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# Vibration Damping of Flax Fibre-reinforced Polypropylene Composites

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**Abstract:** This work investigates the effects of fibre content and fibre orientation on the damping of flax fibre-reinforced polypropylene composites. Laminates of various fibre contents were manufactured by a vacuum bagging process; their dynamic behaviour were then found from the vibration measurements of beam test specimens using an impulse hammer technique to frequencies of 1 kHz. The frequency response of a sample was measured and the response at resonance was used to estimate the natural frequency and loss factor. The single-degree-of-freedom circle-fit method and the Newton's divided differences formula were used to estimate the natural frequencies as well as the loss factors. The damping estimates were also investigated using a "carpet" plot. Experiments were subsequently conducted on a range of samples with different fibre volume fractions and orientations. The results show significant variations in natural frequencies and loss factors according to the variations in fibre orientation. Composites containing 45 $^{o}$, 60 $^{o}$ and 90 $^{o}$ fibre orientation exhibit approximately the same natural frequencies. Composites with differing fibre orientations exhibit different loss factors for the various modes of vibration, and the maximum loss factor is obtained for the case of 45 $^{o}$ fibre orientation, with the loss factor generally lying in the range of 2-7 %. It was found that the loss factor increases with increasing frequency and decreases slightly with increasing fibre content. These outcomes indicate that flax fibre-reinforced composite could be a commercially viable material for applications in which noise and vibration are significant issues and where a significant amount of damping is required.

**Keywords:** Composite materials, Flax-polypropylene composites, Damping, Loss factor, Natural frequency

## Introduction

In some areas, for example, the automotive industry (electric/hybrid cars), aerospace and sport, reduction in the mass of a structure is becoming increasingly important and desirable, as it relates directly to cost, performance and better fuel efficiency. However, reduction of mass can cause a structure to be more vulnerable to audible noise and vibration. To attenuate the vibrations to a desirable level, damping materials may be added to a structure to dissipate vibrational energy. Furthermore, increased environmental consciousness, the reduction of available non-renewable sources and the problems inherent to the disposal of waste materials, have all led to a growing interest in the use of plant fibre based composites for such purposes.

One particular advantage of using reinforcing agents such as plant fibres in composites is their multi-scale structure. These plant fibres are composed of elementary fibres bonded by a pectin matrix, where each of the elementary fibres can be considered as a composite structure. This structure consists of stiff cellulose microfibrills reinforced in a hemicellulose and lignin matrix [1]. These fibres are viscoelastic and hierarchical in nature which contributes to the dissipation of energy [2,3]. Polymers also behave similar to viscoelastic materials and show high damping when compared to metallic materials [4]. Viscoelastic materials have the inherent ability to dissipate energy via converting vibration energy into heat energy during mechanical deformation [5]. Furthermore, interfacial friction between fibre and matrix provides additional damping. Therefore, the embedding of plant fibres into polymeric matrix materials can have multifunctional capabilities [6] such as vibration control, energy dissipation and heat dissipation along with a high stiffness to weight ratio.

To investigate the vibration damping of PFPCs (plant fibre-reinforced polymer composites), experimental dynamic mechanical analysis (DMA) has been extensively used in the past decade [2,3,7-15]. For example, Duc *et al*. [2,3] measured the damping of flax, carbon and glass fibre-reinforced epoxy composites and showed that flax fibre composites possess a higher damping than do glass and carbon fibre composites. Wielage *et al*. [7] also found that the loss factors of flax and hemp fibre-reinforced polypropylene (PP) composites are greater than those of glass fibre composites. The loss factors increase with the twist angle of the flax yarns and the crimp in the flax fabrics; this is due to increasing intra-yarn and inter-yarn friction, respectively, as stated in [2,8]. Idicula *et al*. [9] studied the effect of fibre volume fraction on the damping of short banana-sisal hybrid fibre-reinforced polyester composites and found that composites with a fibre volume fraction of 0.40 display the maximum damping. Joseph *et al*. [10] and Nair *et al*. [11] reported that the incorporation of short sisal fibre reduces the loss factors of the composites when compared with the polypropylene and polystyrene samples, respectively. Low frequencies results indicate less damping of the banana fibre-reinforced polyester composites compared to measurements at higher frequencies, as described by Pothan *et al*. [12]. In another study, Guen *et al*. [13] reported that the damping of polyol-treated flax fibre-reinforced epoxy composites is higher than that of non-treated flax fibre composites.

In the aforementioned references, except for [1,6], DMA

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tests were generally conducted at various temperatures with a specific frequency less than or equal to 100 Hz. Etaati *et al.* [16] performed measurements on hemp fibre-reinforced PP composites with excitation frequencies of up to 200 Hz. The maximum loss factor was found for 30 % by weight hemp fibre composites, and the damping exhibited a slight dependence on frequency below 30 Hz. However, it is necessary to investigate a broader frequency range to characterise the dynamic behaviour of a material, in particular, the stiffness and loss factor, as audible frequencies range from 20 to 20,000 Hz. In order to reduce noise and vibration in transport, NFPCs can be considered as potentially useful materials for interior application. In vehicles, for example, frequencies of up to a few kHz are often important, and the frequency range from 100-1000 Hz is particularly significant in causing fatigue for both driver and passengers [17]. This range also includes much of the energy associated with internally and externally radiated noise in transport such as cars and trains. Hence, the ability to add damping over a wider frequency range is important, and this provides the motivation in this paper to measure damping over a wider frequency range of up to 1000 Hz.

