NONDESTRUCTIVE EVALUATION OF WOOD USING ULTRASONIC FREQUENCY DOMAIN ANALYSIS

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INTRODUCTION

In-situ performance assessment of wooden structural components are very important for maintenance and rehabilitation of timber structures. Nondestructive evaluation (NDE) methods can play an important role in the in-situ assessment of structural performance. The ultrasonic technique has been found to be more accurate than the conventional practice of visual inspection in assessing the defects such as decays, knots, and splits in wood [1].

Most of the ultrasonic applications to wood, in the past, have relied solely on velocity measurements [2]. Such measurements do not make use of the valuable information provided by wave attenuation. The objective of this research is to develop an ultrasonic frequency domain analysis for the condition assessment of wooden structural members in the field. Before applying the proposed technique to field evaluation of wood, it is important to understand the effect of various parameters such as distance, moisture content and the presence of defects such as knots, rots etc. on ultrasonic measurements. It is also important to assess the natural variation of the ultrasonic parameters (e.g., wave velocity, signal amplitude) among different samples of sound wood [3]. Experiments were conducted on several yellow pine samples with and without knots, with varying travel distances in all the three directions (longitudinal, radial, and tangential). The use of wave attenuation measurements (in the frequency domain) have led to a more accurate technique for detection of defects such as knots.

DETERMINATION OF OPTIMAL EXPERIMENTAL SETTINGS

Before conducting a frequency domain analysis on the acquired data, it is very important to standardize the testing procedures so as to obtain consistent and repeatable results. The standardization includes application of constant pressure on the sensors

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and use of a couplant such as Vaseline Petroleum Jelly to minimize the effect of surface roughness. Consideration should also be given to factors such as sampling rate and number of waveforms to be averaged.

The ultrasonic pulse generator used in this research transmits a square wave into the piezoelectric transducer. The output of this transducer (i.e., input into the material) is not a pure sine wave but a complex signal with lot of ringing. The frequency of the input signal was about 125 KHz. Such low frequency was used in this study in order to achieve a better penetration depth. The diameters of the transmitting and receiving transducers were 1" and 0.5", respectively. The received signal was digitized using a sampling rate of $1x10^6$ samples/sec. This sampling rate was considered adequate since no difference was observed in varying the sampling rate over $1x10^6$. For this sampling rate, a record length of 1000 points (i.e., 1000 μsec) was used because it was found to be adequate to store the entire received signal [4]. The received waveforms were averaged to reduce the noise level. An averaging of 100 was selected since higher averaging did not reduce the noise level any further.

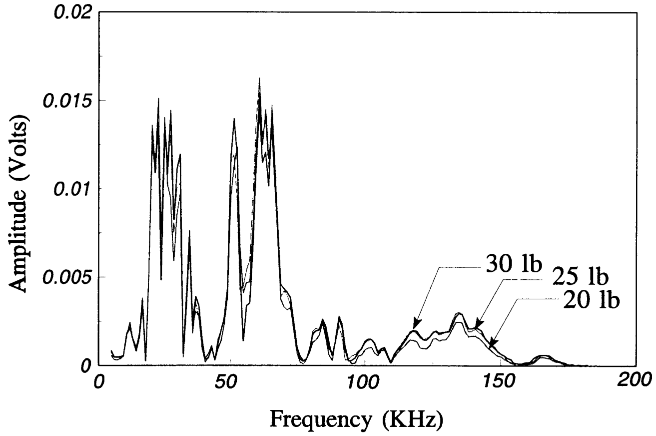

Figure 1. Comparison of FFT (magnitude) plots for yellow pine sample at varying clamping forces (20, 25, and 30 lbs) on the 125 KHz sensors (1" transmitter and 0.5" receiver) in longitudinal direction.

Laboratory experiments (through-transmission) using clamps with a load cell showed that the amplitude of the received ultrasonic signal in the frequency domain is very sensitive to the pressure applied on the ultrasonic transducers. Therefore, a constant clamping force has to be applied on the transducers to compare the Fast Fourier Transforms (FFT's) of different signals. High precession load cells with a capacity of 50 lb and an accuracy of 0.125 lb were used in this study along with quick grip clamps to apply a consistent pressure on the sensors so that the frequency domain amplitudes (FFT magnitude plots) between different experiments could be compared. A set of load display meters were used in conjunction with the load cell to read the load applied by the clamps on the sensor. In order to establish the optimum load on the sensors, waveforms were acquired from a given wood specimen at varying loads (20,25 and 30 lbs) on the sensors. The FFTs of the received signal from the same location are shown in Figure 1. It can be seen from this figure that the amplitude of FFT does not change in this load range for this particular set of 125 KHz sensors (1" diameter transmitter and 0.5" diameter receiver). However, the amplitude reduced significantly for lower clamping force (not shown in Figure 1). As no significant difference was observed in a load range of 20 to 30 lb (as shown in Figure 1) a constant clamping force of 25 lb was maintained throughout the experiments. This corresponds to a pressure of 127 psi on the 0.5" diameter receiving transducer.

