Identification of the Dynamic Characteristics of Luffa Fiber Reinforced Bio-Composite Plates

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Luffa cylindrica plant fiber is a new biodegradable engineering material. However, the dynamic behaviors of these new green materials or their composites should be explored to consider them for practical applications. The dynamic characteristics including modal behavior and the elastic and sound isolation properties of luffa-based bio-composite plates were explored in this study. Structural frequency response function measurements were conducted using a few luffa bio-composite plates to identify their modal behavior. The modal frequencies and loss factors of the luffa bio-composite plates were identified by analyzing the frequency response function measurements using a few modal analysis methods such as half-power, circle-fit, and line-fit. The same luffa bio-composite structures were modelled using a finite element formulation with damping capability, and the elastic moduli of the composite plates were identified. In addition, the transmission loss levels of the same luffa composite samples were measured using the impedance tube method. The results showed that luffa composite structures have considerably high stiffness (elasticity modulus: 2.5 GPa), damping levels (loss factor: 2.6%), and transmission loss level (25 to 30 dB for a 1 cm thickness), and their mechanical properties are promising as an alternative disposable material for noise and vibration control engineering applications.

Keywords: Bio-composites; Luffa Composites; Elastic Properties; Damping Levels; Transmission Loss; FEM Modeling

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INTRODUCTION

Petroleum-based materials are widely used in the industry due to their superior features such as high strength and low density. However, finding and developing new materials as alternatives to these chemical materials is necessary due to their adverse effects including the enormous amount of carbon dioxide released into the atmosphere resulting from the burning of such substances (Wambua *et al*. 2003). The use of natural fibers for the reinforcement of composite structures has received increasing attention (Wambua *et al*. 2003; Chen and Lin 2005; Cheung *et al*. 2009; Xu *et al.* 2012). *Luffa cylindrica* fibers (also called loofah or sponge gourd) are a noteworthy alternative to mineral fibers. Their low cost and low density are the major benefits for their use in composites (Boynard and d'Almeida 2000; Chen and Lin 2005; Paglicawan *et al*. 2005; Zampieri *et al.* 2006; Demir *et al*. 2008; Kocak 2008; Seki *et al*. 2012; Shen *et al*. 2013). However, the characteristics (especially the dynamic or modal properties) of these new materials should be investigated in order to use them effectively in practical applications such as vibration attenuation of machines and sound isolation of conference rooms.

As reported in the literature, the sound absorption coefficient of flax fiber reinforced composites is approximately 25% higher than that of glass fiber reinforced composites, and the vibration damping of flax fiber reinforced composites is approximately 50% higher than that of glass fiber reinforced composites (Prabhakaran *et al.* 2014). Some other studies on natural fibers such as ramie, flax, jute, and broom fibers (Zhu *et al.* 2014; Yang and Li 2012; Umberto *et al.*

2017) suggest that natural fibers and their composites could be a viable candidate for noise and vibration applications.

There have been some studies on the morphology, thermodynamics, energy absorption, and elastic properties of luffa materials (Boynard and D'Almeida 2000; Chen and Lin 2005; Paglicawan *et al*. 2005; Zampieri *et al*. 2006; Demir *et al*. 2008; Kocak 2008; Ghali *et al*. 2009; Satyanarayana *et al*. 2009; Seki *et al*. 2012; Shen *et al*. 2012, 2013; Kocak *et al*. 2013; Genc 2015; Genc and Koruk 2016a). Koruk and Genc (2015) showed that the sound absorption of luffa composites is considerably high. It was shown that the sound absorption coefficients of luffa composite samples (with a thickness of 10 mm) are 0.3 and 0.7 when the luffa/epoxy ratio is 1.5 and 4, respectively, for the frequency of 6 kHz. It is seen that that the sound absorption coefficients of luffa fiber and their composites are comparable with those of traditional acoustic materials (Ersoy and Kucuk 2009; Koruk 2014a). It is worth remembering that the sound absorption coefficient of a widely used conventional material, *i.e.*, a polyester and polypropylene based material with a thickness of 10 mm, is 0.5 for the frequency of 6 kHz (Ersoy and Kucuk 2009). On the other hand, as previously reported (Genc and Koruk 2016b), the difficulties and restrictions during the manufacturing process of the composites combined with the defects and structural differences in raw bio materials such as luffa plant result in large variations in mechanical properties. This is a disadvantage of all natural fibers.

For practical applications, composites of natural fibers including luffa should have not only superior acoustic properties (*i.e*., sound absorption and transmission loss) but also acceptable elastic and damping properties. In this study, the modal behavior of a few luffa bio-composite plates were explored based on structural frequency response function measurements. The elastic properties of these structures were extracted by using a finite element formulation with damping capability, and the transmission loss levels of luffa bio-composite samples were determined using impedance tube measurements.