Some studies [14,15,18] have estimated the natural frequencies and loss factors of NFPCs. Landro and Lorenzo [14,15] examined the dynamic behaviour of plant fibre mat (flax, kenaf and hemp fibres were used in the mat, 50 % by weight) reinforced PP composites over excitation frequencies of up to 4 kHz. An increase in damping with frequency was seen. Kumar *et al.* [18] reported only the first three natural frequencies and the loss factors associated with short sisal and banana fibre-reinforced polyester composites for various fibre lengths (3 mm, 4 mm and 5 mm) and contents (30 %, 40 % and 50 % by weight). They demonstrated that the natural frequencies of the composites are not affected significantly by variations in fibre length. For a constant fibre length (3 mm), two kinds of damping trends were observed with an increase in banana and sisal fibre contents in the case of the first mode: for the former, damping decreases; for the latter, it increases. In those studies (i.e., [14,15,18]), the estimation of loss factor was carried out using the half-power bandwidth method, also known as the peak-picking method. This method produces an overestimation of damping; this is due to the assumption that only a single mode contributes to the response around each resonance frequency. However, off-resonant modes can contribute a significant amount to the total response at any resonance. The damping estimation errors can be up to 20 % or more for a multiple-degree-of-freedom system [19] depending on the mode number, modal overlap and loss factor. On the other hand, the single-degree-of-freedom (SDoF) circle-fit method [20] significantly improves the accuracy of damping estimation compared to the half-power bandwidth method, as it considers the frequency range in the close vicinity of a natural frequency. This approach is particularly accurate when the modal overlap is less than one. In this approach, the total contribution of all the off-resonant modes is assumed to vary very slowly over the narrow frequency band around a specific resonance. It also provides more robust estimates of loss factor because a number of estimates can be found from responses at different frequencies around each resonance and then averaged. In addition, for both techniques, frequency response is typically measured using a digital spectral analyser with a given frequency resolution which may also lead to inaccuracies. Thus, in this paper, natural frequencies and loss factors are estimated using the SDoF circle-fit method [20] and the Newton's divided differences formula [21,22].

One further problem associated with experimental measurements reported in the literature [14-16,18,23,24] is that in those studies accelerometers were attached to the specimens. However, the accelerometer and its lead add mass and damping to the structure and affect the estimates of natural frequencies and loss factors. Therefore, in this work, a non-contacting transducer such as a laser vibrometer is used.

To date, a number of researches have been carried out on the vibration damping of PFPCs, but few studies have been conducted to ascertain the structural damping levels of PFPCs over a broader frequency range. The present work is, therefore, an attempt to measure the dynamic characteristics of PFPCs over a broader frequency range. The dynamic characterisation concerns various composite beams of different lengths with three different volume fractions and five different orientations of flax fibre. The quality of the damping estimates from the "carpet" plots is also investigated.

## Experimental

### Materials

Polypropylene, a thermoplastic polymer is chosen as a matrix material. Among the thermoplastic polymers (e.g., polypropylene, polyethylene and polystyrene), polypropylene is the most widely used in plant fibre composites due to its low density, good mechanical properties, relatively high-temperature resistance, excellent processability and good impact resistance. It is also an attractive choice for vibration damping due to its glass transition temperature being below room temperature [4]. Polypropylene shows the nature of free volume, amorphous and high flexibility of molecules below the glass transition temperature. Moreover, it undergoes molecular deformation and can dissipate vibration energy [25]. Polypropylene has a loss factor of 0.06 [26,27] (similar to that found in this study) which is higher than widely-used thermosets (e.g., epoxy, loss factor of 0.015 [28,29]). In addition, PP has great potential for composite materials as it can be processed using traditional technologies, for example, extrusion, vacuum bagging, compression and injection moulding.

Sheets of PP random copolymer (MOPLEN RP241G)

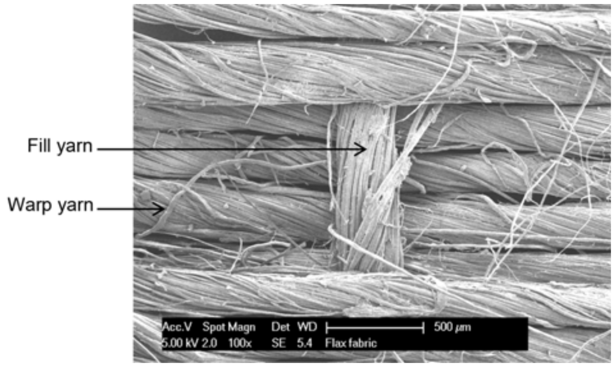


**Figure 1.** Unidirectional stitched flax fabric.

with a melt flow rate of 1.5 g/10 min determined by ISO 1133 and a thickness of 0.38 mm were used as matrix material. The polypropylene sheets were produced by Lyondell Basell Industries and supplied by Field International Ltd., Auckland, New Zealand. The properties of PP are shown in reference [30].

Flax is chosen in the present study as a reinforcement material. Among the various plant fibres (flax, hemp, jute, ramie and kenaf), flax has high inherent vibration absorption capability [31,32] in addition to its high specific stiffness [33,34]. Flax fibres also offer a combination of low cost, light weight and high stiffness for applications [33,35,36], such as infrastructures, automobiles and consumer products. High-quality long flax yarns are available in fabric form [37].

Unidirectional flax fabric (FlaxPly UD180) with a nominal specific weight of 180 g/m$^2$ and density of 1.42 g/cm$^3$ was used as reinforcement. A micrograph of the flax fabric is shown in Figure 1. The flax fabric (42.5 yarns/cm (warp) and 3 yarns/cm (weft)) was supplied by Lineo, Meulebeke, Belgium. The weight distribution of flax fabric in the warp and weft directions was 95.5 % and 4.5 %, respectively, according to the manufacturer's datasheet. The role of weft (or fill) yarns is to keep the warp yarns together. The flax fibres are twisted to some degree within the yarns.