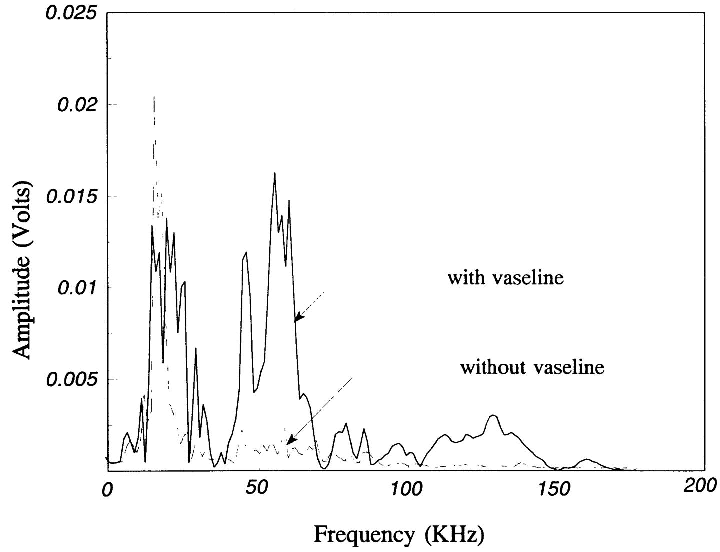

Figure 2. Comparison of FFT (magnitude) plots for clear yellow pine sample with and without vaseline at constant pressure (25 lb) using 125 KHz sensors in the longitudinal direction.

Since wood used in construction usually has a rough surface, a couplant such as vaseline was used to ensure proper contact between the sensor and the surface of the wood. Figure 2 shows the effect of vaseline on the signal's FFT at the same location on a yellow pine sample. Both waveforms in this figure correspond to the same location of wave transmission and reception on the specimen. It is obvious from this figure that a lot of energy is lost due to the small air gaps between the sensor and the rough surface of wood. Use of vaseline to fill up these air gaps greatly increases the amount of energy (specially the high frequency components) transmitted into wood, resulting in a higher signal to noise ratio. In addition, use of vaseline minimizes the effect of surface roughness.

PROCEDURE FOR DATA ANALYSIS

The received ultrasonic signal is stored in the computer. Time domain analysis (i.e., velocity and modulus of elasticity computations) can be done by measuring the travel time using an oscilloscope. The FFT of the received ultrasonic signal was obtained using the DADISP software. The first 800 points of the received signal were extracted before doing the FFT analysis. This length included the entire received signal, and enabled a constant record length. A DADISP function called "SPECTRUM" was used to obtain FFT plots which are normalized with respect to the record length. Different FFTs can be conveniently compared (during rapid field use) in terms of the signal strength using area under the FFT magnitude plot (A). The total area under the FFT (magnitude plot) has been chosen in this study as a measure of the signal amplitude.

Before interpreting the differences in FFTs for detection of defects in wood, it is important to understand the magnitude of the natural variation of the FFTs in clear wood. Results from experiments conducted during this study [4] have shown that the natural variation of the FFT values are generally within a range of 15 to 20%, whereas the variation due to defects is much higher (over 40%). Therefore, it is possible to distinguish defects from normal variations in sound wood.

