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Comparing Idealized Acoustic Wave Behavior to that Observed in Clear Wood and Lumber

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Abstract

In this paper, the behavior of an acoustic wave within an idealized wood specimen are compared and contrasted to the acoustic behavior observed in clear wood and lumber using signal processing and analysis. Published information on the physical and mechanical properties of clear, defect-free wood is used to derive a model of acoustic wave behavior. The model closely matches results observed from defect-free wood. Wave behavior is also examined in a series of wood specimens containing strength reducing defects such as knots and slope of grain. Differences between the idealized model results and those observed from the specimens are noted and attributed to characteristics observed through visual inspection and X-ray scanning. A series of metrics are examined with the goal of developing mathematical indicators from the acoustic signals to assess how the presence of defects affect wood strength. This research paper is the first phase of a study designed to examine the use of advanced signal processing techniques with acoustic based lumber grading technologies to evaluate the modulus of elasticity and strength of structural lumber.

Keywords: conference, paper, instructions, template

Introduction

Various nondestructive methods are currently used to evaluate, and grade structural lumber. Evaluation of visual characteristics of a piece of lumber is arguably the most widely used nondestructive evaluation technique in the forest products industry. Characteristics such as the size, number, and location of knots are common visual characteristics considered when grading lumber.

Research has shown that several physical and mechanical characteristics can be used to grade lumber (Senft et al. 1962; McKean and Hoyle, 1964; Ross, 1984a; Ross, 1985b; Ziegler, 1997; Galligan and McDonald 2000; França et at., 2017a; França et al., 2018b; França et al., 2019c). Products of this research have evolved into commercially available, rugged equipment that is used in the lumber grading process.

One of the technologies that is currently in use is based on measurement of the acoustic properties of a lumber specimen. Specifically, the speed at which a mechanically induced acoustic wave flows along the length of a specimen is measured and coupled with its density to determine its modulus of elasticity (MOE). This information, along with certain visual characteristics, can result in the assignment of a grade to the piece of lumber.

The flow of an acoustic wave in a lumber specimen is influenced by a variety of factors, such as the size, number, and location of knots. It is widely accepted that these factors have an influence on the MOE of a particular piece of lumber. Consequently, determination of MOE with this technique is useful from a practical viewpoint (Hoyle, 1968; Galligan et al. 1986).

The measurement system currently employed to determine MOE yields an electronic signature that contains additional information regarding the movement of an acoustic wave in a lumber specimen. While a significant number of published research findings exist on the measurement and use of acoustic-based MOE for evaluating lumber and other wood products (Beall, 1987; Kánnár, 2000; Sandoz et al. 2000; Ballarin et al., 2002; Seeling, 2002), little more than cursory information is published on the effects that naturally occurring characteristics have on acoustic wave behavior in lumber and the potential impact these have on evaluating lumber strength.

The objectives of the research presented in this research paper were to: 1. Examine fundamental acoustic wave behavior in clear wood and lumber; 2. Explore the effect that naturally occurring defects such as knots have on acoustic wave behavior in lumber, and; 3. Investigate the possibility of using advanced signal processing techniques to enhance acoustic-based lumber processing.

Material and Methods

The specimens utilized in the experimental phase of this study were cut from a sample of visually graded (No. 2) southern pine 2 by 8 in (nominal) lumber. Sixty-one (61) 1.5 in. by 1.5 in by 96 in (38 x 38 x 2438 mm) specimens were used (Figure 1). These specimens were conditioned to approximately 12 percent equilibrium moisture content prior to testing. Each specimen’s dimensions and weight were measured prior to testing. Specimens were selected based upon visual inspection with the goal of obtaining a wide range of characteristics. The specimens included several that were visually free from significant strength reducing defects, including knots. Other specimens contained large knots.