### Manufacturing of Composites

Flax fabrics were dried for 24 hours at 70 °C in a vacuum dryer (Squaroid duo-vac vacuum oven) to reduce the moisture content. Vacuum bagging technique (Figure 2) was used to manufacture the composite samples. This technique uses atmospheric pressure (acts uniformly over the laminate) for holding the laminate in place during the cure cycle. The consolidation temperature of 190 °C was applied based on the differential scanning calorimetry curve of PP, as shown in Figure 3, which was greater than the peak melting temperature of 143.58 °C. Dry flax fabrics and PP sheets were interleaved by a hand lay-up process and placed on an aluminium plate. Then, a peel ply was used to separate the breather from the laminate, and the breather was employed

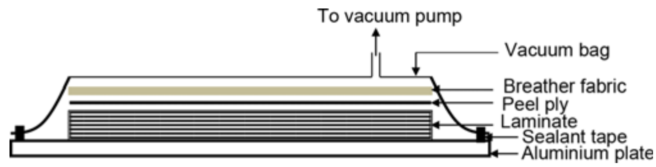


**Figure 2.** Vacuum bagging technique.

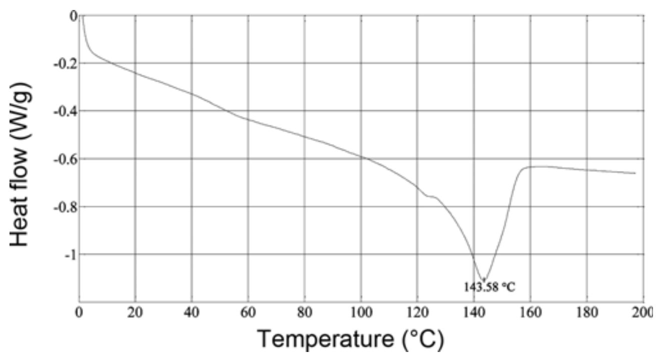


**Figure 3.** A differential scanning calorimetry curve of neat polypropylene.

to ensure all the air inside the vacuum bag could be drawn into a vacuum port. After sealing the material stack, the air was evacuated from inside the vacuum bag using a vacuum pump. The mould was subsequently placed inside the Elecfurn (FAC 100) oven and heated to a temperature of 190 °C for 1 hour. After this, the mould was cooled to a room temperature of around 24 °C. The temperature-pressure cycle (cycle 1) was applied according to reference [38]. The size of the panels was nominally 600 mm×500 mm, with a target thickness of 3 mm and target fibre volume fractions of 0.31, 0.40 and 0.50. Corresponding to each fibre composition, beams (450 mm×20 mm) with fibre orientations of 0 °, 30 °, 45 °, 60 ° and 90 ° were cut from the panels using an automatic saw. Neat PP samples were also manufactured for comparison with the respective flax/PP samples.

### Impulse Hammer Technique

An impulse hammer technique was used to measure the frequency response of flax/PP composite beams (300/350/400 mm×20 mm×thickness) at an ambient temperature of about 21 °C. One end of the composite beam was clamped to a fixed support and the other end was free to vibrate, as illustrated in Figure 4. The excitation was provided by an impact hammer (PCB model: 086E80) with a soft tip at a distance of 5 mm from the free end of the beam, and the beam response was measured by a laser vibrometer (Polytec model: PDV-100) at a distance of 20 mm from the free end of the beam. The excitation and response signals were then processed by a spectrum analyser which gave the frequency response functions. Subsequent data processing were performed in MATLAB [39]. The estimation of natural frequencies and

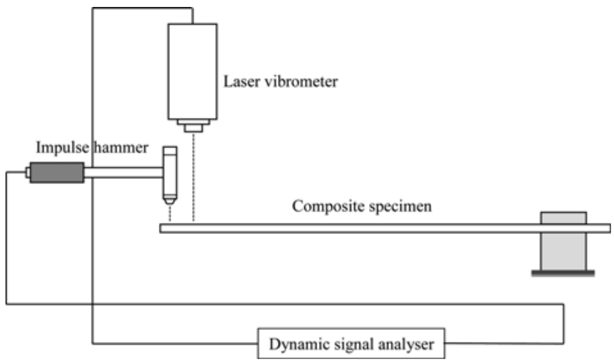


**Figure 4.** Schematic diagram of experimental setup for an impulse hammer technique.

loss factors was made on composite beams of lengths 300, 350 and 400 mm with different fibre volume fractions and orientations. The results are reported for beams of differing lengths to provide a range of resonance frequencies.

## Frequency Response Functions

The accelerance (acceleration per unit force) was measured over a frequency range to 1 kHz. Figures 5-7 show examples of the magnitude of the measured accelerance for flax/PP samples of various fibre volume fractions and orientations, and a neat PP sample. There are a number of resonance peaks for the various modes of vibration in the frequency range, with the natural frequencies being determined by the stiffness and length of the beam. The data in the vicinity of these peaks was then post-processed to determine the natural frequencies and the loss factors.

## Modal Analysis Using the SDoF Circle-fit Method

The extraction of modal parameters such as natural frequencies and loss factors from measured frequency responses (see Figures 5-7) was performed using the SDoF circle-fit method [20]. An illustrative example is shown in Figure 8.

