NONDESTRUCTIVE DETECTION OF THE EFFECT OF DRILLING ON ACOUSTIC PERFORMANCE OF WOOD

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The aim of this paper is to determine the effect of hole diameter (LR Direction) on acoustic performance indicators such as acoustic coefficient and acoustic conversion efficiency of wooden beams using flexural vibration of a free-free bar test. The drilling from 0 to 8 millimetres diameter was made exactly at the middle of the bar, on the node of the second mode of vibration. The results revealed that holes of diameter from 0 to 8 millimeters didn't cause any sever change on acoustic coefficient and acoustic conversion efficiency when the beam was impacted on both radial and tangential surfaces. Nevertheless, these acoustic properties changed a bit when the beam was impacted on the tangential surface. Thus, the changes of the acoustic coefficient and acoustic conversion efficiency for both radial and tangential impacts were not significant, even with an 8 mm hole. Therefore, hole diameter not only didn't cause any severe effect on acoustic coefficient and acoustic conversion efficiency but also somewhat increased their values. So, a hole having a relatively small diameter may cause improved acoustical performance of a wooden beam.

Keywords: Acoustic Coefficient; Acoustic Conversion Efficiency; Flexural vibration; Hole; Radial Impact; Tangential Impact;

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INTRODUCTION

Wood has been used mainly as a construction material or as fuel by people for a long time, but in more modern times it has been used very widely in our life, including for interior decoration materials, furniture, and wooden floorings. Because wood is a natural material, parts of manufactured items that are touched by human skin are often made of wood, helping to fulfill the human desire to return to nature in the midst of an increasingly artificial modern life.

Humans seek beauty and desire in art, so wood is used as the material for musical instruments. Although the materials of the musical instruments have been replaced by iron, plastic, and many other materials, wooden musical instruments retain a characteristic sound color and acoustic properties. So, many musical instruments continue to be made from wood.

Wooden beams are very important construction elements because of their widespread usage in construction and machinery. Despite all positive aspects of wooden beams, they are prone to defects. Generally the defects of wood such as cracks, holes, fissures, etc. can be produced from climatic stresses and poor structure of wooden beams. Defects influence in a negative way the service life of structures and the end products. Thus, detection of them even at a very small size is very important in order to guarantee structural safety and to minimize costs related to safety. So, it is important to understand the dynamic behaviour of defective beams.

Damage assessment methods attempt to determine whether structural damage has occurred, as well as the location and extent of any such damage. Nondestructive techniques are generally used to investigate the critical changes in the structural parameters so that an unexpected failure can be prevented. Holes, as one type of structural damage, present a serious threat to the proper performance of structures. Holes can decrease strength properties of wooden beams. This means that presence of a cavity or hole will result in loss of mechanical strength, possibly leading to failure. Hole formation due to loads leads to fatigue of the structure and to discontinuities in the interior configuration. Holes in vibrating components can initiate catastrophic failures.

Although it is useful to identify holes locations and magnitudes, detection of the effect of a hole has not been studied in detail by researchers. Among defects, cracks have been studied to a greater degree than holes. The finite elements method has been used to determine the crack locations and magnitudes for a cantilever beam that has one crack. Natural frequency of the beam has been also determined and verified experimentally (Kam and Lee 1992). A crack occurring in a structural element causes a local variation in stiffness, affecting the dynamic behaviour of the structure to a considerable degree (Chati et al 1997). Frequencies that give the specific Young's modulus of the low order modes are significantly influenced by damage within a beam (Kubojima et al. 2005). The variation of the instantaneous frequency increases with increasing crack depth, and consequently instantaneous frequency can be used for estimation of crack size (Loutridis et al 2005). Cracks have been detected in elastic beams by static measurements (Caddemi and Morassi 2006). A thermo-graphic camera was used to detect the defects in wood and wood-based materials (Meinlschmidt 2005). A method was used to determine the type and size of a defect at the boundary of two elastic bodies. The proposed method was based on the difference in the character of the stressed deformed state inside a body in the near vicinity of a defect, depending on the type of the defect and its presence. The method relied on the solution of a number of direct boundary-value problems (by the method of finite elements) and inverse problems (by the method of boundary integral equations) (Vatul'yan and Solov'ey 2004). It was verified that there is a difference between two series of evaluations of shear modulus through LT and LR vibrations (shear modulus obtained by impact on tangential (LT) and radial (LR) transverse directions) in clear beams. So the introduced differences might be an indicator of a defect. Greater differences between shear modulus evaluations of a proper bar may indicate greater defects, i.e. holes (Roohnia et al. 2010). The effects of longitudinal cracks (which were induced at one end of the specimen longitudinally parallel to annual rings) were studied on elastic parameters of poplar wooden rectangular bars. Their study revealed that if longitudinal specific modulus of elasticity evaluated from both LR and LT flexural vibrations were almost equal and GLR (shear modulus obtained from LR transverse Direction), was slightly larger than GLT (shear modulus obtained from LT transverse Direction), then the user could be confident enough to consider the specimen as not having any severe longitudinal cracks (Roohnia et al. 2010).

