Experimental and numerical modal analysis of short carbon fiber reinforced polyethersulfone composites

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Abstract. Damping is the resistance to the vibratory motion. Viscous dampers are generally used to resist the repetitive motion and dissipate the energy out of the vibrating system. However, material of the vibrating body itself will have ability to dissipate the vibratory energy which is often referred as material damping. Even though, material damping is very small compared to viscous damping, in many practical situations, this may also play significant role. This work was focused on the evaluation of material damping of short carbon fiber (SCF) reinforced polyethersulfone (PES) composites by adopting free vibration test methodology. In addition, Young's modulus of the PES/SCF composites was determined through their natural frequencies. Investigation was made by reinforcing the PES with 10, 20 and 30 wt.% of SCF using twin screw extruder and injection moulding machine. Free vibration response of the clamped-free composite beam was captured through an accelerometer sensor. Free vibration test revealed that PES composites showed reduction in damping with increase in SCF content due to stiffening of the polymer. Natural frequencies of PES composites increased with increase in SCF loading. Tensile modulus enhanced by 267% with respect to neat polymer for 30 wt. % of SCF reinforcement. Also, numerical frequency analysis was carried out using Abaqus finite element package and simulated results closely fitted with the experimental data.

1. Introduction

In aerospace, marine and automobile industries, components are generally made by polymer composites reinforced with carbon fibers[1]–[3]. Carbon fiber reinforced plastics will have high strength to weight ratio [4], [5]. Damping is one of the most important property of the material due to which energy is dissipated from the vibrating system in the form heat [6]. Pure polymers will have better damping properties due to their visco-elastic nature. Generally, addition of fibers to polymers enhances the stiffness of composite which may result in reduction in their damping properties. Modal analysis is a tool to determine the vibration parameters such as natural frequencies and their corresponding mode shapes[7],[8]. Vibration techniques can be used as non-destructive tests to detect and locate the flaws in fiber reinforced composites[9]. Modal analysis is also used to optimize the dynamic response of the structures. Present modal investigation was carried out in order to understand the effect of short carbon fibers on damping behaviour of polyethersulfone composites.
2. Materials and Methods

2.1. Materials
The polyethersulfone (PES) was procured from the company Solvay (USA) and was used as matrix material. The short carbon fiber (SCF) based on polyacrylonitrile (PAN) was purchased from the company Teijin (Japan) and was used as reinforcement material. Materials formulation adopted in the present work is referenced in table 1. The properties of PES and SCF are stated in the previous work [10].

Table 1. Material formulations and designations [10].

| Composites | Matrix wt. % | Fiber wt. % | Density (g/cm$^3$) | Elastic modulus (GPa) |
|------------|--------------|-------------|--------------------|----------------------|
| C$_{00}$PES | 100          | 00          | 1.364              | 2.760                |
| C$_{10}$PES | 90           | 10          | 1.395              | 5.886                |
| C$_{20}$PES | 80           | 20          | 1.415              | 8.798                |
| C$_{30}$PES | 70           | 30          | 1.423              | 9.191                |

2.2. Fabrication methods
PES and SCF were mixed with different fiber weight fraction of 0, 10, 20 and 30% in ZE 40 twin screw extruder (KraussMaffei Berstorff) at slightly above the melting temperature of PES which is 330 °C and composite pellets were formed. These pellets were preheated to remove moisture and then melted again in a single screw injection molding machine (Milacron 80T) and filled to the molds having dimensions length 120 mm x width 10 mm x thickness 3.85±0.05 mm at a high pressure of 140 bar for a duration of 3 second, after that specimens were allowed to cool at atmospheric pressure for 15 seconds. Injection molded test specimen is shown in figure 1.

2.3. Free vibration test
Damping properties of the PES/SCF composites were determined by single cantilever free vibration decaying test [11]–[13]. The developed samples were mounted as cantilever beam and 10 mm length was used for clamping purpose. Effective length of the beam was taken as 110 mm for analytical calculations and numerical simulations. Piezoelectric accelerometer, model PCB 356A15 was used to capture the response of the vibrating beam as indicated in figure 2. Mass of the accelerometer used is 10.5 grams and it is capable to measure the frequency in the range 2 to 5000 Hz with ± 5 % accuracy.

Accelerometer was mounted at the free end of cantilever beam arrangement with an temporary adhesive (petro wax) as in figure 3. Analog response captured by accelerometer was then digitalized with the help of NI 9234 IEPE input module. Digitalized response was then transferred to the
computer system through NI compact data acquisition module cDAQ 9178. Data received by the computer was then analyzed using NI Labview software package.