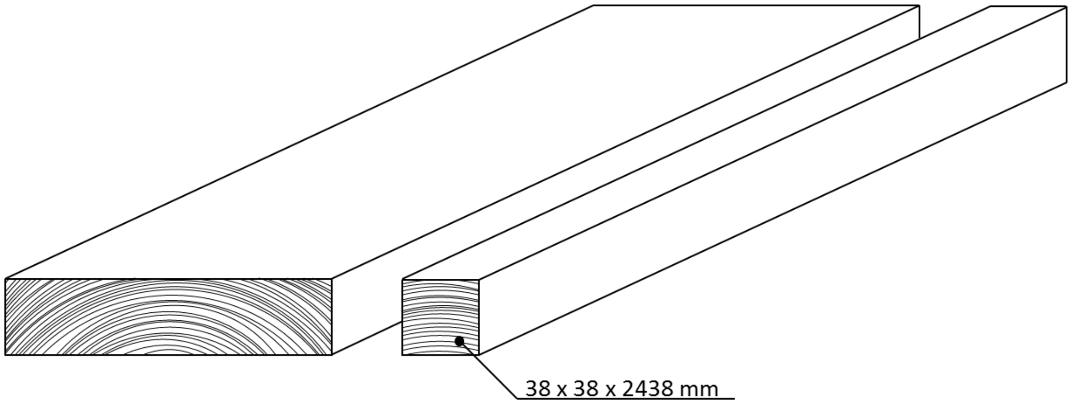


Figure 1 – Description of specimen size

The measurement system developed and employed is illustrated in Figure 2. Simple eraser type rubber was used as supports to insulate the specimens from external damping. A pendulum with a small lead weight (5 grams) was used as excitement system. Same height (potential energy) was used for all specimens. The longitudinal vibration waves that traveled though the piece was measured under equilibrium moisture content conditions (12% MC).

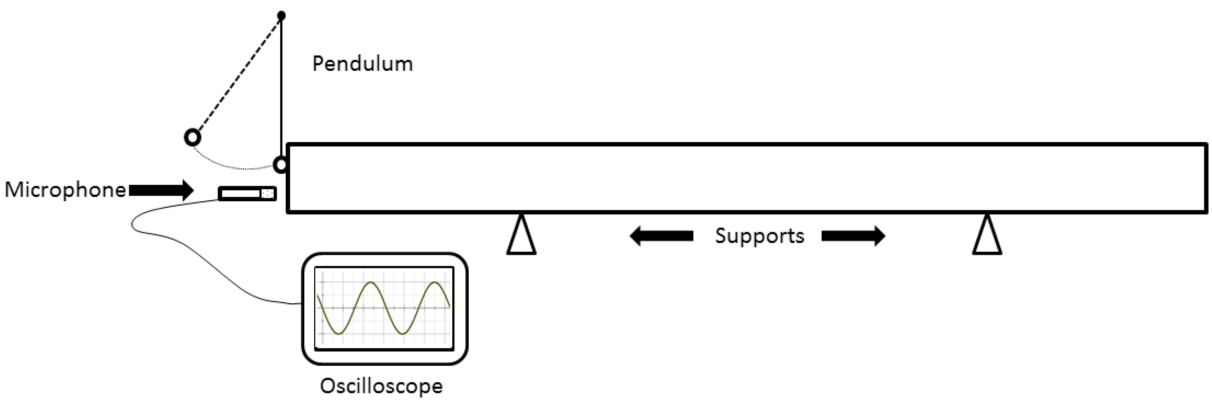


Figure 2 – System for measuring and recording time and frequency domain signal

The time domain signal from each specimen was recorded and a fast Fourier transformation (FFT) was performed to reach the frequency domain spectrum. The MOE of each piece was then calculated from the first harmonic peak in the frequency domain signal. The primary sensing element was a small, commercially available microphone and condenser (microphone USB 2.0, condenser SF-555B, with a frequency response range of 100Hz-16 KHz and a sensitivity of -47dB ± 4dB). This was coupled to an IBM compatible laptop personal computer (Dell Model Latitude E6540). Software from the Fakopp Portable Lumber Grader (Version 2.0) was used for data acquisition and waveform analysis. The frequency domain signal from each specimen was further analyzed. Extra peaks in the signal were investigated as associated to natural characteristics/defects in the wood specimens.

Longitudinal vibration measurement was conducted on each board to obtain the stress wave velocity. A stress wave was initiated by a hammer impact on one end of the specimen. Stress wave propagation in the wood specimen was sensed by a piezoelectric transducer mounted on the same end of the pendulum hit. Stress wave velocity can be determined by Equation 1:

$$C = \frac{2L}{\Delta t} \quad (1)$$

where C is stress wave velocity (m.s^{-1}), L is length of specimen (m), and Δt is time of flight (s).
The relation between acoustic velocity, density and wood stiffness is described by the fundamental wave equation (Bucur, 2003). The dynamic MOE of the specimens obtained by stress wave timer were determined using one-dimensional propagation waves, based on Equation 2.

$$E_{SW} = \rho C^2 \tag{2}$$

where E_{sw} is stress wave modulus of elasticity, ρ is the density at 12% moisture content (kg.m^{-3}), and C is stress wave velocity (m.s^{-1}).
Wave attenuation (logarithmic decrement) can be determined from the rate of decay of the amplitude of pulses using the following equation:

$$\lambda = -\frac{1}{T}\ln\left[\frac{x_{n+1}}{x_n}\right] \tag{3}$$

where $\boldsymbol{\lambda}$ is the logarithmic decrement, T is the period of the damped oscillation, x_{n+1} and x_n are the maximum amplitudes of two successive oscillations.