The acoustic coefficient and acoustic conversion efficiency are two important acoustic properties related to wood strength. They strongly affect the acoustic performance of wood. So, identification of acoustic behaviour of wooden beams having holes is a critical issue in fracture and damages mechanics. The effect of the damage of a beam on acoustic properties of wood, however, has not been studied sufficiently. We focused on making holes in a wooden beam, and then the changes of two main acoustic properties, the acoustic coefficient and the acoustic conversion efficiency. This work will lead to a better knowledge of the acoustic behaviour in holed wooden beams, so that wooden beams can be employed in the best way.

METHODOLOGY

In accordance with ISO 3129 international standard (Wood-Sampling Methods and General Requirements for Physical and Mechanical Tests – 1975-11-01- International Standard ISO 3129), seventeen rectangular absolutely clear wooden beams of ashwood (*Fraxinus excelsior*), with the exact radial and tangential surfaces 20×20×360 mm (R×T×L) were randomly cut and sampled. This wood is widely dispersed in many Asian, European, and American countries and also it is the preferred wood for making some percussion instrument in Iran and its west and north neighbouring countries.

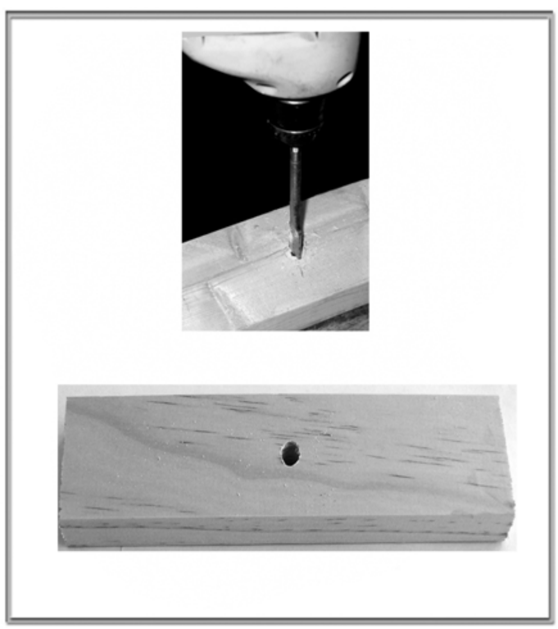

Figure 1

Fig. 1. Hole image LR direction

Samples with the exact radial and tangential surfaces 20×20×360 mm (R×T×L) were cut, starting from the chest-height diameter of the tree. The specimens were conditioned at 22 ºC and 65 % relative humidity (R.H.) until their moisture content and dimensions were stabilized. Holes were made in the middle of the longitudinal direction (18 cm) in four steps 0, 3, 5, and 8 mm, using a hand drill, such that the holes were visible on both two opposite tangential surfaces (Fig. 1).

To obtain the acoustic coefficient and acoustic conversion efficiency, free-free flexural vibration tests were made in accordance with Fast Fourier Transform analyses and Timoshenko beam theory (Bordonné 1989; Brancheriau and Bailleres 2002) using MATLAB® 7.1 software (equation 1). Density was calculated simultaneously, using the direct method. In each step of perforation, free vibration was induced on a free-free bar, with each of the beams resting on soft thin rubber, using individual impacts on each radial and tangential surface excited to vibrate in tangential (LT) and radial (LR) transverse directions, respectively (Fig. 2).