A portion of the data in a narrow frequency range around each resonance was analysed. A circle was fitted through the use of a least-squares error fit to the data when plotted in the complex plane; the centre and the radius of the circle were estimated. The Newton's divided differences formula was used to determine the location of the natural frequency ($\omega_r$)

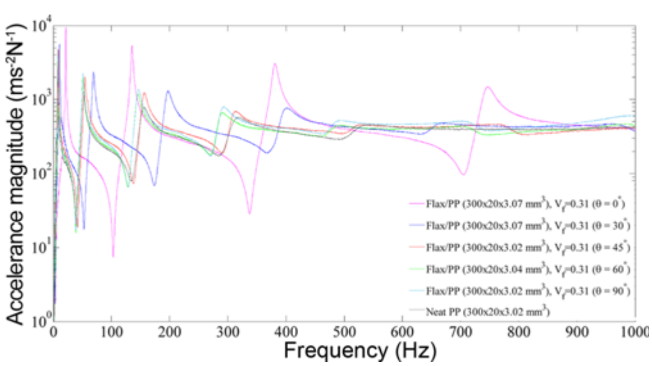


**Figure 5.** Accelerance magnitude for flax/PP beams of different fibre orientations and a fibre volume fraction of 0.31, and a neat PP beam.

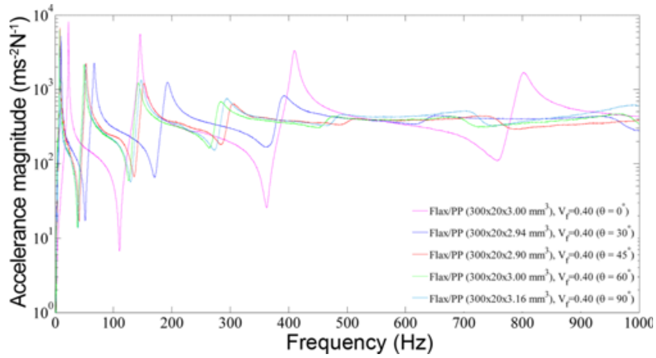


**Figure 6.** Accelerance magnitude for flax/PP beams of different fibre orientations and a fibre volume fraction of 0.40.

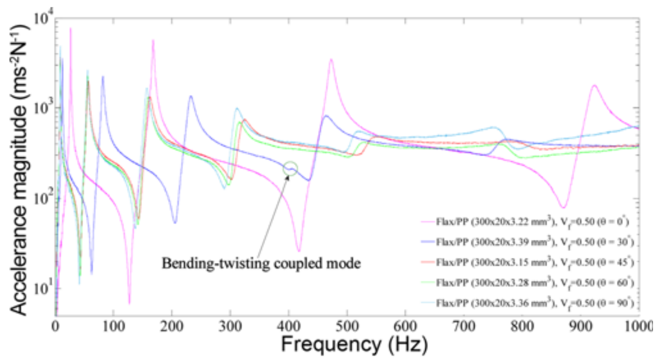


**Figure 7.** Accelerance magnitude for flax/PP beams of different fibre orientations and a fibre volume fraction of 0.50.

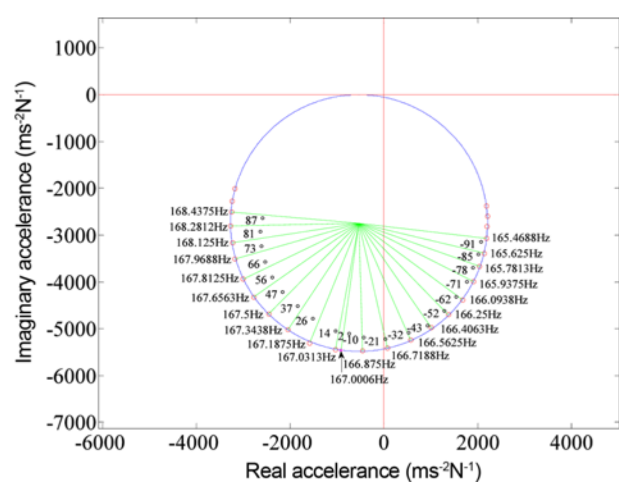


**Figure 8.** Modal circle for extracting natural frequency and loss factor:* Estimated natural frequency (indicated by an arrow) and o discrete frequency data, angles are in degrees.

and its value corresponding to the maximum rate of change of phase [21,22]. The loss factor ($\eta_r$) was estimated from the frequency response measurements at frequencies $\omega_a$ and $\omega_b$ above and below the natural frequency using equation [20] as

$$\eta_r = \frac{\omega_a^2 - \omega_b^2}{\omega_r^2\left(\tan\left(\frac{\theta_a}{2}\right) - \tan\left(\frac{\theta_b}{2}\right)\right)} \tag{1}$$

where $\theta_{a,b}$ are the angles between the radii from the centre of the circle to the natural frequency and the frequency response at the chosen frequencies $\omega_a$ and $\omega_b$, respectively. The mean loss factors were then calculated from 100 estimates by considering 20 data points, 10 data points below the natural frequency and 10 data points above the natural frequency.

## Results and Discussion

### Natural Frequency

The variation of natural frequency with fibre orientation for different fibre volume fractions are shown in Figures 9-11. In general, the natural frequencies of the neat PP beam are lower than those of the composite beams, and this is expected as the stiffness of the neat PP sample is lower. In regard to the fibre orientation of 0 ° samples, the natural frequencies increase with higher fibre content. This is due to the presence of a higher proportion of fibres producing greater stiffness, and hence the natural frequency is increased. For the composite orientations of 30 °, 45 ° and 60 °, the natural frequency either decreases by a small amount or is almost constant with increasing fibre content.

This is consistent with the results obtained from static three-point bend tests (see Figure 12); the flexural moduli decreased somewhat for these fibre orientations with increasing fibre content. The flexural moduli were measured in accordance with ASTM D760-10 using an Instron 5567 with a 10 kN load cell. The average value and standard error obtained from at least five specimens (nominal size of each specimen: 75 mm×12.7 mm×the thickness of the sample) are given.

