Effect of carbon nanotube reinforcement on the natural frequencies and damping ratios of nanocomposite beams

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Abstract
In this study, the effect of carbon nanotube (CNT) reinforcement on the natural frequencies and damping ratios of nanocomposite beams are examined. Three nanocomposite plates reinforced with different CNT weight ratios (0% neat epoxy-glass fiber composite beam, 0.25%, 0.5%) are produced. Multi Walled Carbon Nanotubes (Purity > 96%, outside diameter < 8nm) are mixed into the epoxy resin with an ultrasonic stirrer. The plates also contain glass fibres as an additional reinforcement. Test specimens are cut parallel and perpendicular to the direction of the fibres to obtain two different sets of specimens. Free vibration tests are performed by a wireless accelerometer sensor (WAS), a wireless data acquisition system (WDA) and a PC. Natural frequencies and damping ratios are determined from the acceleration data obtained from the experiments. For both the 0° and 90° specimens an increase in natural frequency is observed. However, while the damping ratio of the 0° specimen increases, the damping ratio of 90° one decreases.

1. Introduction
Nanocomposites have been a popular area of research in recent years due to their exceptional mechanical properties. Carbon nanotubes (CNT) are widely used in nanocomposites as a filler to improve the physical properties final composite product. CNTs have an elastic modulus over 1 TPa and tensile strength over 150 GPa which makes them stronger than steel while being lighter. As a result of this, nanocomposites become an appropriate material for robot manipulators where lightness is a desired property. Lighter manipulators mean less power consumption which is also another important quality. This study focuses on the effect of the CNT ratio on the natural frequencies of simple nanocomposite beams.

Addition of CNTs to the matrix of fiber-reinforced composites also provides further energy dissipation as a result of the interaction between CNTs and the surrounding matrix. DeValve & Pitchumani [1] modeled this interaction with a stick-slip damping term and developed a numerical model using Euler–Bernoulli beam equation in a rotating frame of reference. They performed a parametric study to examine the effects of different beam geometries, angular speed profiles. Their simulations showed that by adding 1%–2% of CNT addition can reduce the vibration settling time of a rotating composite beam by an average of 40%–60%.

Her & Lai [2] studied the dynamic behaviour of nanocomposites reinforced with multi-walled carbon nanotubes (MWCNTs). Natural frequency and damping ratio were determined using free vibration tests. Experimental results showed that the damping ratio of nanocomposites decrease with the increase of the MWCNT addition. They explained that increasing the ratio of MWCNT increases the adhesion between epoxy and the CNTs, which leads to less slippage and less dissipation of energy. Functionalized MWCNTs improved the interfacial bonding between the nanotubes and epoxy resin resulting in the reduction of the interfacial energy dissipation ability and enhancement of the stiffness. Carbon nanotubes have also been considered as a damping enhancement because of the interfacial friction between the nanotubes and the polymer resin. Zhou et al [3] investigated the structural damping characteristics of polymeric composites containing SWCNTs with a focus on the interfacial interaction between the resin and the CNT. By comparing neat resin specimens with the
ones that have CNT fillers, they observed that the damping is enhanced by adding CNT fillers into polymeric resins. Influence of multiwall carbon nanotube alignment on vibration damping of nanocomposites is also a topic of research in the literature. By aligning the CNTs using DC electric field during the curing of the composite different specimens are fabricated with different CNT ratios. Dynamic mechanical analysis and flexural vibration experiments are performed to observe the behavior of the specimens. In case of aligned nanocomposites, significant enhancement is noticed in the material damping for the tested frequency band width of 0–30 Hz; also the flexural tests have shown an improvement up to 37% in structural damping compared to randomly oriented [4].

There has also been studies about the mechanical behaviors of helical springs containing CNTs as a reinforcement in the epoxy resin. Mechanical properties of the springs (Young's moduli, shear modulus, Poisson ratio) were computed by the micromechanics approach for different CNT-ratios. Deformation values and distributions of shear stress of composite springs were compared to the regular steel springs. The results proved that composite springs were better than the steel ones in terms of deformations and shear stresses [5].