Figure 3. (a) Free vibration test setup (b) Cantilever arrangement

Composite beam was made to vibrate by disturbing it with a small force by an impact hammer. As there was no viscous damper connected, neglecting the air damping, it was assumed that vibrating beam decreases its amplitude of oscillation in every cycle and finally after some finite time attains the equilibrium position. Decrease in the amplitude in every successive cycle is measured using logarithmic decrement parameter.

Logarithmic decrement (δ) is the ratio of natural logarithm of two successive amplitudes and is mathematically expressed as in equation (1).

\[
\delta = \frac{\ln x_1}{\ln x_2} = \frac{1}{n} \ln \left( \frac{x_1}{x_{n+1}} \right)
\]  

(1)

Damping ratio (ζ) is related to the logarithmic decrement according to equation (2).

\[
\zeta = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}}
\]  

(2)

Since damping offered by the material is very small, the term \( \delta^2 \) can be neglected.

\[
\zeta = \frac{\delta}{2\pi}
\]  

(3)

Damped natural frequency (\( f_d \)) is determined by taking the ratio of number of cycles (n) to time taken to complete 'n' number of cycles (t).

\[
f_d = \frac{1}{2\pi} \left( \frac{n}{t} \right)
\]  

(4)

Undamped natural frequency (\( f_u \)) of the a single degree-of-freedom (DOF) system is related to damped natural frequency as expressed in equation (5).

\[
f_u = \frac{2\pi f_d}{\sqrt{1-\zeta^2}}
\]  

(5)

For a single DOF cantilever system with beam mass 'm' and point load 'M' at its tip, natural frequency is given by equation (6).
In the present modal analysis study, point load 'M' indicates the mass of the piezoelectric accelerometer sensor and beam mass 'm' depends on the density and volume of the composite sample [14].

Generally, short fibers are aligned in the direction of melt flow during the injection process based on the theoretical approach. However, short fibers reinforced to composites take the random orientations along and across the thickness due to the fabrication limits and tolerances. Different fiber orientation leads to variation in tensile modulus of the composites. Instead of conducting destructive tensile test, free vibration test can be conducted on specimens without breaking them [9], [13]. From the vibration-time plot, damped natural frequency is calculated using the equation (4). Further, damped frequency is converted into undamped frequency using the relation (5). At last, tensile modulus (E) can be determined with the help of natural frequency using the expression (6), where, I is bending moment of inertia of beam having rectangular cross section and l is the length of beam.

2.4. Numerical analysis
Numerical modal simulation was performed to understand the nature of anisotropic composite material behaviour during the vibration [15], [16]. Finite element based numerical modal analysis was carried out using Abaqus CAE 2017 software package. Mass of the accelerometer sensor (10.5 g) was considered for the analysis by modeling it as a solid volume of dimensions 13 mm x 13 mm x 13 mm with density of 4560 kg/m³. Geometry of the composite beam was modelled separately as per the dimensions of actual specimens and then interaction was applied between beam and sensor with tie constraint as represented in figure 4(a).

![Figure 4.](image)

Material of the beam was assumed as homogeneous and elastic for numerical analysis. Modulus of elasticity determined by free vibration test was given as material input parameter. Geometry was fixed at one end by arresting all the degrees of freedom of the nodes present at that end. Both the geometries were meshed with C3D8R elements as in figure 4(b) and then linear frequency perturbation analysis was carried out.

3. Results and discussion

3.1. Free vibration test
Acceleration signals recorded for PES/SCF composites were plotted against time using the Matlab tool as shown in figure 5. Amplitudes of acceleration and their corresponding time were labeled for five successive cycles.
By means of these amplitude and time data, logarithmic decrement for the composites were determined using the equation (1), damping ratio were determined with the help of equation (2) and/or (3). All the computed parameters are presented in table 2.

Table 2. Free vibration test results of PES/SCF composites.

| Parameters                      | Composites |
|--------------------------------|------------|
|                                | C_{00}PES  | C_{10}PES  | C_{20}PES  | C_{30}PES  |
| Time t₁ (s)                    | 0.014      | 0.003      | 0.004      | 0.007      |
| Time t₂ (s)                    | 0.215      | 0.140      | 0.115      | 0.114      |
| Amplitude at time t₁ (m/s²)    | 65.7       | 93.0       | 104.4      | 95.1       |
| Amplitude at time t₂ (m/s²)    | 1.7        | 15.8       | 21.5       | 21.6       |
| Logarithmic decrement, δ       | 0.731      | 0.355      | 0.316      | 0.296      |
| Damping ratio, ξ               | 0.116      | 0.056      | 0.050      | 0.047      |
| Time period (s)                | 0.040      | 0.027      | 0.022      | 0.021      |
| Damped natural frequency, f₀ (Hz) | 24.88     | 36.50      | 45.05      | 46.73      |
| Undamped natural frequency, f₀ (Hz) | 25.04     | 36.55      | 45.10      | 46.78      |
| Tensile Modulus, E (GPa)       | 2.737      | 5.847      | 8.916      | 9.599      |

