the *Y* variable of the knot samples were assigned with a dummy number '0'. In the predicted results, samples with $Y > 0.5$ and a deviation that did not cross the 0.5 line were recognized as knot-free samples, samples with $Y < 0.5$ and a deviation that did not cross the 0.5 line were recognized as knotted samples, and samples with a deviation that crossed the 0.5 line could not be safely recognized (Yang *et al.* 2008).

Table 1. Number of Samples for the Calibration and Prediction Set at Different Species and Different Knots Types

Species	Knot Types	Number of Samples		
		Calibration Set	Prediction Set	Total
Eucalypt	M	36	18	54
	S	40	20	60
	N	40	20	60
Masson Pine	B	40	20	60
	M	40	20	60
	S	40	20	60
	N	40	20	60
Poplar	M	40	20	60
	N	40	20	60
All species		356	178	534

*Note: B, M, S, and N: big knots, middle-sized knots, small knots, and normal wood, respectively

RESULTS AND DISCUSSION

NIR Spectra

Near infrared mean spectra collected from the same samples of various knot types of the three wood species are shown in Fig. 1. Several differences between the NIR spectra among these samples can be observed, although only rough information can be provided by the raw spectra. The second overtone of C-H stretching vibration in the region of 1188 to 1195 nm shows a change in absorption. The bands between 1916 and 1942 nm arise from the O-H asymmetric stretching and O-H deformation of water. Further, a greater variation can be found in the 1400 to 1600 nm and 2000 to 2500 nm regions. Bands between 1400 and 1660 nm are primarily attributed to the first overtone O–H stretching in cellulose, hemicellulose, and water, while the strength peak at approximately 2267 nm arose from the overtone of O-H stretching and C-O stretching in lignin. A more detailed description of band assignments of near infrared spectra of wood or wooden products has been reported by Schwanninger *et al*. (2011).

Effect of Knot Dimensions and Spectral Pretreatment on Calibration and Prediction

The PLS regression was used to classify the samples with knots and the samples without knots. Statistical summaries of the PLS1 models based on the raw spectra, first derivative, and SNV in the region of 780 to 2500 nm are shown in Table 2. The results of the models with and without different pretreatment methods are well represented with R^2_C values ranging between 0.96 and 0.99 and R^2_p values ranging between 0.94 and 0.99.

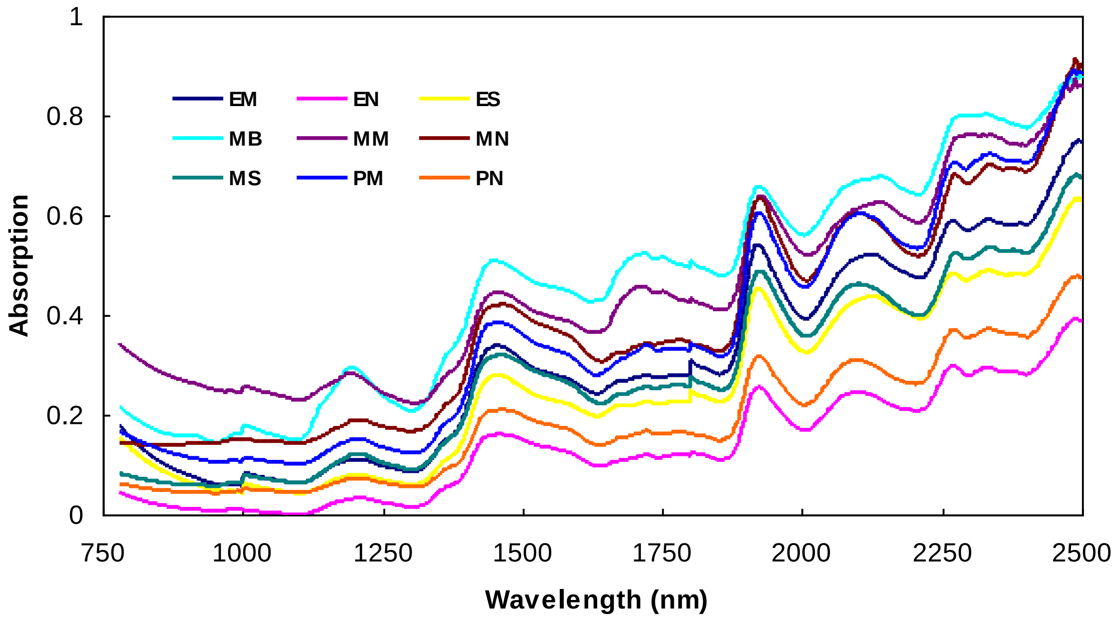

Fig. 1. Near infrared mean spectra of samples from different knot types of three wood species. Note: The first letter stands for the wood species (E - Eucalypt, M - Masson pine, and P - Poplar); The second letter stands for the knot type (B - big knots, M – middle-sized knots, S - small knots, and N - normal wood)