EXPERIMENTAL AND THEORY

Materials

Luffa cylindrica fibers of the Mediterranean region of Turkey were used to prepare composites. Hybrid composites (without any modification) were produced in this study, though some previous studies (Kocak *et al.* 2013; Jayamani *et al*. 2014; Wang *et al*. 2016) studied the effect of surface modification. It should be noted that sufficient adhesion was observed at the interface between the fiber and matrix. Epoxy resin was used as a matrix to produce the composite specimens. The volume fraction of the luffa fiber was 60 percent, and the material was compressed with a pressure of p = 500 kPa and cured at T = 80 °C for 300 minutes. Three *L. cylindrica* plants with an approximate diameter of 110 mm and length of 225 mm (Fig. 1a) were used to manufacture three composite plates (Fig. 1b) in this study.

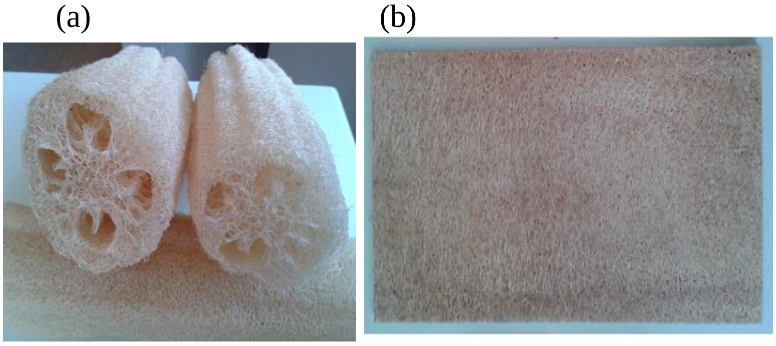

Fig. 1. Dried luffa fiber material used to prepare (bio) composites (a) and manufactured luffa composite structure (b)

The length and width of the plates were 200 mm and 100 mm, respectively. The densities and thicknesses of the composite plates had small differences because the three different *L. cylindrica* fibers were used. The density and thickness values for the so called Luffa-1, Luffa-2, and Luffa-3 plates were ρ = 777.8, 800.0, and 857.1 kg/m^3 and h = 5.4, 4.5, and 4.9 mm, respectively. Here, the density of each plate was calculated by using its measured mass and dimensions (or volume).

Methods

Frequency response function measurements

The frequency response function $H_{ij}(\omega)$ measured using the luffa bio-composite plates is expressed by Eq. 1 (Ewins 2000),

$$H_{ij}(\omega) = \frac{F_j^*(\omega)A_i(\omega)}{F_j^*(\omega)F_j(\omega)} \tag{1}$$

where $F_j(\omega)$ and $A_i(\omega)$ are the Fourier transforms of the time domain excitation force $f_j(t)$ applied at the point j and the vibration acceleration $a_i(t)$ measured at point i, respectively, t is time, ω is the excitation frequency, and the superscript $*$ indicates the complex conjugate. A instrumented impact hammer (Endevco 2302-10) and a lightweight piezoelectric (B&K 4507B) accelerometer (mass of about 4.5 g) were used for the frequency response function measurements. First, preliminary H_{ij} (ω) measurements were conducted to determine the best signal processing parameters. For example, the measurement period was selected to be long enough so that there was no need to apply any windowing functions to the signals. Therefore, there was minimal uncertainty in the identified modal loss factors. The experiments were also performed under free-free boundary conditions to eliminate uncertainty due to boundary damping and stiffness. The free-free boundary conditions were provided by hanging the test sample using a fishing line. This method is quite common in practice as the effect of the interaction between a light fishing line and test structure is almost negligible (Ewins 2000; Koruk 2014b). The H_{ij} (ω) measurements were conducted with a frequency resolution of Δf = 2 Hz (or with a period of T = 0.5 s), and each power spectrum was estimated using N = 5 averages. The auto spectrum of the force signal was examined to ensure that the structure was adequately excited over the frequency range of interest. The coherence function γ_{ij} (ω) was also checked to assess the quality of measurements.

Extraction of modal parameters

Half-power, circle-fit and line-fit methods were used to identify modal loss factors using measured structural frequency response functions $H_{ij}(\omega)$. In the half-power method (Ewins, 2000), the loss factor (η_r) for mode r is determined by Eq. 2,

$$\eta_r = \frac{\omega_{r,2}^2 - \omega_{r,1}^2}{2\omega_r^2} \tag{2}$$

where $\omega_{r,1}$ and $\omega_{r,2}$ are the frequencies corresponding to half power points around ω_r. In the circle-fit method (Kennedy 1947), the modal loss factor is determined by Eq. 3,

$$\eta_r = \frac{\omega_{r,b}^2 - \omega_{r,a}^2}{\omega_r^2\left(\tan\left(\varphi_{r,a}/2\right) + \tan\left(\varphi_{r,b}/2\right)\right)} \tag{3}$$

where the frequencies $\omega_{r,a}$ and $\omega_{r,b}$ correspond to the angles $\varphi_{r,a}$ and $\varphi_{r,b}$ around ω_r when the $\tilde{H}_{ij}(\omega)$ function is plotted using the Nyquist diagram (Kennedy 1947; Ewins 2000). In the line-fit method (Dobson 1987), which is very effective for the determination of modal parameters