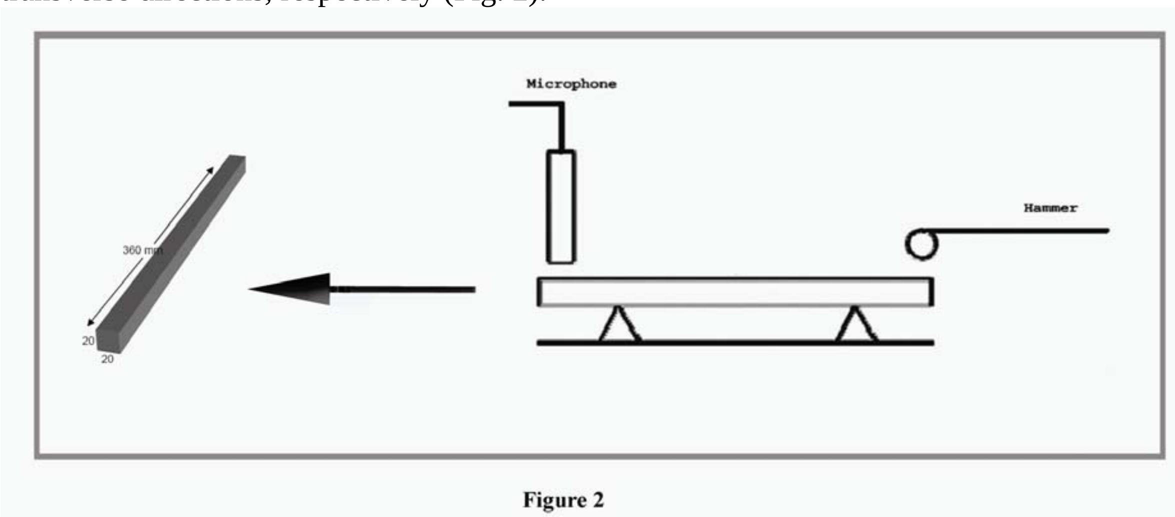

Fig. 2. Schematic view of the most common setup for free vibration on a free-free bar test. Sound was recorded at one free end, and hammer impact excites the bar on the other free end (ASTM C1548-02)

Sounds were recorded by Audacity® software (Sampling rate: 44100Hz) (Roohnia et al. 2010 and 2011). Then, the three initial modes of vibration were obtained from Fast Fourier Transform spectrum (Fig. 3).

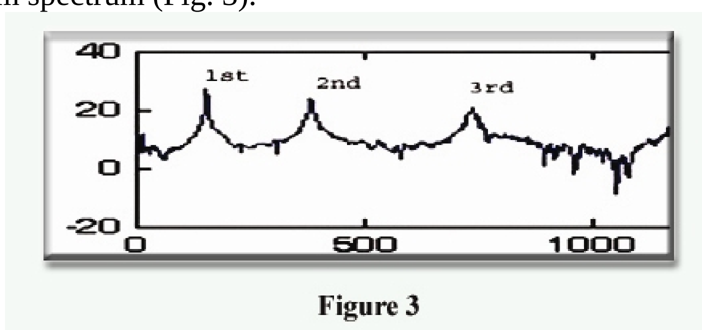

Fig. 3. Magnitude of Fourier Transform, showing first three modes of vibration. The y-axis corresponds to amplitude in dB and the x-axis to the frequency in Hz

Sounds were recorded by Audacity® software and by free-free flexural vibration tests which were made in accordance with Fast Fourier Transform analyses and Timoshenko beam theory, using MATLAB® 7.1 software (which was explained above). Based on the collected data, the amplitude can be calculated as in Eq. 1,

$$a_n = \left(\frac{E}{\rho}\right) - \left(\frac{E}{k \times G}\right) b_n \tag{1}$$

where $\boldsymbol{\rho}$ is the density (gr/cm^3), E is the modulus of elasticity (MPa), G is the shear modulus (MPa), k is the shape index (which for a prism is 0.883), and a_{n} and b_{n} are given by the following expressions,

$$a_n = \frac{[4\pi^2 l^2 f_n^2 (1 + F_{1n})]}{m_n^4} \tag{2}$$

$$b_n = \frac{4\pi^2 l^2 f_n^2 F_{2n}}{m_n^4} \tag{3}$$

where f_n is the frequency of n$^{\mathrm{th}}$ mode of vibration, and m_n is the result of $\cos(m_n).\cosh(m_n)=1$ corresponding to the n$^{\mathrm{th}}$ mode of vibration. To calculate a_n and b_n from (Eqs. 2 and 3), F_{1n} and F_{2n} must be calculated. They can be calculated by (Eqs. 4 and 5).

$$F_{1n} = \Theta^2(\mathrm{mn}) + 6\Theta(\mathrm{mn}) \tag{4}$$

$$F_{2n} = \Theta^2(\mathrm{mn}) - 2\Theta(\mathrm{mn}) \tag{5}$$

$$\Theta_{m_n} = \left[\frac{m_n.\tan(m_n).\tanh(m_n)}{\tan(m_n) - \tanh(m_n)}\right] \tag{6}$$