EXPERIMENTAL RESULTS

Table 1 presents the summary of the time and frequency domain results obtained from the yellow pine samples with and without knots in the longitudinal direction at varying distance. The samples that were tested in this study were 11.5 cm x 7.5 cm in lateral dimensions (radial and tangential directions, respectively). Such big size sections were chosen for this study in order to avoid edge effects. Through-transmission tests were conducted on 9 clear wood samples and 10 samples with knots using three travel distances (15, 20 and 25 cm) for each sample in the longitudinal direction. Samples with knots were selected in such a way that the knots (approximately 1" in diameter) were in the path of transmission for all the three travel distances. Table 1 shows that there is very little difference between the velocities for clear wood samples and samples with knots. On the other hand, the average area under the FFT magnitude plot (A) for a travel distance of 15 cm is 742 volt.Hz for clear wood samples and 404 volt.Hz for samples with knots (i.e., 46% difference). This difference in the magnitude of FFT is due to the fact that the presence of a knot creates two interfaces and part of the energy gets reflected from these interfaces, thus causing a reduction in the transmitted energy. The corresponding standard deviations are 92 KHz and 119 KHz, respectively.

Table 1 also shows the change in the centroidal frequency for the two sets of samples. The samples with knots exhibit a lower centroidal frequency when compared to the clear wood samples. This shift is due to the fact that the high frequency components get attenuated more in the wood samples with defects. The decrease in centroidal frequency (C.F) of the received signal may be related to the types of defects (e.g., rotten areas, knots, checks etc.) in wood. This issue has not been studied fully and needs further investigation.

Table 1. Results from yellow pine samples (12% MC) with and without knots in longitudinal direction at varying distance using 125 KHz sensors.

No. of samples	Distance (cm)	Average of A (volt.Hz)	S_A (volt.Hz)	Average C.F (KHz)	S_{CF} (KHz)	Average Velocity (m/sec)	S_V (m/sec)
Clear yellow pine samples							
9	15	742	92	71	3.7	5146	402
9	20	609	136	72	3.2	5087	396
9	25	466	107	69	3.0	5100	413
Yellow pine samples with knots							
10	15	404	119	64	6.1	5137	426
10	20	316	99	63	6.5	5041	385
10	25	220	31	62	4.8	5047	377

A	Area under FFT (magnitude) plot
S_A	Standard deviation of A
C.F	Centroidal frequency
S_{CF}	Standard deviation of the centroidal frequencies
S_V	Standard deviation of the velocities

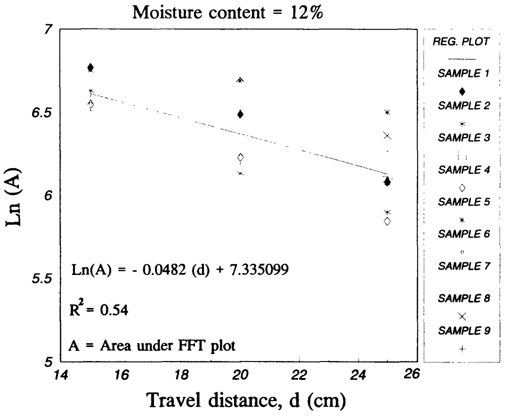

Figure 3. Regression plot for attenuation versus distance in longitudinal direction for clear yellow pine samples using 125 KHz sensors.

The results in Table 1 for clear wood samples show that the area under FFT magnitude plot (A) decreases with increase in distance. This is because the ultrasonic wave attenuates with travel distance. This wave attenuation usually follows a logarithmic relationship. Figures 3 and 4 show the regression plots in the longitudinal direction for clear samples and samples with knots, the knots being oriented in the tangential direction. The negative of the slope of the regression line (i.e., attenuation coefficient) is 0.0482 cm^{-1} for clear wood samples and 0.05749 cm^{-1} for samples with knots. This implies that the attenuation is 16% higher in samples with knots.

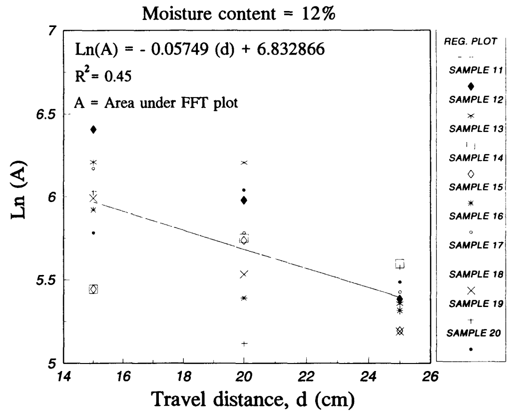

Figure 4. Regression plot for attenuation versus distance in longitudinal direction for yellow pine samples with knots using 125 KHz sensors.

Similar tests were conducted in the radial and tangential directions to obtain attenuation versus distance. The attenuation coefficient (i.e., negative slope of the regression line) in the radial and tangential directions were obtained as 0.22 cm^{-1} and 0.21 cm^{-1}, respectively. These attenuation coefficients (in the transverse directions) are approximately 4 to 5 times that in the longitudinal direction.