(Koruk and Sanliturk 2011a), an inverse parameter is defined for modal analysis given by Eq. 4,

$$Z(\omega)=\frac{\left(\omega_{mn}^2-\omega^2+j\eta_r\omega_r^2\right)\left(\omega_r^2-\beta^2+j\eta_r\omega_r^2\right)}{{}_rB_{ij}} \tag{4}$$

where ${}_rB_{ij}$ is the so called modal constant for the mode *r* corresponding to *i* and *j*. The inverse parameter in Eq. 4 is separated into real and imaginary parts, which fit onto a line when plotted against ω^2.

The modal parameters are then estimated by determining the best lines that provide the best fits for the measured data (Kennedy 1947; Dobson 1987; Ewins 2000; ICATS 2009; Koruk and Sanliturk 2011a; Koruk *et al.* 2014).

Extraction of elastic properties of luffa bio-composites

Notably, luffa material has a special structure in which the fibers are interlocked. A recently developed finite element formulation with damping capability (Sanliturk and Koruk 2013, Sanliturk and Koruk 2014; Koruk 2014b) was used to model the luffa composite plates. This formulation is based on complex eigenvalue method, and the damping capability is added to the element by defining the complex elasticity modulus of the material as $\tilde{E}=E(1+j\eta)$, where E and η are the storage elasticity modulus and the loss factor, respectively.

The specific shell element utilized in this formulation includes the physical drilling degrees of freedom in the normal direction to the element (Sanliturk and Koruk 2013). After the elemental stiffness and mass matrices are obtained, these matrices are transformed to a common global coordinate system and the modal frequencies and damping levels for a bio-composite luffa plate can be obtained by solving the conventional eigenvalue problem given by Eq. 5,

$$\left(\mathbf{K}-\lambda^2\mathbf{M}\right)\mathbf{\Psi}=\mathbf{0} \tag{5}$$

where **K** and **M** are the global stiffness and mass matrices of the structure, respectively, λ^2 is the eigenvalue, and $\mathbf{\Psi}$ is the eigenvector. The solution of the eigenvalue problem above results in eigenvalues (λ_{r}^2) and eigenvectors ($\mathbf{\Psi}_{\mathrm{r}}$). The natural frequencies (ω_{r}) and loss factors (η_{r}) are determined by defining $\lambda_{\mathrm{r}}^2=\omega_{\mathrm{r}}^2\left(1+j\eta_{\mathrm{r}}\right)$ and using the following equations. Here, the plates are modelled using a fine mesh (n = 800 elements).

$$\omega_{\mathrm{r}}^2=\mathrm{Re}\left(\lambda_{\mathrm{r}}^2\right) \tag{6}$$

$$\eta_{\mathrm{r}}=\mathrm{Im}\left(\lambda_{\mathrm{r}}^2\right)/\mathrm{Re}\left(\lambda_{\mathrm{r}}^2\right) \tag{7}$$

Measurement of transmission loss levels of luffa bio-composites

The transmission loss levels of the luffa bio-composite samples were identified using an impedance tube with four microphones. A B&K Type 4206 T small tube setup was used for measurements, and the calculation of the transmission loss levels was based on the four-microphone transfer-function method (ASTM E2611-09 Standard 2009; Bolton *et al.* 2007; Pulse LabShop 2013). For this purpose, circular luffa bio-composite samples with a diameter *d* of approximately 30 mm were prepared.

As it was difficult to measure the transmission loss of the luffa bio-composite samples with thicknesses of h = 5 mm using the impedance tube, thicker samples (h = 10 mm) were prepared using the manufacturing method explained before.

RESULTS AND DISCUSSION

Frequency Response Function Measurements

A number of frequency response function measurements were conducted for various impact and response locations of the plate samples. The sample time domain $f_j(t)$ and $a_i(t)$ signals, $F_j(\omega)$ and $A_i(\omega)$ spectrums, and $H_{ij}(\omega)$ frequency response and $\gamma_{ij}(\omega)$ coherence functions for the Luffa-1 composite plate are plotted in Fig. 2. The signals approached zero at the end of the measurement period. Also, the force spectrum decreased dramatically after *f* = 1.5 kHz due to the inability to properly excite the structure beyond this frequency, and the effect of damping at higher frequencies; hence, the measurements were conducted up to *f* = 1.5 kHz. Furthermore, the coherence function was at least γ = 0.999 at and around the natural frequencies. Notably, the frequency domain based methods used data at and around natural frequencies to identify modal parameters. It should be noted that coherence function indicates how much of the output is due to the input and it is an indicator of the quality of the frequency response function measurement (Ewins 2000). Overall, the $\tilde{H}_{ij}(\omega)$ functions were measured using the Luffa-1, 2, and 3 composite plates using the determined data acquisition and signal processing parameters. Their modal parameters (below *f* = 1.5 kHz) were extracted as described in the next section.