Considering the a_{n} and b_{n} parameters (Eqs. 2 and 3), the Young's moduli were obtained from a linear regression. The acoustic coefficient was then obtained from Eq. 7 (Tsoumis 1991; Yoshikawa 2007),

$$K = \sqrt{\frac{E}{\rho^3}} \tag{7}$$

where E is the longitudinal modulus of elasticity (MPa), ρ is the density of the air-dried wooden specimens (gr/cm^3), and K is the acoustical coefficient. Damping of vibration is calculated from logarithmic decrement as follows (Bodig and Jayne 1989; Bremaud 2008),

$$\lambda = \frac{1}{n}\ln\left|\frac{x_1}{x_{n+1}}\right| \tag{8}$$

where x_1 is the amplitude of the first wave. The loss of vibrational energy is given by,

$$\tan\delta = \frac{\lambda}{\pi} \tag{9}$$

where λ is the logarithmic decrement and $\tan\delta$ corresponds to damping of vibration (Bremaud 2008).

Combining the acoustic coefficient (K) and damping of vibration ($\tan\delta$), the acoustical conversion efficiency *ACE* (Eq. 10) is derived as a very useful formula to show the grouping effects (internal friction and sound radiation together) (Obataya 2000; Rujinirun et al. 2005; Yasuda and Minato 1994).

$$ACE = \frac{K}{\tan\delta} \tag{10}$$

The effects of step-wise holes on acoustic coefficient and acoustic conversion efficiency were tested by one-way Analysis of Variances (ANOVA), and then the existence of significant correlations before, during, and after damage in clear wooden beams were studied.

RESULTS AND DISCUSSION

The objective of this paper was to determine the effect of hole diameter (LR direction) on acoustic performance parameters such as acoustic coefficient and acoustic conversion efficiency of wooden beams using the flexural vibration test. When a structure suffers from damage, its dynamic properties can change. As there was only one longitudinal specific Young's modulus for a normal grain wood and it has a direct relation with acoustic coefficient and acoustic conversion efficiency, there would be equal amounts estimated from LT or LR vibrations before the presence of any damage. After making holes, at least one of these vibrations would result in smaller natural frequencies with smaller amounts of longitudinal specific modulus of elasticity and so smaller amount of acoustic coefficient and acoustic conversion efficiency. Also, it is significant to mention that vibration-based nondestructive methods are totally suitable for isotropic or orthotropic directions. A damage that could fade homogeneities could result in weakening the existed correlations. From such changes, the hole position and magnitude can be identified. The results for acoustic coefficient and acoustic conversion efficiency are shown in Table 1 and 2.

Table 1. Data of Acoustic Coefficient (*K*) Obtained from Each Step of Hole for Radial and Tangential Impacts

	K Radial 0 hole	*K* Tangential 0 hole	*K* Radial 3 mm hole	*K* Tangential 3 mm hole	*K* Radial 5 mm hole	*K* Tangential 5 mm hole	*K* Radial 8 mm hole	*K* Tangential 8 mm hole
1	180.79	177.58	181.47	178.09	180.66	176.83	180.91	174.47
2	198.03	203.96	197.87	203.64	203.69	251.34	200.35	197.53
3	175.93	179.94	176.92	179.89	177.79	179.09	177.22	176.11
4	193.39	195.43	196.58	192.93	197.04	192.57	196.12	189.61
5	157.09	174.67	158.41	174.68	159.00	174.01	158.28	172.00
6	182.85	179.80	183.60	179.42	184.32	178.55	184.45	174.58
7	171.76	171.01	171.67	171.07	172.12	170.40	172.23	170.00
8	204.08	200.20	192.67	189.09	193.12	187.40	193.17	182.93
9	176.81	175.03	178.02	175.05	178.13	174.36	178.23	171.12
10	194.61	189.12	195.91	189.07	196.02	186.37	196.39	183.62
11	171.98	169.86	173.37	170.65	173.49	170.63	174.02	169.00
12	200.39	180.64	201.19	180.31	200.41	179.63	200.69	176.98
13	199.52	206.75	198.60	208.58	200.39	208.81	206.31	201.11
14	157.73	160.24	160.07	158.99	160.38	158.80	159.20	156.14
15	194.97	201.52	195.45	201.51	195.57	200.94	198.18	194.67
16	174.23	194.67	175.32	195.10	175.35	194.72	174.34	191.93
17	187.52	191.25	180.59	191.75	180.91	190.01	181.85	184.60