As the angle between the longitudinal and fibre axes increases, the drop in natural frequencies is substantial. However, the rate of decrease in natural frequencies reduces when the angle between them is greater than 30 °. Increasing the angle of fibres from 0 ° to 60 ° reduces the natural frequency by 63.72 % (from 21.64 Hz to 7.85 Hz) in the

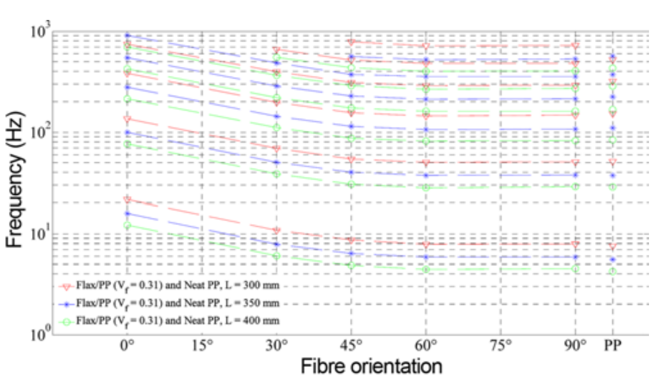


**Figure 9.** Variation of natural frequency with fibre orientation for flax/PP beams of a fibre volume fraction of 0.31, and neat PP beams.

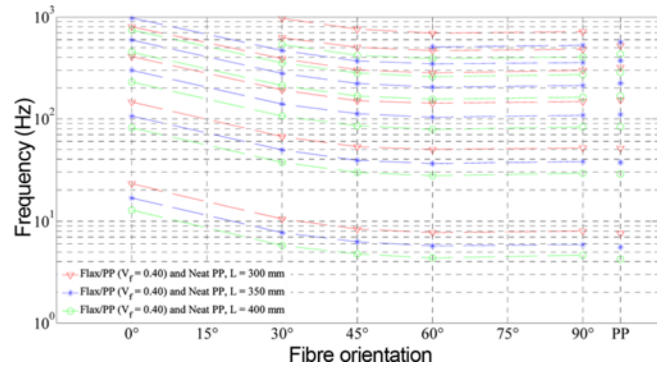


**Figure 10.** Variation of natural frequency with fibre orientation for flax/PP beams of a fibre volume fraction of 0.40, and neat PP beams.

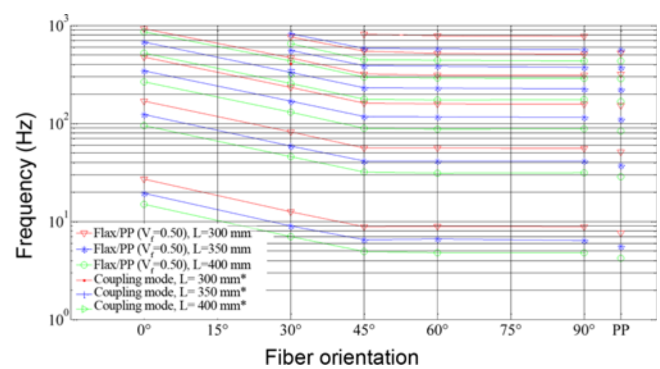


**Figure 11.** Variation of natural frequency with fibre orientation for flax/PP beams of a fibre volume fraction of 0.50, and neat PP beams. *Natural frequency of bending-twisting coupled modes.

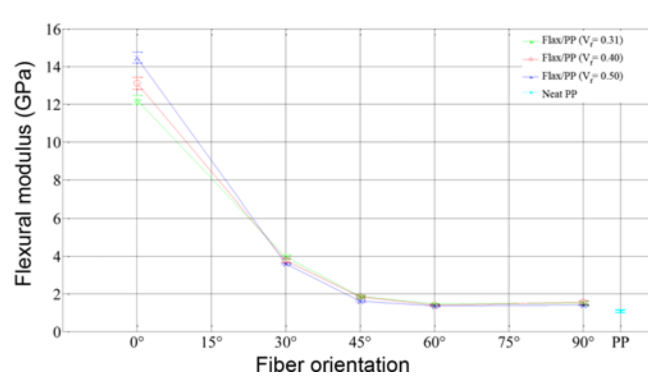


**Figure 12.** Flexural modulus for flax/PP samples of different fibre volume fractions and orientations, and a neat PP sample.

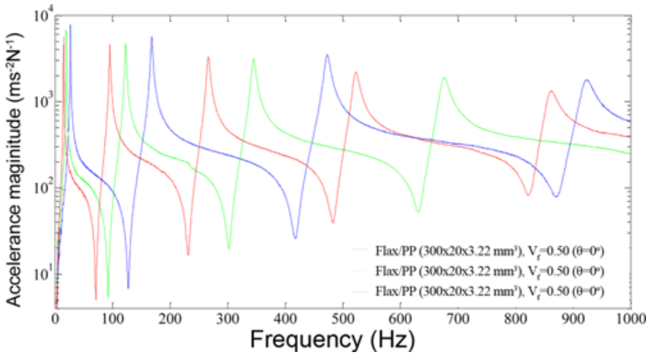


**Figure 13.** Accelerance magnitude for different flax/PP beam lengths of a fibre volume fraction of 0.50.

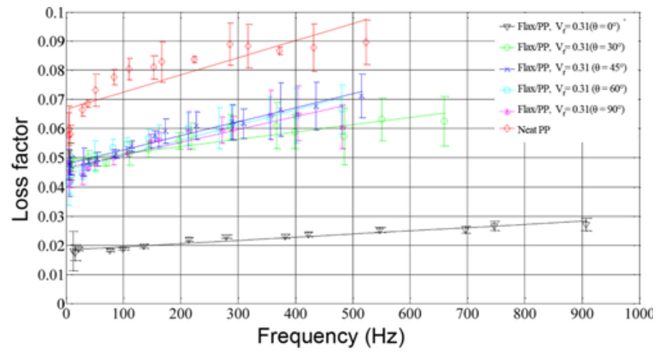


**Figure 14.** Variation of loss factor with frequency for flax/PP beams of different fibre orientations and a fibre volume fraction of 0.31, and neat PP beams.