Tensile tests were conducted according to ASTM D 198-15 (2015) to evaluate the tensile strength of each specimen. The tensile test machine (Metriguard Model 401) was used for the tension test. The tension proof machine was equipped with serrated plates to grip the specimens. Test span was 1500 mm and the loading rate set to cause failure was between 1 to 3 minutes. An extensometer was attached to the specimen to determine the tension modulus of elasticity.
Ultimate tension stress (UTS) was determined using the following equation:

$$UTS = \frac{P}{t \cdot w} \tag{4}$$

where UTS is the ultimate tensile stress (MPa), P is the maximum load (N), t is the thickness (m), and w is the width (m) of the specimen.
Tensile modulus of elasticity (MOE_t) was determined using the following equation:

$$MOE_t = \frac{P_{\Delta} a_n}{tw\Delta_t} \tag{5}$$

where MOEt is the tensile modulus of elasticity (MPa), P_{Δ} is the load at the elongation Δ_t (MPa), a_n is the gage length (m), t is the thickness (m), w is the width (m) of the specimen, and Δ_t is the elongation (m).

Results and Discussion

Table 1 summarizes the testing data. The average density of the pieces was 578 kg·m^{-3}, ranging from 416 to 744. The stress wave velocity ranged from 2982 to 5667 m·s^{-1}. Stress wave MOE ranged between 4203 and 20764 MPa. Logarithmic decrement ranged between 0.0312 and 0.0899. Ultimate tensile stress range from 13.61 to 125.76 MPa. Tensile modulus of elasticity ranged between 5271 and 24525 MPa.

Table 1. Summary of testing data

ID	Density (kg·m^{-3})	Velocity (m·s^{-1})	dMOE (MPa)	MOEt (MPa)	UTS (MPa)	Log decr.	ID	Density (kg·m^{-3})	Velocity (m·s^{-1})	dMOE (MPa)	MOEt (MPa)	UTS (MPa)	Log decr.
1	571	5233	15634	15998	69.64	0.0466	32	744	5067	19091	15933	125.76	0.0502
2	554	3930	8558	10607	60.71	0.0551	33	728	5130	19170	20930	105.17	0.0437
3	465	4350	8805	11021	23.27	0.0621	34	664	5447	19701	19938	109.91	0.0451
4	581	5355	16655	16832	73.44	0.0392	35	479	5018	12066	12005	36.39	0.0522
5	547	4265	9953	9976	51.69	0.0564	36	416	4515	8479	8304	17.94	0.0522
6	648	5482	19465	24963	50.08	0.0431	37	570	5579	17737	20275	77.74	0.0367
7	560	4853	13187	12745	20.79	0.0702	38	556	5603	17466	22756	73.47	0.0419
8	629	4984	15636	13761	93.61	0.048	39	590	5564	18256	22528	76.00	0.0338
9	441	5174	11800	13134	25.30	0.0454	40	597	5584	18622	21936	91.57	0.0416
10	601	5087	15554	16200	49.63	0.0709	41	609	5521	18572	21294	46.25	0.0375
11	554	5145	14658	15099	54.34	0.0563	42	578	5628	18317	19716	81.72	0.0454
12	541	4708	11992	11007	40.38	0.0685	43	578	5521	17608	20851	87.50	0.0446
13	628	4847	14762	14164	63.93	0.0622	44	571	5525	17440	19558	86.89	0.0391
14	566	5189	15236	15274	52.97	0.0414	45	601	5589	18778	25402	47.62	0.0383
15	525	4161	9083	10030	52.64	0.0835	46	488	2982	4335	6746	15.61	0.0899
16	479	4789	10993	13618	27.87	0.0706	47	570	5438	16866	17617	94.83	0.05
17	593	4804	13686	18077	62.06	0.056	48	615	5482	18489	17367	42.85	0.0495
18	464	4562	9656	6500	20.48	0.0499	49	599	5667	19234	22975	47.86	0.0362
19	605	4437	11908	18619	32.37	0.0702	50	460	4555	9537	11285	17.66	0.0563
20	653	5038	16577	16072	44.85	0.0558	51	555	4955	13629	13393	52.95	0.0398
21	706	5023	17821	15871	84.92	0.0587	52	549	4807	12695	9260	20.67	0.0496
22	627	4916	15149	19945	104.64	0.0513	53	464	4552	9626	13062	27.54	0.0601
23	591	5496	17845	19618	83.29	0.0385	54	510	4492	10295	10935	14.79	0.0577
24	540	4916	13060	13549	45.20	0.054	55	484	4495	9784	8498	36.35	0.0524
25	671	5394	19512	17301	111.14	0.038	56	535	5486	16115	13482	95.53	0.0391
26	681	5443	20176	25472	81.60	0.0312	57	556	5062	14240	18614	101.34	0.0389
27	551	4179	9623	6396	26.79	0.0594	58	560	5525	17104	18280	92.70	0.0401
28	687	5399	20025	20839	78.76	0.0433	59	446	3069	4203	5861	13.61	0.0829
29	697	5379	20159	17513	89.58	0.035	60	603	4687	13251	17393	45.89	0.0402
30	691	5482	20764	23287	101.65	0.0387	61	593	4644	12796	11884	15.70	0.0488
31	738	4911	17804	15729	115.67	0.0463							