Table 2. Data of Acoustic Conversion Efficiency (ACE) Obtained from Each Step of Hole for Radial and Tangential Impacts

	ACE Radial 0 hole	ACE Tangential 0 hole	ACE Radial 3 mm hole	ACE Tangential 3 mm hole	ACE Radial 5 mm hole	ACE Tangential 5 mm hole	ACE Radial 8 mm hole	ACE Tangential 8 mm hole
1	11849.39	11449.67	12771.81	14363.76	16609.97	17503.16	17646.99	17050.32
2	9663.26	15172.12	15736.44	20790.65	24284.10	26622.64	17398.41	15575.29
3	7846.98	16455.56	15197.83	16186.78	15607.83	15445.41	14024.70	15967.34
4	9061.44	7661.79	25102.72	19306.43	19812.83	18644.38	18426.90	17302.31
5	8142.17	13526.46	12977.54	12867.78	13154.32	12041.86	13424.81	12809.20
6	15006.09	14664.28	12464.79	13617.34	12237.29	15237.84	14791.67	15562.50
7	17057.13	16206.49	17601.56	15466.39	15234.84	14334.97	15812.48	13591.81
8	12693.69	12797.37	18100.34	18381.59	17727.77	17509.69	15526.31	15815.33
9	8452.18	8709.91	12780.97	15558.77	12638.79	13413.32	14149.46	12449.41
10	14713.53	16855.55	14957.87	19356.74	16700.79	16540.87	16213.10	15761.10
11	8324.61	8776.60	12794.16	10930.89	12730.78	11069.10	12028.23	11868.39
12	12583.74	12166.03	15746.64	13061.37	14911.85	12796.29	11251.96	13950.04
13	11837.72	6174.05	14004.05	12020.72	11152.26	13173.99	12005.38	9509.65
14	8277.53	9626.12	9194.26	8033.18	10726.42	6273.75	10259.66	9691.40
15	16847.05	16639.02	18388.58	20530.05	16830.14	20395.41	18083.45	15874.16
16	11530.31	12632.97	12949.88	11000.18	13058.91	13342.95	12537.97	16110.80
17	11927.90	10383.30	10878.84	12501.12	10134.35	11596.42	8524.59	9075.67

The effects of making a hole on the acoustic coefficient and the acoustic conversion efficiency were studied using one-way analysis of variances (ANOVA) and Duncan multiple comparison tests (Tables 3 and 4).

Table 3. ANOVA for the Effects of the Four Steps of Hole Size from Zero to 8 mm on Evaluated Acoustic Coefficient (*K*)

		Sum of Squares	Df	Mean Square	F	Sig.
***K* obtained from impact on radial surface**	Between Groups	7.119	3	2.373	.012	.998
	Within Groups	12625.990	64	197.281		
	Total	12633.109	67			
***K* obtained from impact on tangential surface**	Between Groups	5817.990	3	1939.330	.897	.448
	Within Groups	138397.055	64	2162.454		
	Total	144215.045	67			

Duncan multiple comparison test for the *K*. impact on radial surface at different steps of perforation

STEP	N	Subset for alpha = .05 1
0	17	183.6547
3	17	183.3947
5	17	184.0229
8	17	184.2318
Sig.		.877

Duncan multiple comparison test for the *K*. impact on Tangential surface at different steps of perforation

STEP	N	Subset for alpha = .05 1
0	17	185.3753
3	17	184.6953
5	17	204.3800
8	17	180.3765
Sig.		.176

Table 4. ANOVA for the Effects of the Four Steps of Hole Size from Zero to 8 mm on Evaluated Acoustic Conversion Efficiency (ACE)

		Sum of Squares	df	Mean Square	F	Sig.
ACE obtained from impact on radial surface	Between Groups	119644907.402	3	39881635.801	3.495	.021
	Within Groups	730410349.519	64	11412661.711		
	Total	850055256.921	67			
ACE obtained from impact on tangential surface	Between Groups	176655016.198	3	58885005.399	1.582	.202
	Within Groups	2382070529.268	64	37219852.020		
	Total	2558725545.467	67			

Duncan multiple comparison test for the ACE impact on radial surface at different steps of perforation

STEP	N	Subset for alpha = .05
		1
0	17	11646.9653
3	17	14802.8400
5	17	14914.8965
8	17	14241.5335
Sig.		.589