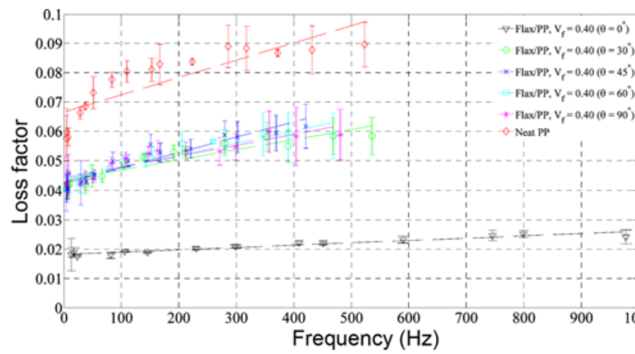


**Figure 15.** Variation of loss factor with frequency for flax/PP beams of different fibre orientations and a fibre volume fraction of 0.40, and neat PP beams.

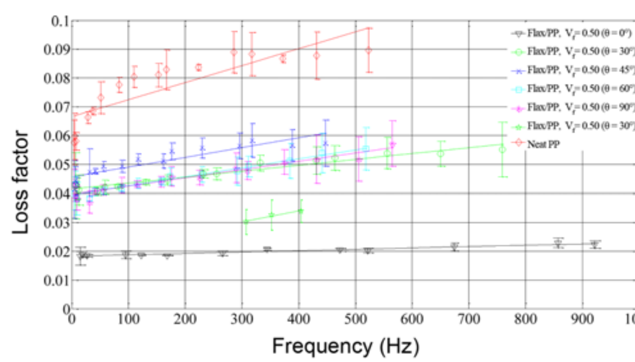


**Figure 16.** Variation of loss factor with frequency for flax/PP beams of different fibre orientations and a fibre volume fraction of 0.50, and neat PP beams. *Loss factor of bending-twisting coupled modes.

case of the first mode of a sample with a fibre volume fraction of 0.31. Incorporation of fibres ($V_f$=0.50) into PP increases the natural frequency of the 0 ° fibre oriented samples from approximately 7.59 Hz to approximately 26.95 Hz. The highest natural frequency occurs for 0 ° fibre orientation because the fibres are stiffer in tension than the matrix. Kumar *et al*. [18] also reported that the more rigid specimens have higher natural frequencies. The lowest natural frequency occurs for 90 ° fibre orientation in the instance of two distinct fibre volume fractions of 0.31 and 0.40; in contrast, in the case of 0.50 fibre volume fraction, the maximum natural frequency occurs at 0 ° fibre orientation and the minimum at 60 °, although the variation between 60 °and 90 ° is negligible.

The magnitude of the peak value of the response at resonance decreases with increasing beam length, as illustrated in Figure 13. The modal density increases with increasing length. A bending-twisting mode (see Figure 7) appears for beam lengths of 300 mm, 350 mm, 400 mm, and a fibre volume fraction of 0.50 and orientation of 30 °. It originates from the coupling between bending and twisting when fibre orientation is different from 0 ° or 90 °.

## Loss Factor

### *Effect of Fibre Content*

Figures 14-16 show the variation of mean loss factor with frequency of flax/PP composite beams for fibre volume fractions of 0.31, 0.40 and 0.50, respectively, and neat PP beams. Linear fits are also shown for each set of data.

The loss factor of neat PP is approximately 0.06 at low frequencies. This value matches with the value reported by a number of authors [26,27]. As the frequency increases, the loss factor of neat PP increases, rising to 0.090 at approximately 500 Hz.

With increased fibre contents of 40 % and 50 % by volume, flax/PP samples exhibit approximately the same loss factors (loss factors lie predominantly in the range of 4-6 % for the fibre orientations of 30 °, 45 °, 60 ° and 90 °, and 2-2.5 % for the fibre orientation of 0 °) as 31 % by volume, despite a decrease in the amount of the viscoelastic polymer. In general, as fibre content increases, the loss factor decreases. However, no significant difference in the loss factors was observed with the addition of an increase in the amount of flax fibre. This is probably due to the existence of more fibres offering more fibre/matrix interfaces. This results in an increase in the number of energy dissipation sites. This is also supported by the statement of Chauhan *et al*. [40] that increasing filler content can contribute to the creation of large number of interfacial areas which increases vibrational energy dissipation. A similar observation was reported by Liang and Tjong [41]. Moreover, this is due to the internal structure of the fibre which induces high internal friction [23]; in particular, this occurs between the cellulose and hemicellulose in each wall and the friction between the cell walls [2,3,8]. The addition of plant fibres also contributes to energy dissipation, even at ambient temperature, and results in the significant damping of the composites over a wide range of frequency [14]. In addition, high damping can be attributed to the presence of voids (e.g., the intrinsic porosity of plant fibres) and the viscoelastic nature of matrix and reinforcement.