For the model based on the middle-sized knots and normal wood of eucalypt (M-N), the calibration with the first derivative spectra gave a higher correlation, with a R^2_C of 0.99, RMSEC of 7.9, R^2_P of 0.99, and RMSEP of 8.4. Likewise, for the model based on small knots and normal wood of eucalypt (S-N), the best results could also be provided by the first derivative spectra, with a R^2_C of 0.98, RMSEC of 9.6, R^2_P of 0.96, and RMSEP of 14. When comparing the results of the two models of eucalypt, the model based on middle-sized knots achieved a better modeling result than that based on small knots. Further, for the model of big knots and normal wood of masson pine (B-N), the calibration result based on SNV provided a higher R^2_C value of 0.99 and a lower RMSEC of mean value of 8, and the prediction result exhibited the same trends. As for the model of middle-sized knots and normal wood from masson pine (M-N), the best calibration and prediction results were given by the raw spectra, with a R^2_C of 0.98, RMSEC of 10, R^2_P of 0.98, and RMSEP of 11. With regard to the model based on the small knots and normal wood from masson pine (S-N), the strongest correlation was found in the first derivative spectra, with a R^2_C of 0.98, RMSEC of 11.1, R^2_P of 0.96, and RMSEP of 14.3. A similar conclusion was obtained that the calibration and predication performance might be affected by the dimension of knots and would decrease with a decrease in knot dimensions. This might indicate that NIR coupled with PLS-DA is very sensitive to the dimensions of the knots, which is different than the results using NIR coupled with SIMCA. In addition, the model from middle-sized knots and normal wood of poplar based on the first derivative spectra provided better calibration and prediction results than the other species, with the highest R^2_C value of 0.99 and the lowest RMSEC of mean value of 5.8, the highest R^2_P of 0.99, and the lowest RMSEP of mean value of 6.9. As a whole, the pretreatment methods including the first derivative and SNV did not significantly improve the performance of the models, and in some cases the R^2_C and R^2_P even decreased after pretreatment; therefore, the raw spectra were selected for the remainder of this study.

Table 2. Results of the Partial Least Squares Models with Different Spectra Pretreatments on the Full Near-infrared Range of 780 to 2500 nm

Pretreatment Methods		No. of PCs	R^2_C	RMSEC (%)	R^2_P	RMSEP (%)
Eucalypt (M-N)	Raw	4	0.99	8.4	0.98	9.7
	First Derivative	2	0.99	7.9	0.99	8.4
	SNV	5	0.99	8.3	0.98	9.4
Eucalypt (S-N)	Raw	5	0.98	9.6	0.96	16.5
	First Derivative	5	0.96	14.3	0.94	14.0
	SNV	5	0.98	10.3	0.97	16.6
Masson Pine (B-N)	Raw	4	0.99	8.0	0.98	12.2
	First Derivative	3	0.98	10.0	0.98	11.1
	SNV	3	0.98	10.2	0.97	9.3
Masson Pine (M-N)	Raw	4	0.97	11.7	0.96	11.0
	First Derivative	3	0.98	11.1	0.96	11.4
	SNV	2	0.97	11.5	0.96	11.7
Masson Pine (S-N)	Raw	7	0.99	5.8	0.99	14.2
	First Derivative	4	0.99	8.0	0.99	14.3
	SNV	6	0.99	8.4	0.98	13.7
Poplar (M-N)	None	4	0.99	8.3	0.98	8.0
	First Derivative	2	0.96	14.7	0.94	6.9
	SNV	4	0.98	9.6	0.96	8.8

*Note: PCs - principal components; RMSEC - root mean square error of calibration; RMSEP - root mean square error of prediction; and SNV - standard normalized variate

PLS Discriminant (PLS-DA) Classification Results Based on Models for Different Dimensions of Knots

To explore whether or not big or middle-sized knots could be discriminated using the model based on small knots, and *vice versa*, the samples from eucalypt and masson pine, which included different types of knots, were used for PLS regression and classification. The classification accuracies are presented in Tables 3 and 4. Table 3 shows that the classification accuracies of middle-sized knots and normal wood from the prediction set using the model based on samples from the corresponding calibration set both reached 100%; however, with the model built from the samples of small knots and normal wood from the calibration set, the classification accuracies of middle-sized knots and normal wood from the prediction set were 88.89% and 100%, respectively. Though the classification accuracy of middle-sized knots was reduced from 100% to 88.89%, these results were still favorable and higher than the results from NIR coupled with SIMCA, in which the classification accuracies of middle-sized knots and normal wood from the prediction set were 77.78% and 90%, respectively. Conversely, when using the model based on the samples of middle-sized knots and normal wood in the calibration set to classify the small knots and normal wood, the classification accuracies were 75% for small knots and 100% for normal wood, which were lower than the results of the model built with samples from the corresponding calibration set, in which the classification accuracies were 95% for small knots and 100% for normal wood. This might indicate that the model based on small knots and normal wood has the ability to predict and classify large knots and normal wood, but the ability to use the model based on large knots and normal wood to classify small knots has a slightly low probability. This might be explained by the fact that the spectra data from small knots also contains large amounts of information about normal wood due to the dimensions of small knots being much smaller than the spot diameter and that these are different from the spectra data of middle-sized knots.