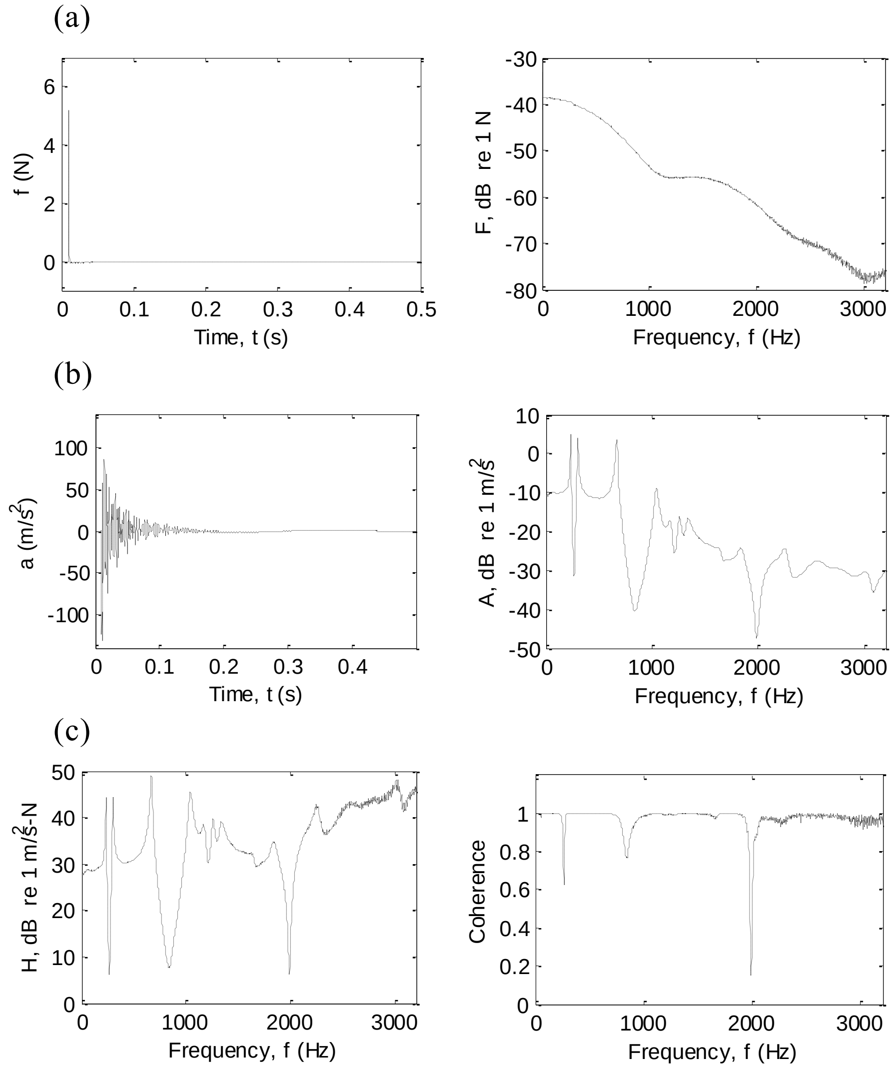

Fig. 2. The sample acceleration (a) and force (b) signals in time domain (left) and their spectrums (right) and structural frequency response (left) and its coherence (right) functions (c) for the Luffa-1 bio-composite plate

Extraction of Modal Parameters

The natural frequencies and modal loss factors of three luffa bio-composite plates are listed in Tables 1 through 3. The modal frequencies for the three luffa plates were similar, with less than 10% standard deviations in modal frequencies for the given first six modes. While some variations were due to the small differences in densities and thicknesses of the plates, some deviations may have occurred due to differences of the properties of different cylindrica fibers.

Table 1. Identified Natural Frequencies and Modal Loss Factors of the Luffa-1 Bio-Composite Plate

Analysis Method		Half-Power	Circle-Fit	Line-Fit	Average
Mode No, *r*	f_r (Hz)	η_r (%)			
1	249.1	3.67	3.66	3.27	3.53
2	312.2	2.40	2.41	2.21	2.34
3	672.1	2.29	2.30	2.29	2.29
4	695.8	2.46	2.19	2.01	2.22
5	1063.9	2.68	3.05	2.86	2.86
6	1182.2	2.42	2.45	2.52	2.47
Average η (%)		2.65	2.68	2.53	2.62

Table 2. Identified Natural Frequencies and Modal Loss Factors of the Luffa-2 Bio-Composite Plate