The loss factor of composites is, however, lower than that of neat PP because of the lower amount of viscoelastic PP. This coincides with the trend reported by Chandra *et al*. [42] that high content of resin leads to higher damping due its viscoelastic nature. The composite samples are stiffer than the neat PP resulting in more stored energy for the same deformation. The higher stored energy leads to lower damping in the composites as compared to the neat PP. The stiffness is strongly dependent on the presence of fibres, while the loss factor is dominated by the matrix; this results in decreased loss factors due to the incorporation of flax fibres into PP. A similar observation was also reported by other authors [3,16,40,42,43]. However, interfacial damping ameliorates this. When compared to the base PP samples, at a fibre volume fraction of 0.31, the flexural stiffness of the composite material increases by about 270 % (from 1.07 GPa to 3.96 GPa, as shown in Figure 12), whereas the loss factor decreases by about 30 % (from 0.076 to 0.054) in the case of 30 $^{\circ}$ fibre oriented samples.

***Effect of Fibre Orientation***

Figures 17-19 illustrate the variation of mean loss factor with fibre orientation of flax/PP composite beams for fibre volume fractions of 0.31, 0.40 and 0.50, respectively, and neat PP beams. Notably, these variations of loss factor with fibre orientation are also due to the effect of different natural frequencies. However, in these particular cases, the effect of the different natural frequencies is not mentioned to show the trend of loss factor with fibre orientation only.

The effect of reinforcement orientation on the damping of composites is noticeable. The 0$^{\circ}$ fibre oriented samples demonstrate sharper resonance peaks (see Figures 5-7), while 30$^{\circ}$, 45$^{\circ}$, 60$^{\circ}$ and 90$^{\circ}$ fibre oriented samples exhibit broader peaks with the exception of the first two peaks. This indicates that the damping is greater for such orientations.

The loss factor increases with increasing fibre orientation up to 45$^{\circ}$, and it can then be seen to decrease slightly as the fibre orientation increases to above 45$^{\circ}$. Maximum damping is obtained for the fibre orientation of 45$^{\circ}$ in the case of all

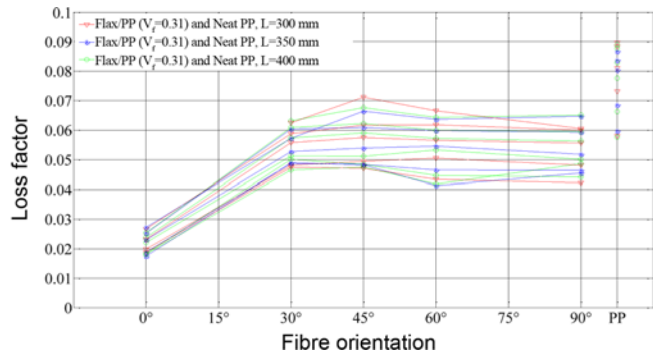


**Figure 17.** Variation of loss factor with fibre orientation for flax/PP beams of a fibre volume fraction of 0.31, and neat PP beams.

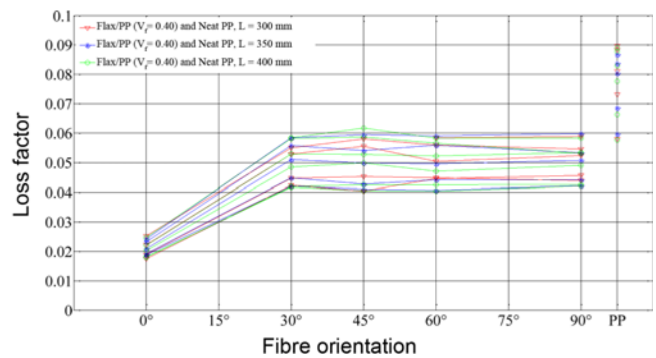


**Figure 18.** Variation of loss factor with fibre orientation for flax/PP beams of a fibre volume fraction of 0.40, and neat PP beams.

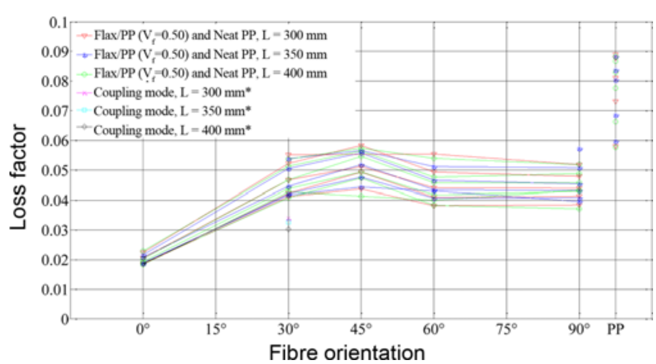


**Figure 19.** Variation of loss factor with fibre orientation for flax/PP beams of a fibre volume fraction of 0.50, and neat PP beams. *Loss factor of bending-twisting coupled modes.

fibre volume fractions, and the damping is found to lie in the range of 4-7 % for this fibre orientation. A similar trend was observed by Gao *et al*. [44] and Adams and Maheri [45] in the cases of carbon fibre-reinforced epoxy, and carbon and glass fibre-reinforced plastic composites, respectively. This is because the total energy is dominated by the in-plane shear strain energy [46]; the in-plane shear strain energy is maximised at this fibre orientation in flax/PP composites. The maximum loss factor of 0.071 is observed for a 300 mm beam ($V_f$=0.31 and $\theta$=45$^{\circ}$) at approximately 500 Hz. The average loss factor for the 45 $^{o}$ fibre oriented samples show a significant increase in loss factor of around 150 % (from 0.021 to 0.052) when compared to the 0 $^{o}$ fibre oriented samples. At very low frequency, fibre orientations other than 0 $^{o}$ fibre orientation exhibit almost the same damping. The damping is minimal and the stiffness is at its maximum at 0 $^{o}$, i.e., in the fibre direction. This is reasonable, since the fibres play a dominant role at 0 $^{o}$ fibre orientation and fibres exhibit less damping and a much higher stiffness than the matrix material. As the orientation angle increases, the general trend is for the damping to increase (up to a certain angle) and the stiffness to decrease. The bending-twisting modes exhibit a loss factor of 0.032 on average; this is less than other modes of the same sample.