Duncan multiple comparison test for the ACE impact on Tangential surface at different steps of perforation

STEP	N	Subset for alpha = .05
		1
0	17	12362.9935
3	17	14939.6318
5	17	16820.1206
8	17	13997.9247
Sig.		.054

Results showed that holes did not significantly change the acoustic coefficient and acoustic conversion efficiency (Table 3 and 4). On the other hand, the Pearson product moment correlations between the acoustic coefficient and acoustic conversion efficiency and the results of tangential against radial impacts proved the stability of the equality of the two obtained series even in beams having 8 mm holes (Figs. 4 and 5). Thus, it was found that holes did not have any particular effect on acoustic coefficient during drilling up to 8 mm hole diameter (Figs. 4a, 4b, 4c, 4d).

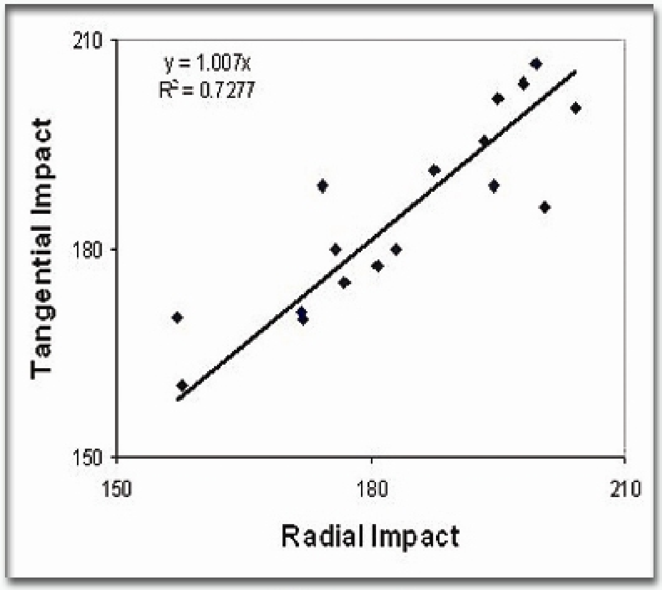

Figure 4a

Fig. 4a. Correlation (Linear regression) of acoustic coefficient result of impact of hammer on tangential and radial surfaces of clear beams

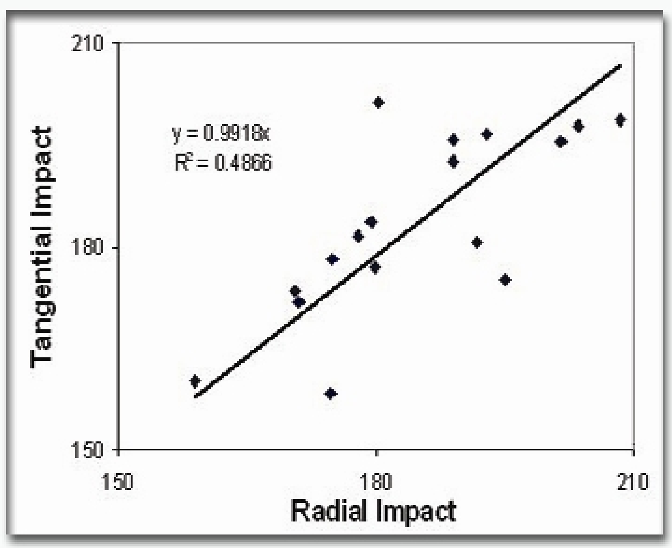

Figure 4b

Fig. 4b. Correlation (Linear regression) of acoustic coefficient result of impact of hammer on tangential and radial surfaces of 3 mm holed beams