Analysis Method		Half-Power	Circle-Fit	Line-Fit	Average
Mode No, *r*	f_r (Hz)	η_r (%)			
1	202.2	2.95	3.11	2.68	2.91
2	247.0	2.64	2.63	2.20	2.49
3	552.2	2.29	2.36	2.32	2.32
4	562.6	2.24	2.24	2.09	2.19
5	834.9	2.79	*	*	2.79
6	944.6	2.51	2.49	2.48	2.50
Average η (%)		2.57	2.56	2.35	2.53

*Could not be identified with high accuracy using the individual response function

Table 3. Identified Natural Frequencies and Modal Loss Factors of the Luffa-3 Bio-Composite Plate

Analysis Method		Half-Power	Circle-Fit	Line-Fit	Average
Mode No, *r*	f_r (Hz)	η_r (%)			
1	210.2	2.82	3.17	2.73	2.91
2	260.2	2.48	2.62	2.29	2.46
3	570.0	2.36	2.32	2.24	2.30
4	588.1	*	*	*	
5	902.0	2.76	2.88	2.82	2.82
6	990.7	2.43	2.41	2.27	2.37
Average η (%)		2.57	2.68	2.47	2.57

*Could not be identified with high accuracy using the individual response function

The differences between the modal loss factors identified using the half-power, circle-fit, and line-fit methods were small. For example, the average loss factors of the Luffa-1 bio-composite plate in the frequency range of interest were η = 2.65, 2.68, and 2.53% when the half-power, circle-fit, and line-fit methods, respectively, were used. In general, the identified damping levels using the line-fit method were a little bit smaller than those of the other methods. The modal loss factors for the three luffa plates were quite close. The standard deviation in the first modal frequencies was 9.4%, and the deviations were less than 2.2% for the second to sixth modes. Although the modal loss factors of the first modes of the bio-composite plates were a bit higher, the damping variation with respect to the frequency was low. A few potential reasons for the higher levels and larger variations for the damping of the first mode are the mass loading effect of the accelerometer, the adverse effect of the frequency resolution and the additional damping due to the air around the structure being more apparent at lower modes (ICATS 2009; Koruk and Sanliturk 2011a; Sanliturk and Koruk 2013; Koruk 2014b; Koruk *et al*. 2014). Overall, the average loss factors of the Luffa-1, 2, and 3 bio-composite plates in the frequency range of interest were η = 2.62, 2.53, and 2.57%, respectively. It is seen that the modal loss factors of luffa composite samples are higher than those of conventional materials such as glass composites and steel (Prabhakaran *et al.* 2014; Koruk and Sanliturk 2010) though the modal loss factors of luffa composite samples are less than those of conventional viscoelastic damping materials (Koruk and Sanliturk 2011b). The modal frequencies and loss factors for the three luffa plates produced from different *L. cylindrica* fiber materials were similar to each other (Tables 1 through 3). The standard deviations in modal frequencies and loss factors were less than 10% for the given first sixth modes; some variations were due to the small differences in densities and thicknesses of the plates. It is clear that the modal properties of luffa bio-composite structures can be maintained within some limits.

Extraction of Elastic Properties of Luffa Bio-composites

The elasticity moduli of the luffa bio-composite plates were determined by comparing experimental and theoretical modal parameters. Importantly, the loss factors for the Luffa-1, 2, and 3 bio-composite plates used in modal analyses were $\eta_{c,\mathrm{Luffa-1}}$ =2.62%, $\eta_{c,\mathrm{Luffa-2}}$ =2.53%, and $\eta_{c,\mathrm{Luffa-3}}$ =2.57%, respectively, in the frequency range of interest. The Poisson's ratio was assumed to be v = 0.3 (Wang *et al.* 2015). Overall, the elasticity moduli of the luffa bio-composite plates were $E_{c,\mathrm{Luffa-1}}$ = 2.55 GPa, $E_{c,\mathrm{Luffa-2}}$ = 2.45 GPa, and $E_{c,\mathrm{Luffa-3}}$ = 2.40 GPa.

Table 4. Differences between the Measured and Predicted Natural Frequencies of the Luffa Bio-Composite Plates using the Identified Material Properties

Sample	Luffa-1	Luffa-2	Luffa-3
Mode No, *r*	Difference (%)		
1	1.3	0.6	0.7
2	-1.4	0.8	-0.6
3	0.6	-1.0	-0.3
4	0.3	0.1	-0.4
5	-3.1	-0.4	-4.1
6	-1.0	0.3	-0.7

The differences between the measured and predicted natural frequencies of the luffa bio-composite plates using the identified material properties are compared in Table 4. The experimental and theoretical natural frequencies of the luffa bio-composite plates were similar; the average differences between the experimental and theoretical natural frequencies were 1.3, 0.5, and 1.1% for the Luffa-1, 2, and 3 bio-composite plates, respectively, when the identified material properties of the luffa bio-composite plates are used.