Mean trends in the relationship between stress wave MOE and tensile MOE for the 2 by 2 southern pine pieces are shown in Figure 3. Linear regression was significant.

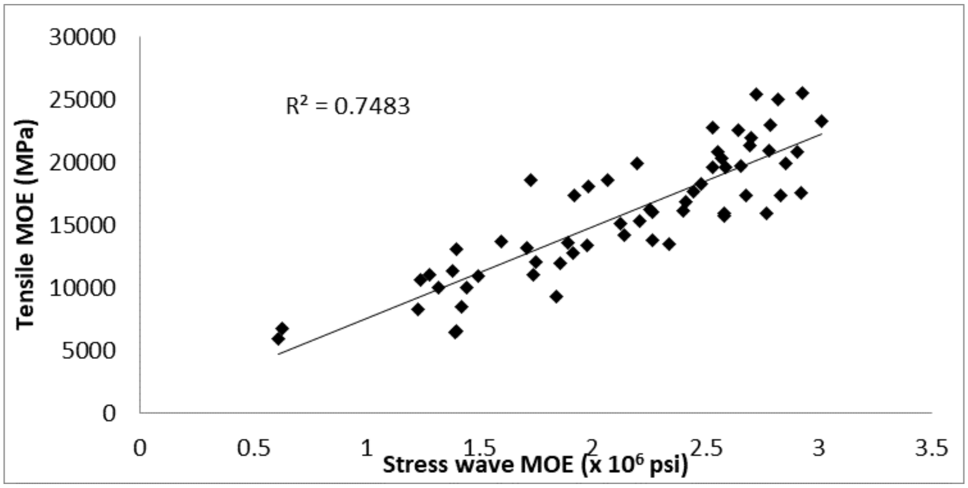


Figure 3 – Tensile MOE versus stress wave MOE

Mean trends in the relationship between stress wave MOE and ultimate tensile stress (UTS) for the 2 by 2 southern pine pieces are shown in Figure 4.

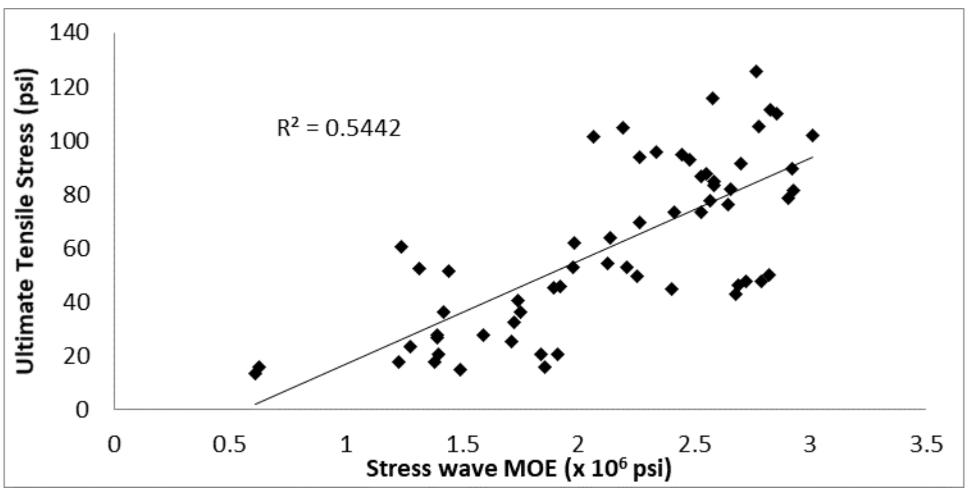


Figure 4 – Ultimate Tensile Stress versus stress wave MOE

Mean trends in the relationship between logarithmic decrement density^{-1} and ultimate tensile stress (UTS) for the 2 by 2 southern pine pieces are shown in Figure 5.