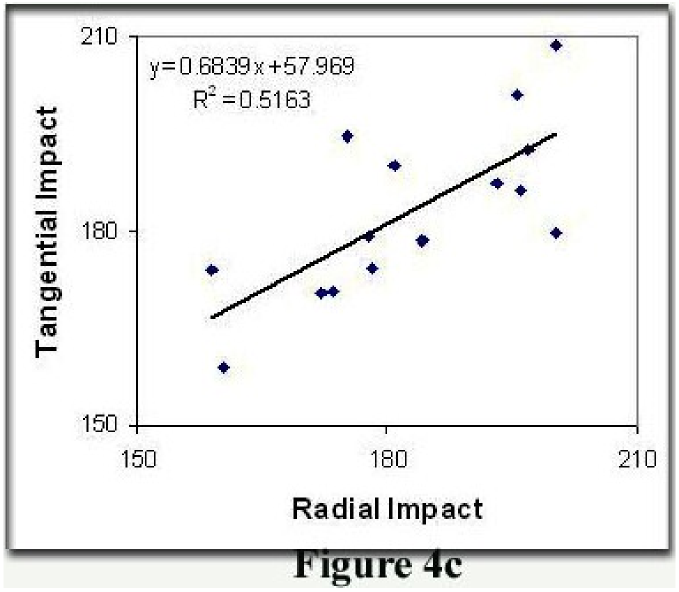

Fig. 4c. Correlation (Linear regression) of acoustic coefficient result of impact of hammer on tangential and radial surfaces of 5 mm holed beams

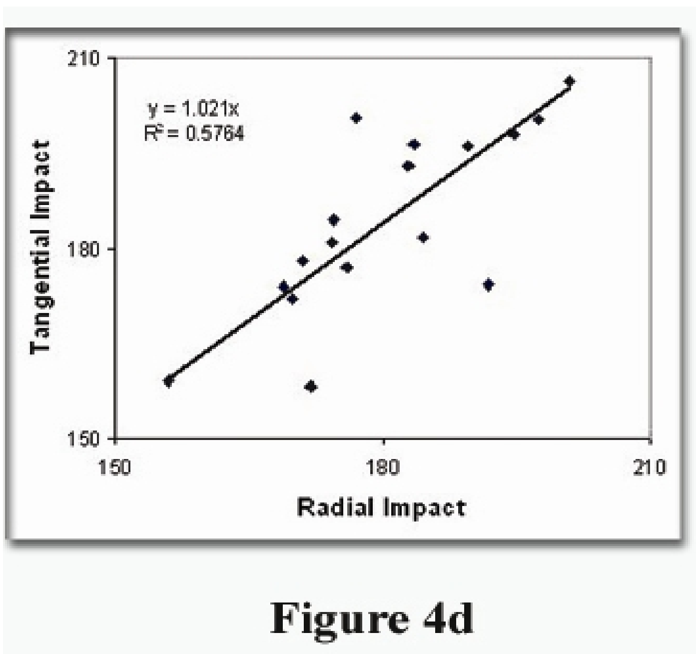

Fig. 4d. Correlation (Linear regression) of acoustic coefficient result of impact of hammer on tangential and radial surfaces of 8 mm holed beams

The results for acoustic conversion efficiency showed even at 8 mm diameter that the correlation between LT and LR vibration didn't change (Figs. 5a, 5b, 5c, 5d). This means that when the beams had been drilled in either the radial or tangential direction, the resulting holes did not have any particular effect. However, it is worth noting that changes of the acoustic coefficient and acoustic conversion efficiency were unambiguous during the making of a hole.

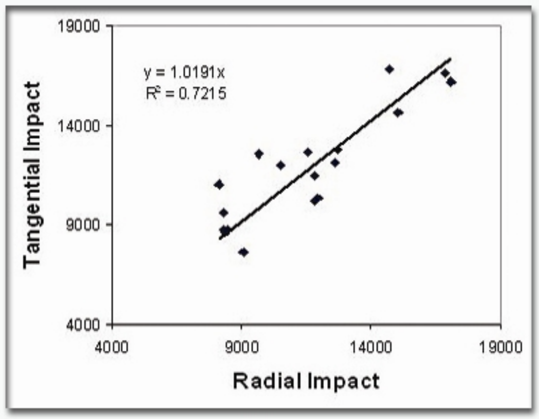

Figure 5a

Fig. 5a. Correlation (linear regression) of acoustic conversion efficiency result of impact of hammer on tangential and radial surfaces of clear beams

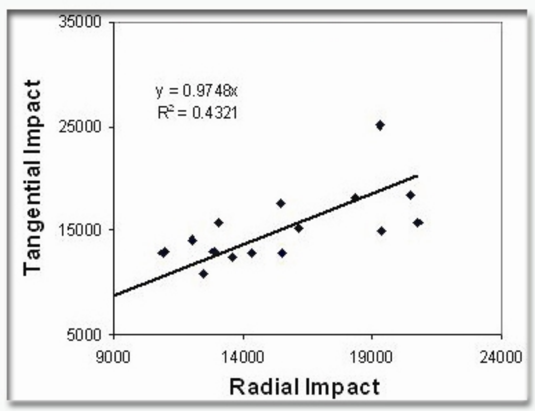

Figure 5b

Fig. 5b. Correlation (linear regression) of acoustic conversion efficiency result of impact of hammer on tangential and radial surfaces of 3 mm holed beams