Transmission Loss Levels of Luffa Bio-composites

The transmission loss levels of the luffa bio-composite samples are presented for *f* = 500 to 6400 Hz in Fig. 3. The transmission loss values of the luffa bio-composite samples were similar. The transmission loss decreased from *f* = 0.5 to 1 kHz and then increased from *f* = 1 to 2 kHz. There was approximately a 3 dB/octave increase in the region of approximately *f* = 2 to 5 kHz. The transmission loss values of the luffa bio-composite samples with *h* = 1 cm were 25 to 30 dB for *f* = 2 to 6 kHz.

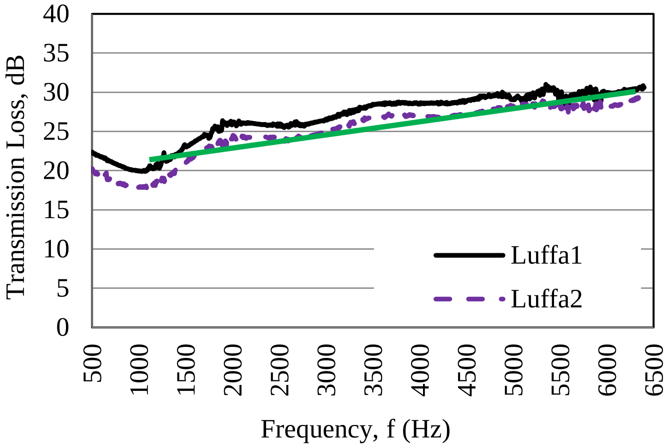

Fig. 3. The measured transmission loss levels of the luffa bio-composite samples

The elasticity modulus and loss factors of the three bio-composite structures were E_c = 2.47 ± 0.06 kPa and η_c = 2.57 ± 0.04%, respectively. High values of transmission loss and damping levels are desired for sound isolation and vibration attenuation. The transmission loss values of the thin luffa bio-composite samples with *h* = 1 cm were quite high, being 25 to 30 dB for *f* = 2 to 6 kHz. It should be underlined that the transmission loss level of a cement panel of 1 cm is 25 to 30 dB at 2 kHz (Ng and Hui 2008). The considerably high values of both elasticity moduli and damping levels as well as high values of transmission loss levels for luffa bio-composite structures make them very attractive for a variety of applications, including sound isolation and vibration attenuation in practical applications.

The surface chemical modification on the fibers improves the bonding between the fiber and the matrix interface; hence, it changes the mechanical properties of luffa composites (Kocak *et al*. 2013). The structural defects and differences caused between the sowing and harvesting periods of natural fibers result in some variations in the mechanical properties of luffa composites (Genc and Koruk 2016b).

It should be noted that the examined composite is not fully environmental friendly because of the chemical resin used. The search for natural resins that are alternatives to chemical resins is ongoing. Consequently, it might be possible to manufacture a green luffa composite in near future.

CONCLUSIONS

1. Modal frequencies and loss factors of a few luffa bio-composite plates were identified by analyzing the frequency response functions measured using the luffa composite plates and a few modal analysis methods.
2. The elastic moduli of luffa composites were determined by modelling the luffa composite plates using a finite element formulation with damping capability.
3. The transmission loss levels of the luffa composite samples were determined using the impedance tube experiments.

4. Modal frequencies and loss factors of composite plates made from different luffa cylindrica fiber materials are close to each other.
5. The identified loss factors of luffa composite plates are quite high (*i.e.*, 2.6%).
6. The luffa bio-composite plates have considerably high elasticity moduli (*i.e.*, 2.5 GPa) and transmission loss levels (*i.e.*, 25 to 30 dB for a thickness of 1 cm).
7. These superior features of luffa composites as well as their low densities, costs, and degradability feature make the luffa composites very attractive for various noise and vibration control engineering applications.

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REFERENCES CITED

ASTM International Standard (2009). ASTM E2611-09: Standard test method for measurement of normal incidence sound transmission of acoustical materials based on the transfer matrix method.

Bolton, J. S., Yoo, T, and Olivieri, O. (2007). “Measurement of normal incidence transmission loss and other acoustical properties of materials placed in a standing wave tube: Technical review,” *Bruel and Kjaer Sound & Vibration Measurement A/S*, Naerum, Denmark.