Material damping primarily occurs due to friction interaction between various constituents in the composites and/or within the polymer chains. Materials absorb the vibration energy to create friction interaction between constituents which in turn releases heat energy. This heat needs to be dissipated out from the material [4]. Addition of SCFs into neat PES resulted in improvement in stiffness of the composites. Due to increase in stiffness, vibration energy absorption by the composites decreased.
Neat PES showed the logarithmic decrement of 0.731 resulting in its damping factor as 0.116. Logarithmic decrement values of the composites reduced by 51.4 %, 56. 8% and 59.5% with the reinforcement of 10, 20 and 30 wt.% of SCF into PES. This in turn resulted in lowering of the damping nature of PES/SCF composites. With addition of 10 wt. % of SCF, damping factor decreased drastically by 51.7%. However, with addition of 20 and 30 wt.% of SCF, further reduction in damping factor was very small with respect to C\textsubscript{10}P composite.

Figure 6. Damping of PES/SCF composites.

Incorporation of SCF into PES resulted in improved stiffness (tensile modulus) of composites. Improvement in tensile modulus was due to good adherence of polymer with fiber surface. Fiber breakage with very few fiber pull-outs were seen on the fractured surface of tensile specimen of C\textsubscript{30}PES composite shown in figure 7 taken by scanning electron microscopic (SEM), indicating good bonding between fiber and polymer.

Due to good stickiness, the relative motion between the polymer molecules as well as polymer and fiber during the vibration was restricted. This reduced the fiber-matrix friction interaction during vibration and hence, composites lost the ability to absorb the vibration energy and damping of SCF reinforced composites were reduced.

Figure 7. SEM image of fractured tensile specimen of C\textsubscript{30}PES composite

Damped and undamped natural frequencies were computed according to equations (4) and (5). In addition, Fast Fourier Transform (FFT) analysis was carried out with the help of signal processing tool available in National Instruments Labview software. FFT analysis transformed the acceleration in time domain to frequency domain. Accelerations in frequency domain are shown in figure 8.
Frequency corresponding to the first largest peak represents the damped natural frequency of the composite materials. Damped natural frequencies of the composites were in agreement with analytical values computed by equation (4).

Finally, modulus of elasticity of PES/SCF composites were determined using the natural frequency of free vibration test as per equation (6) and the correlated data was mentioned in table 3. It was worthwhile to note that modulus of elasticity of composites determined through free vibration test were found in close match with the tensile test results [10] with less than 5% error.

Table 3. Tensile modulus of PES/SCF composites.

| Composites | Density [5] (kg/m³) | Voids (%) | Elastic modulus (GPa) |
|------------|---------------------|-----------|-----------------------|
|            |                     |           | Tensile test [10] | Free vibration test | Error (%) |
| C₀₀PES     | 1364                | 0.44      | 2.760                | 2.737                | 0.83      |
| C₁₀PES     | 1395                | 0.86      | 5.886                | 5.847                | 0.66      |
| C₂₀PES     | 1415                | 2.05      | 8.798                | 8.916                | 1.34      |
| C₃₀PES     | 1423                | 4.08      | 9.191                | 9.599                | 4.44      |

3.2. Numerical simulation

Numerically simulated first mode shape of PES/SCF composites along with the accelerometer mounted on the beam were shown in figure 9. Numerical frequencies were found close to the experimental results as reported in table 4. Since experiments were conducted in air, damping due to air may be one of the factors accounting for the error between numerical and experimental values.
addition, modeling the composite beam with visco-elastic material model may further reduce the error between numerical and experimental frequencies.

![Figure 9. Abaqus CAE simulated frequencies of composites (a) C00PES (b) C10PES (c) C20PES (d) C30PES.](image)

| Composites | Natural undamped frequencies (Hz) | Error (%) |
|------------|----------------------------------|-----------|
|            | Experimental | Numerical |         |
| C00PES     | 25.04       | 26.328    | 5.1     |
| C10PES     | 36.55       | 38.407    | 5.1     |
| C20PES     | 45.10       | 47.367    | 5.0     |
| C30PES     | 46.78       | 49.123    | 5.0     |

4. Conclusion
In conventional tensile test, material is loaded till it breaks and with the help of deformation variation with applied load, tensile modulus is evaluated. Free vibration test is non destructive in which material is subjected to a small impact force and specimen is made to vibrate freely. Experimental results revealed that with increase in SCF loading into PES, damping values of the composites were decreased. Maximum reduction in damping was found in C30PES composite whose tensile modulus enhanced by 267% with respect to neat polymer. Young’s moduli of the PES/SCF composites based on free vibration test were in well agreement with tensile test results. In addition, natural frequencies obtained by numerical simulation matched with that of experimental values.

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