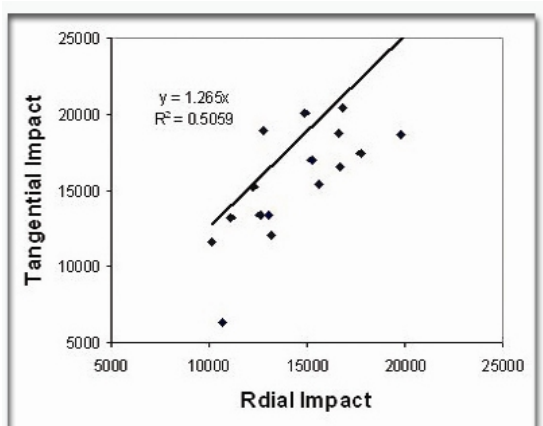

Figure 5c

Fig. 5c. Correlation (linear regression) of acoustic conversion efficiency result of impact of hammer on tangential and radial surfaces of 5 mm holed beams

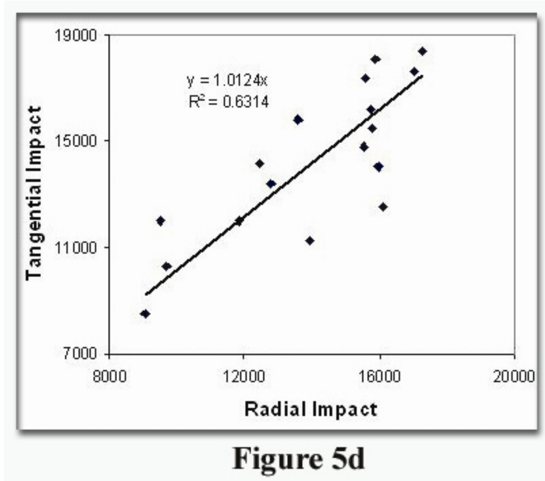

Fig. 5d. Correlation (linear regression) of acoustic conversion efficiency result of impact of hammer on tangential and radial surfaces of 8 mm holed beams

In comparison to the results of others, frequencies that give specific Young's modulus of the low order modes are significantly influenced by damages within a beam (Kubojima et al 2005). A crack occurring in a structural element causes a local variation in stiffness, affecting the dynamic behaviour of the structure to a considerable degree (Chati et al 1997). As it could be predicted, making hole had no significant effects on acoustic coefficient and acoustic conversion efficiency when they were impacted on both radial and tangential surface. This could be due to the same dimensions of cross section of each leg of the holed beams in comparison with the original beam in free vibration. In theory, there is no effect from cross section dimensions on each elastic parameter. But when the beam was impacted on the transverse surface, the vibration excited in the LR direction and frequently two legs hit together which resulted in fading of the resonance frequency. By decreasing the natural frequency, the elastic parameters decreased due to the direct correlations between them and the resonance frequency in Timoshenko beam equations.

Even at 8 mm diameter the correlation did not lose its significance (Figs. 4 and 5). These results indicated that the hole didn't cause any severe changes affecting the acoustic coefficient and acoustic conversion efficiency of wooden specimens.

CONCLUSIONS

An attempt has been made to nondestructively evaluate the effect of a hole on the acoustic coefficient and acoustic conversion efficiency of wooden specimens using flexural vibration. When a structure suffers from damage, its dynamic properties can change, and from these changes the damage position and magnitude can be identified.

1. The results indicated that drilling a hole in the LR direction and enlarging its diameter from 0 to 8 millimetres not only didn't cause any severe effect on acoustic coefficient and acoustic conversion efficiency, but instead somewhat increased their values.
2. When acoustic coefficient and acoustic conversion efficiency obtained in both surface impacts (radial and tangential) has direct relation (exactly like the results of this

study), such results would be considered sufficient evidence for the nonexistence of significant damage, especially a hole. On the other hand, in cases where the acoustic coefficient and acoustic conversion efficiency obtained in both surface impacts (radial and tangential) do not have a direct relation, this observation would be taken as evidence for the existence of damage.

3. Therefore, if the acoustic coefficient and acoustic conversion efficiency obtained from both impact (radial and tangential) are nominally equal, exactly like the results of this study, then the user can be confident enough that his specimen is free of severe holes.

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