Boynard, C. A., and D'Almeida, J. R. M. (2000). “Morphological characterization and mechanical behavior of sponge gourd (*Luffa cylindrica*) - Polyester composite materials,” *Polymer-Plastics Technology and Engineering* 39(3), 489-499. DOI: 10.1081/Ppt-100100042

Chen, J. P., and Lin, T. C. (2005). “Loofa sponge as a scaffold for culture of rat hepatocytes,” *Biotechnology Progress* 21(1), 315-319. DOI: 10.1021/Bp049684v

Cheung, H. Y., Ho, M. P., Lau, K. T., Cardona, F., and Hui, D. (2009). “Natural fibre-reinforced composites for bioengineering and environmental engineering applications,” *Composites Part B: Engineering* 40(7), 655-663. DOI: 10.1016/j.compositesb.2009.04.014

Demir, H., Top, A., Balköse, D., and Ülkü, S. (2008). “Dye adsorption behavior of Luffa cylindrica fibers,” *Journal of Hazardous Materials* 153(1–2), 389-394. DOI:10.1016/j.jhazmat.2007.08.070

Dobson, B. J. (1987). “A straight-line technique for extracting modal properties from frequency-response data,” *Mechanical Systems and Signal Processing* 1(1), 29-40. DOI: 10.1016/0888-3270(87)90081-1

Ersoy, S., and Kucuk, H. (2009). “Investigation of industrial tea-leaf-fibre waste material for its sound absorption properties,” *Applied Acoustics* 70(1), 215-220. DOI:10.1016/j.apacoust.2007.12.005

Ewins, D. J. (2000). *Modal Testing: Theory, Practice and Application*, 2nd Ed., Research Studies Press, Hertfordshire, England.

Genc, G. (2015). “Dynamic properties of *Luffa cylindrica* fiber reinforced bio-composite beam," *Journal of Vibroengineering* 17(4), 1615-1622.

Genc, G., and Koruk, H. (2016a). "Investigation of the vibro-acoustic behaviors of luffa bio composites and assessment of their use for practical applications," in: *23rd International Congress on Sound and Vibration (ICSV23),* Athens, Greece, pp. 1-8.

Genc, G., and Koruk, H. (2016b). "On the difficulties in manufacturing of luffa fibers reinforced bio-composites and variations in their dynamic properties," in: *45th International Congress and Exposition on Noise Control Engineering INTER-NOISE 2016*, Hamburg, Germany, pp. 1566-1570.

Ghali, L., Msahli, S., Zidi, M., and Sakli, F. (2009). "Effect of pre-treatment of luffa fibres on the structural properties," *Materials Letters* 63(1), 61-63. DOI: 10.1016/j.matlet.2008.09.008

Imperial College Testing Analysis and Software (ICATS) (2009). Imperial College, London.

Jayamani, E., Hamdan, S., Rahman, M. R., Heng, S. K., and Bin Bakri, M. K. (2014). "Processing and characterization of epoxy/luffa composites: Investigation on chemical treatment of fibers on mechanical and acoustical properties," *Bioresources* 9(3), 5542-5556.

Kennedy, C. C. (1947). "Use of vectors in vibration measurement and analysis," *Journal of the Aeronatical Sciences (Institute of the Aeronautical Sciences)* 14(11), 603-625. DOI:10.2514/8.1474

Kocak, D. (2008). "The study of the effects of different chemical compounds applied on *Luffa cylindrica* fibres with the help of ultrasonic energy," *Journal of Polymer Engineering* 28(8), 501-515.

Kocak, D., Merdan, N., Yuksek, M., and Sancak, E. (2013). "Effects of chemical modifications on mechanical properties of Luffa cylindrica," *Asian Journal of Chemistry* 25(2), 637-641.

Koruk, H., and Sanliturk, K.Y. (2010). "On measuring dynamic properties of damping materials using Oberst beam method," in: *ASME 2010 10th Biennial Conference on Engineering Systems Design and Analysis*, Istanbul, Turkey, Volume 2, pp. 127-134.

Koruk, H., and Sanliturk, K. Y. (2011a). "Damping uncertainty due to noise and exponential windowing," *Journal of Sound and Vibration* 330(23), 5690-5706. DOI: 10.1016/j.jsv.2011.07.006

Koruk, H., and Sanliturk, K.Y. (2011b). "Assessment of the complex eigenvalue and the modal strain energy methods for damping predictions," in: 18th International Congress on Sound and Vibration (ICSV18), Rio De Janeiro, Brazil, pp. 1-8

Koruk, H. (2014a). "An assessment of the performance of impedance tube method," *Noise Control Engineering Journal* 62(4), 264-274. DOI: 10.3397/1/376226

Koruk, H. (2014b). "Quantification and minimization of sensor effects on modal parameters of lightweight structures," *Journal of Vibroengineering* 16(4), 1952-1963.

Koruk, H., Dreyer, J. T., and Singh, R. (2014). "Modal analysis of thin cylindrical shells with cardboard liners and estimation of loss factors," *Mechanical Systems and Signal Processing* 45(2), 346-359.