The combination of logarithmic decrement and density exhibited potential for ultimate tensile stress estimation. There was no significant difference compared to the UTS estimation using the dynamic MOE. Dynamic MOE is recommended for being a common variable in lumber industry.

A theoretical longitudinal vibration of a prismatic bar was generated using physical and mechanical property data for loblolly pine. Figure 6 exhibits a time domain with 9 harmonics of the fundamental frequency and frequency domain analysis, showing the relative magnitude of each harmonic.

Time domain and frequency domain analyses of a high strength piece are shown in Figure 7. In time domain it was possible to see the high and low peaks during longitudinal vibration. In frequency domain it was possible to determine 6 harmonics. The number of harmonics relates to energy conservation during vibration.

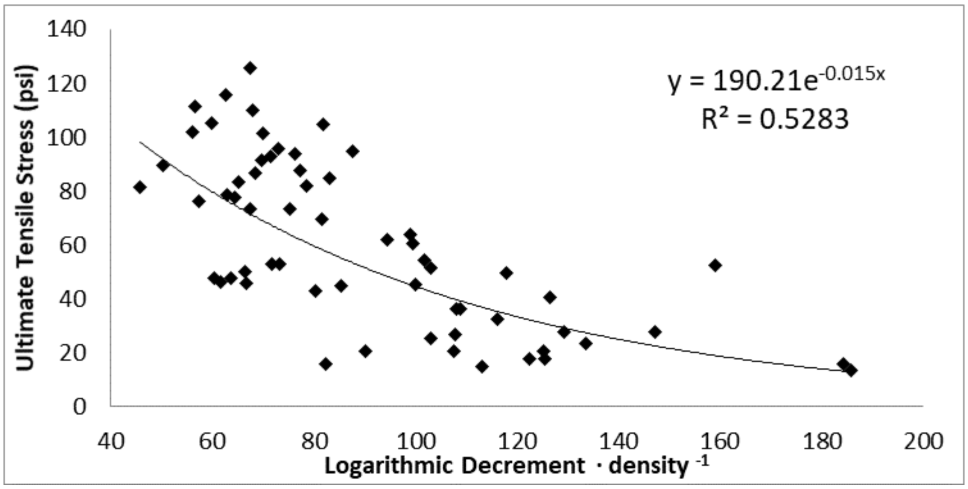


Figure 5 – Ultimate tensile stress versus logarithmic decrement density^{-1}

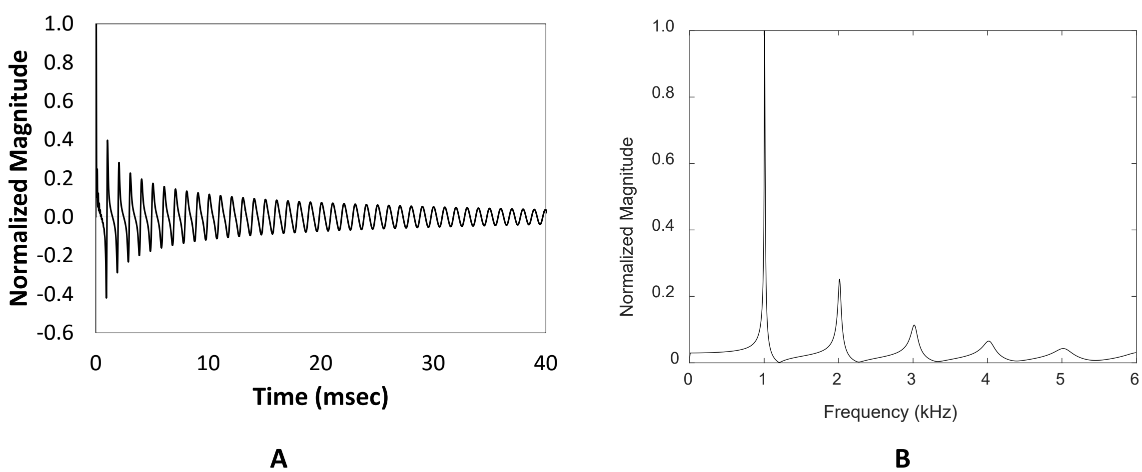
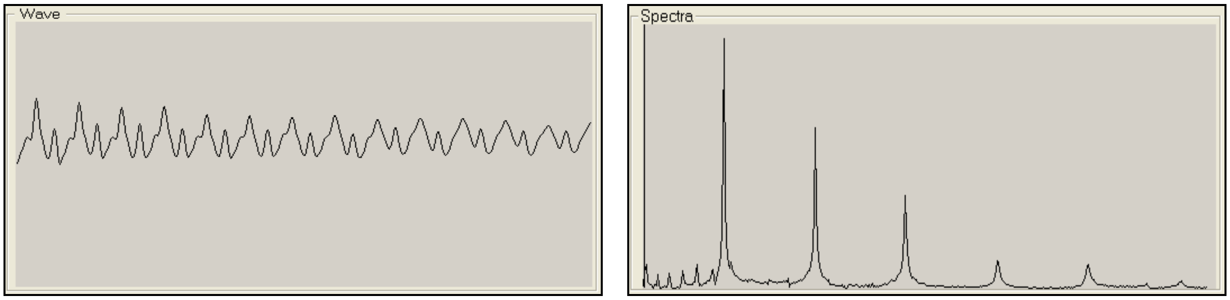


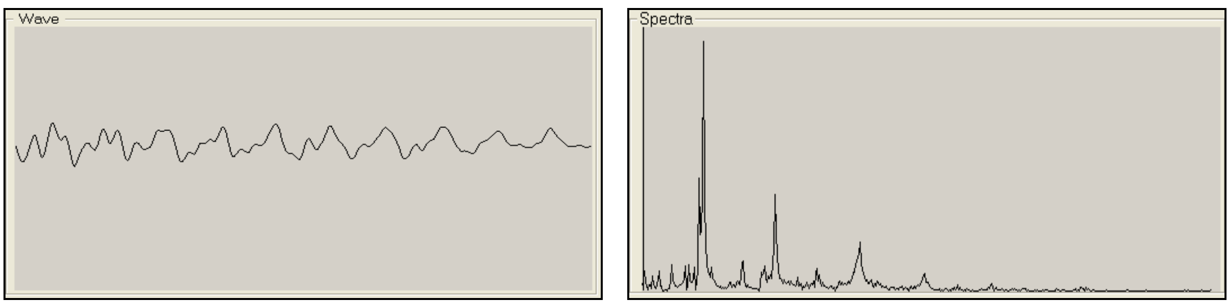
Figure 6 – Theoretical longitudinal vibration of a prismatic bar, generated using physical and mechanical property data for loblolly pine. **A)** Time domain with 9 harmonics of the fundamental frequency. **B)** Frequency domain analysis, showing the relative magnitude of each harmonic.



A B

Figure 7 – A) Time domain of piece 32 (high strength). **B)** Frequency domain analysis, showing 6 harmonics.