Table 2 shows the results for yellow pine samples with and without knots in the transverse directions at constant distance. In these samples the knots were oriented more or less in the tangential direction. It can be seen that the average of "A" in the tangential direction for samples with knots is 45% less than that of the clear wood samples, whereas a reduction of 27% was observed in the radial direction. Since the knots in the samples used in this study were oriented in the tangential direction it is possible that some of the travel paths in the radial direction did not include the knots. This explains the smaller percentage reduction in the amplitude (A) along the radial

Table 2. Results from yellow pine samples (12% MC) with and without knots in tangential and radial direction at constant distance using 125 KHz sensors.

No. of samples	**Distance (cm)**	**Average of A (volt.Hz)**	**S_A (volt.Hz)**	**Average C.F (KHz)**	**S_{CF} (KHz)**	**Average Velocity (m/sec)**	**S_V (m/sec)**
Tangential direction (clear yellow pine samples)							
18	7.5	179	41	49	2.7	1667	121
Tangential direction (yellow pine samples with knots)							
10	7.5	98.4	30	45	4.3	1898	189
Radial direction (clear yellow pine samples)							
19	11.3	119	27	42	2.0	1836	173
Radial direction (yellow pine samples with knots)							
10	11.3	87	16.5	44	4.0	2080	158

A	Area under FFT (magnitude) plot
S_A	Standard deviation of A
C.F	Centroidal frequency
S_{CF}	Standard deviation of the centroidal frequencies
S_V	Standard deviation of the velocities

direction. It is important to note that the transverse velocities in samples with knots is more than the velocities through clear wood samples (Table 2) which might be misleading at times. The frequency domain analysis makes use of the valuable information provided by the wave amplitude and attenuation measurements, which can enable the location of defects with more certainty.

Further tests conducted on a yellow pine sample (obtained from a 12 year old bridge) showed a difference of 34% between the velocities in sound and rotten areas. A much larger (approximately 5 times) difference was observed between the frequency domain amplitudes of the signals (A) from the sound and rotten areas. The higher frequency components were found to attenuate more than the lower frequency components in the rotten wood, that is, there was a shift in the centroidal frequency towards the lower frequency in case of rotten wood. A time domain analysis (using velocity comparisons) does not make use of the valuable information provided by wave attenuation, which can be easily measured in the frequency domain.

CONCLUSIONS

This research presents a new concept involving spectral analysis of ultrasonic signals from wood. The research involved a comparison of results from time and frequency domain analysis on several yellow pine samples with and without knots. The wave attenuation measurements in the frequency domain in conjunction with wave velocity measurements was found to be more accurate in the identification of defects such as knots and rots in wood. For example, measurements (in the time domain) on an yellow pine sample showed a difference of 34% between the velocities in sound and rotten wood. However, a much larger (approximately 5 times) difference was observed between the magnitudes of the fast fourier transforms (FFTs) of the signals from sound and rotten wood.

Linear regression relationships were developed to determine the attenuation of the received ultrasonic signals as a function of distance and travel direction. These attenuation coefficients can be used in the field to apply a correction factor to the signal amplitudes based on the wave travel distance and direction. Very little difference was observed between the velocities for clear wood samples and samples with knots in the longitudinal direction. On the other hand, a difference of 46% was found between the area under FFT magnitude plots (A) for the two sets of samples (with and without knots). The wave attenuation coefficient of the ultrasonic signals in the longitudinal direction as a function of distance is 16% higher in samples with knots when compared to clear wood samples. The attenuation coefficient in the transverse directions (0.22 cm^{-1}) is about 4 times the value in the longitudinal direction (0.05 cm^{-1}) for clear wood samples. It was observed that the average of "A" in the tangential direction for samples with knots is 45% less than that of clear wood samples, whereas a reduction of 27% was observed in the radial direction. On the other hand the transverse velocities in samples with knots is more than the velocities through clear wood samples which might be misleading at times. The samples with knots also exhibited a lower centroidal frequency when compared to the clear wood samples. This shift is due to the fact that the high frequency components get attenuated more in wood with defects. Thus, the frequency domain analysis can provide added information which is not available solely from the time domain (velocity) measurements. Research is in progress to establish the effect of moisture content on the ultrasonic wave attenuation and to correlate the different types of defects to the shift in centroidal frequency.

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