Koruk, H., and Genc, G. (2015). "Investigation of the acoustic properties of bio luffa fiber and composite materials," *Materials Letters* 157, 166-168. DOI:10.1016/j.matlet.2015.05.071

Ng, C. F., and Hui, C. K. (2008). "Low frequency sound insulation using stiffness control with honeycomb panels," *Applied Acoustics* 69(4), 293-301. DOI: 10.1016/j.apacoust.2006.12.001

Paglicawan, M. A., Cabillon, M. S., Cerbito, R. P., and Santos, E. O. (2005). "Loofah fiber as reinforcement material for composite," *Philippine Journal of Science* 134(2), 113-120.

Prabhakaran, S., Krishnaraj, V., kumar, M. S., and Zitoune, R. (2014). "Sound and vibration damping properties of flax fiber reinforced composites," *Procedia Engineering* 97, 573-581. DOI: 10.1016/j.proeng.2014.12.285

Pulse LabShop (2013). Brüel & Kjaer, Copenhagen, Denmark, (https://www.bksv.com/en/products/transducers/acoustic/Acoustic-material-testing-kits/transmission-loss-and-impedance-tube-kits-4206), Accessed December 23, 2016.

Sanliturk, K. Y., and Koruk, H. (2013). "Development and validation of a composite finite element with damping capability," *Composite Structures* 97, 136-146. DOI: 10.1016/j.compstruct.2012.10.020

Sanliturk, K. Y., and Koruk, H. (2014). "A new triangular composite shell element with damping capability," *Composite Structures* 118, 322-327. DOI: 10.1016/j.compstruct.2014.07.053

Satyanarayana, K. G., Arizaga, G. G. C., and Wypych, F. (2009). "Biodegradable composites based on lignocellulosic fibers—An overview," *Progress in Polymer Science* 34(9), 982-1021. DOI: 10.1016/j.progpolymsci.2008.12.002

Seki, Y., Sever, K., Erden, S., Sarikanat, M., Neser, G., and Ozes, C. (2012). "Characterization of *Luffa cylindrica* fibers and the effect of water aging on the mechanical properties of its composite with polyester," *Journal of Applied Polymer Science* 123(4), 2330-2337. DOI: 10.1002/App.34744

Shen, J., Min Xie, Y., Huang, X., Zhou, S., and Ruan, D. (2012). "Mechanical properties of luffa sponge," *Journal of the Mechanical Behavior of Biomedical Materials* 15(0), 141-152. DOI: 10.1016/j.jmbbm.2012.07.004

Shen, J., Xie, Y. M., Huang, X., Zhou, S., and Ruan, D. (2013). "Behaviour of luffa sponge material under dynamic loading," *International Journal of Impact Engineering* 57(0), 17-26. DOI: 10.1016/j.ijimpeng.2013.01.004

Umberto, B., Gino, I., and Di Gabriele, M. (2017). "The acoustic characterization of broom fibers," *Journal of Natural Fibers* 1(1), 1-6. DOI: 10.1080/15440478.2017.1279995

Wambua, P., Ivens, J., and Verpoest, I. (2003). "Natural fibres: Can they replace glass in fibre reinforced plastics?," *Composites Science and Technology* 63(9), 1259-1264. DOI: 10.1016/S0266-3538(03)00096-4

Wang, X. J., Shen, J. H., Zuo, Z. H., Huang, X. D., Zhou, S. W., and Xie, Y. M. (2015). "Numerical investigation of compressive behaviour of luffa-filled tubes," *Composites Part B-Engineering* 73, 149-157. DOI: 10.1016/j.compositesb.2014.12.017

Wang, Q., Shen, F., Ang, G., Zhang, Y., Deng, S., Hu, Y., Zhang, J., Song, C., and Zeng, Y. (2016). "Pretreating luffa sponge (*Luffa cylindrica* L.) with concentrated phosphoric acid and subsequent enzymatic saccharification," *BioResources* 11(1), 899-912. DOI: 10.15376/biores.11.1.899-912

Xu, S. L., Guo, W., Lu, J. J., and Li, W. (2012). "Fabrication and mechanical properties of PLLA and CPC composite scaffolds," *Journal of Mechanical Science and Technology* 26(9), 2857-2862. DOI: 10.1007/s12206-012-0732-9

Yang, W. D., and Li, Y. (2012). "Sound absorption performance of natural fibers and their composites," *Science China-Technological Sciences* 55(8), 2278-2283. DOI:10.1007/s11431-012-4943-1

Zampieri, A., Mabande, G. T. P., Selvam, T., Schwieger, W., Rudolph, A., Hermann, R., Sieber, H., and Greil, P. (2006). "Biotemplating of *Luffa cylindrica* sponges to self-supporting hierarchical zeolite macrostructures for bio-inspired structured catalytic reactors," *Materials Science & Engineering C-Biomimetic and Supramolecular Systems* 26(1), 130-135. DOI: 10.1016/j.msec.2005.08.036

Zhu, X. D., Kim, B. J., Wang, Q. W., and Wu, Q. L. (2014). "Recent advances in the sound insulation properties of bio-based materials," *BioResources* 9(1), 1764-1786.

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