Time domain and frequency domain analyses of a low strength piece are shown in Figure 8. In time domain it was possible to see the difference in peaks compared to a high strength piece. There is not a sine shape formed. In frequency domain it was possible to determine 4 harmonics. The reduced number of harmonics relates to energy dissipation during vibration. A low strength piece tends to loose vibration energy faster.



A B

Figure 8 – A) Time domain of piece 27 (low strength). **B)** Frequency domain analysis, showing only 4 harmonic.

Observation of the vibration signals of the pieces has revealed that pieces with high strength characteristics exhibited a signal with different characteristic in time and frequency domain signals. Time of flight was useful to estimate stiffness. However, this measurement showed a lower estimation happened for lumber strength.

Signal analysis results show that there are potential advantages of using the comparison of the expected and the actual vibrational signal and relates it to tension strength. This would increase the power of the actual grading system and improve the valuation of the southern pine lumber.

Conclusions

- Logarithmic decrement combined with density has a potential for strength correlation;
- Fundamental acoustic wave behavior in clear wood and lumber was evaluated;
- Defects such as knots influence acoustic wave behavior in lumber;
- High strength pieces exhibited more harmonics in frequency domain analysis;
- Pieces with strength reducing defects tends to lose vibration energy quicker;
- The use of advanced signal processing techniques can enhance acoustic-based lumber processing.

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