Table 4 shows that when the models built with the corresponding calibration set were used, the classification accuracies of the samples are all 100%, whether the area considered was a big knot, middle-sized knot, small knot, or normal wood. Further, the classification accuracy of middle-sized knots using the model of big knots reached 100%, while the opposite was only 95%. The classification accuracy of small knots and normal wood using the model of larger knots and normal wood were also poor, with only 25% of classification accuracy. These results all show that the ability of using the model based on large knots and normal wood to classify small knots was relatively weak. In addition, the mutual authentication between big or middle-sized knots and small knots displayed poor results, and the classification accuracies of middle-sized knots and normal wood on the basis of the model built with small knots and normal wood was 85%, which is much better than that of big knots and normal wood using the same model, in which the classification accuracy was only 10%. So it might be concluded that the ability of using the model for small knots and normal wood to classify large knots is limited to samples whose difference in dimensions is relatively small, and if there exist wide variance in dimensions then the results of mutual authentication would be poor.

Table 3. Partial Least Squares Discriminant (PLS-DA) Classification Results of Middle-sized Knots, Small Knots, and Normal Wood using the Raw Spectra between 780 and 2500 nm for Eucalypt

Samples		Classification Accuracy (%)	
		Model $_{M-N}$	Model $_{S-N}$
M-N	M (n=18)	100	88.89
	N (n=20)	100	100
S-N	S (n=20)	75	95
	N (n=20)	100	100

Table 4. Partial Least Squares Discriminant (PLS-DA) Classification Results of Big Knots, Middle-sized Knots, Small Knots, and Normal Wood using the Raw Spectra between 780 and 2500 nm for Masson Pine

Samples		Classification Accuracy (%)		
		Model $_{B-N}$	Model $_{M-N}$	Model $_{S-N}$
B-N	B (n=20)	100	100	10
	N (n=20)	100	100	100
M-N	M (n=20)	95	100	85
	N (n=20)	100	100	100
S-N	S (n=20)	25	25	100
	N (n=20)	100	100	100

As explained, the classification accuracy of samples varied greatly with the models created for various knot types. To avoid the variation in results using models from different types of knots and the interference of other conditions, middle-sized knots and normal wood were the only type selected to research the PLS-DA classification results based on the models from different species. The PLS-DA classification results using the raw spectra between 780 and 2500 nm are listed in Table 5. The classification accuracies of the samples in the prediction set under the model built with the samples in the calibration set from the same species were all 100%. Additionally, the classification accuracy of samples from eucalypt on the basis of the model built with the samples from poplar unexpectedly reached 100%, and *vice versa*. This is a very important result because eucalypt and poplar are both hardwoods, and it seems that there is enormous potential for using a model built with one hardwood species to classify knots from knot-free samples of another hardwood species. On the contrary, the classification accuracy of the samples from masson pine based on the model from the two hardwoods was extremely unsatisfactory, and *vice versa*, and the classification accuracy of the samples were even 0%, which could be explained by the great differences that exist between softwood masson pine and the two hardwood species. From these results, it might be concluded that the classification performance of mutual authentication was very poor between hardwood and softwood, and it is necessary to determine whether samples are softwood or hardwood before classifying knots using NIR coupled with PLS-DA.

Table 5. Partial Least Squares Discriminant (PLS-DA) Classification Results of Middle-sized Knots and Normal Wood Using a Model Built with Observations from One Wood Species to Discriminate the Observations from Other Wood Species (780 and 2500 nm)

Samples		Classification Accuracy (%)		
		Model $_{Eucalypt}$	Model $_{Masson\ pine}$	Model $_{Poplar}$
Eucalypt	M (n=18)	100	25	100
	N (n=20)	100	100	100
Masson Pine	M (n=20)	15	100	25
	N (n=20)	0	100	90
Poplar	M (n=20)	100	0	100
	N (n=20)	100	100	100

CONCLUSIONS

This study successfully classified surface knots from normal wood using NIR spectroscopy coupled with PLS-DA. The specific research conclusions are as follows:

1. For all the models established by PLS-DA, the $R^2{}_C$ values and $R^2{}_p$ values ranged between 0.96 and 0.99, and 0.94 and 0.99, respectively. The performance of the models were not significantly improved by the first derivative and SNV, and it would actually be influenced by the dimension of knots, which would be worse with the decrease in knot dimensions.
2. When using the corresponding model, the classification accuracy of the samples reached 100%, except for the small knots, which reached 95%. When it comes to mutual authentication, it is concluded that the model based on large knots and normal wood cannot be used to classify small knots due to the poor results obtained. Using the model based on small knots and normal wood to classify large knots was only limited to some samples, whose difference in dimensions are relatively small.

3. The classification accuracy of samples from eucalypt on the basis of the model built with the samples from poplar unexpectedly reached 100%, and *vice versa*, while these good results were not obtained when using the model built with the two hardwoods to classify masson pine. There is enormous potential for using the model built with one hardwood to classify knots from knot-free samples of another hardwood. Thus, it is necessary to determine whether the samples belong to softwood or hardwood before classifying the knots using NIR coupled with PLS-DA.

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