Damping increases when frequency increases for a given fibre volume fraction. A maximum increase of loss factor of 60 % (0.042 to 0.067) is found for a fibre volume fraction of 0.31 and orientation of 60 $^{o}$. The increase is in the range of 25-60 % over the frequency range to 1 kHz for all fibre volume fractions and orientations. The increase in damping with frequency may come from fibres and/or fibre/matrix interactions.

The fibre orientation (30 $^{o}$, 45 $^{o}$, 60 $^{o}$ and 90 $^{o}$) of the sample affects the loss factor more than the fibre content (31 %, 40 % and 50 % by volume). Overall, the loss factor of flax/PP composite samples is in the range of 2-7 % for all studied fibre volume fractions and orientations. It can be inferred from the above discussion that plant fibres possess a significant vibration damping capacity.

**Diagnosis of the Quality of the Damping Estimates**

The loss factor estimated using equation (1) depends on the chosen frequencies $\omega_a$ and $\omega_b$ in addition to the natural frequency ($\omega_r$). Different choices of $\omega_a$ and $\omega_b$ give different estimates of loss factor. The variation in the individual estimates of loss factor for many combinations of the selected frequencies can be seen from the damping "carpet" plots, with two examples shown in Figure 20 and Figure 21. The plots are presented for the first and second modes of a beam (beam length=300 mm, $V_f$=0.50 and $\theta$=0 $^{o}$) using all combinations of the 20 selected frequencies below and above the natural frequency. This gives rise to 100 estimates of loss factor from which are obtained the mean and variance of the estimates. For a perfect case, the surface ought to be smooth, flat and level. The surfaces of the plots are almost horizontal, smooth and flat, apart from some tilt and unevenness. The coefficients of variation of the 100 estimates are 1.76 % (where mean loss factor of 0.017 and standard deviation of 0.0003) and 1.58 % (where mean loss factor of 0.019 and standard deviation of 0.0003) for mode 1 and 2, respectively. These are small and indicate that the estimates are of good quality. On the whole, the coefficients of variation are in the range of 1.04-9.92 %, 1.40-10.86 % and 0.43-11.11 % in the case of fibre content of 31 %, 40 %

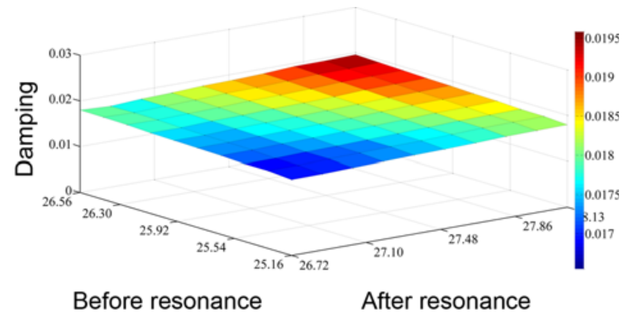


**Figure 20.** Damping "carpet" plot (beam length: 300 mm, $V_f$=0.50, $\theta$=0 $^{o}$ and mode 1).

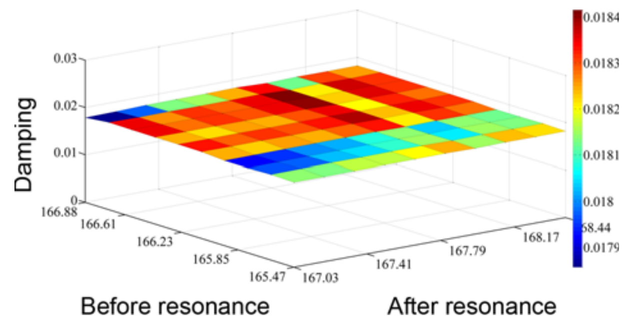


**Figure 21.** Damping "carpet" plot (beam length: 300 mm, $V_f$=0.50, $\theta$=0 $^{o}$ and mode 2).

and 50 % by volume, respectively. In relation to this deviation, some possible measurement errors include measurement noise, clamping pressure, air damping and non-uniformity in the laminate (voids, variations in thickness and improper bonding).

## Conclusion

The effects of the fibre content and fibre orientation on the damping of NFPCs were estimated from vibration measurements. The SDoF circle-fit method and the Newton's divided differences formula provide accurate estimates of natural frequencies and loss factors. Changes in fibre content and orientation produce different natural frequencies and loss factors for the same geometry and boundary condition. This offers an additional freedom for the design of a composite laminate-allowing for the prospect of alternating the fibre orientation to affect the structure's stiffness and damping. This knowledge also makes the use of these materials attractive as it is feasible to increase damping without increasing mass or changing geometry.

Of all the parameters, fibre orientation has the most significant impact on the damping. At each fibre volume fraction, the loss factor increases up to 4-7 % for fibre orientation up to 45 $^{o}$ and then decreases slightly. The loss factor generally lies in the range of 2-7 %, irrespective of fibre volume fraction and fibre orientation. The increase in damping is in the range of 25-60 % over the frequency range of 1 kHz. The damping "carpet" plots indicate the quality of the estimates of loss factor. The coefficient of variation of the loss factor estimated at each resonance is in the range of 0.43-11.11 %.

Given this, it can be concluded that the high damping capability of flax fibre-reinforced composite materials with low weight make these materials appropriate for applications in cases where low weight and high damping are sought.

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