Free vibrations of non-uniform nanocomposite beams have also been studied in the recent years. Seidi and Kamarian [6] employed the Mori-Tanaka (MT) technique to estimate the effective mechanical properties of a three-phase composite beam (CNT/fiber/polymer). They obtained the natural frequencies of the beam by solving the governing equations with Generalized Differential Quadrature (GDQ) approach. The influence of volume fraction and agglomeration of nanotubes and different laminate lay-ups on the natural frequencies of the beam are examined. The alignment of carbon nanotubes has also been proved to have an effect on the natural frequencies and the dynamic behavior of nanocomposites. Thomas et al [7] studied the finite element modeling and free vibration analysis of functionally graded nanocomposite beams reinforced by randomly oriented straight single-walled carbon nanotubes. The effects of CNT orientations, shear deformation, slenderness ratio and boundary conditions on the dynamic behavior of the beam are investigated thoroughly.

Esawi and Farag [8] made a review of carbon nanotube reinforced composites discussing the potential challenges of production costs, application areas and the future of CNTs. Their discussion showed that CNTs needed to be produced in large quantities at a lower cost, to be synthesized in longer lengths and also improved techniques are required to align and evenly distribute them in the matrix.

Kamarian et al [9] studied the free vibrations of laminated beams reinforced with SWCNTs based on various HSDBTs and analytical methods. Extended rule of mixtures is used to calculate the mechanical properties of the nanocomposite and the natural frequencies of the beam are compared with the various solutions that are available in the literature. As for the second part of the study an optimization problem with the amount of the CNTs as a constraint is solved with a novel meta-heuristic approach called Imperialist Competitive Algorithm. CNT reinforced nanocomposite sandwich plates are also studied in the literature. Moradi-Dastjerdi et al [10] investigated the free vibration analysis of functionally graded nanocomposite sandwich plates reinforced with randomly oriented CNTs by applying a refined plate theory. Material properties of the plates are estimated through the Mori-Tanaka method. Effects of CNT ratios, elastic foundation parameters and dimensions of the plate on the natural frequencies are investigated.

Other than CNTs graphene is also a popular reinforcement for nanocomposite beams. Same procedure is applied to these beams as well. The matrix is reinforced by nanographene plates and mechanical properties are estimated using various methods. Shahrjerdi and Yavari [11] performed a temperature-dependent vibration analysis for the functionally graded nanocomposite beams which are reinforced by graphene. They solved the equations of motion using spectral numerical method for the beams under various boundary conditions. It can be seen from this study that the increase of graphene weight percentage in all boundary conditions will cause an increase in the natural frequency of the beams.

Another review [12] with a wider scope has also been made about polymer-matrix nanocomposites. This review explains the preparation and processing methods of different types of nanocomposites such as nanoplatelet-reinforced, nanoclay-reinforced, CNT-reinforced, polymer-inorganic particle nanocomposites and nanofiber-reinforced systems. More specific studies on CNTs can also be found in the literature. Theoretical models of the tensile strength of MWCNTs are developed and investigated [13]. Mechanical properties of epoxy composites such as Young’s modulus and tensile strength are greatly improved by adding CNTs [14] which increases the rigidity of the composite thus increasing the natural frequencies.

Dispersion of the CNTs in epoxy matrix is the main challenge in the production phase of the nanocomposites. Due to long-range van der Waals interactions, nanotubes agglomerate and form bundles or ropes. Because of this, after adding a certain weight% of CNTs, the improvements become smaller until eventually the CNTs form bigger agglomerations and start to decrease the properties of the material [15].
2. Materials and method

2.1. CNT enhancement

In regular composites, neat epoxy is commonly used as matrix and reinforced with fibers to create a two phase material to enhance the material properties. In this study, the epoxy matrix is reinforced with CNTs before the production process to take advantage of the mechanical properties of the CNTs by creating a reinforced matrix. Since CNTs are used in small amounts the weight increase is minimal compared to the pure epoxy composite beam. Figure 1 illustrates the production steps of the nanocomposites.

CNTs have exceptional mechanical properties which makes them a suitable choice for reinforcing the epoxy phase of the composites. These mechanical properties are combined with low density which makes them lighter and high surface area make CNTs even more desirable. High surface area of the CNTs serves as a damping enhancement by creating friction with the epoxy particles. The nanoscale particle size of CNTs means a small particle distance which also influences the properties of nanocomposites even at an extremely low CNT content. Figure 2 shows the SEM images of the Multi-walled CNTs used in this study.
2.2. Production of nanocomposite plates

For the first stage of the testing 10 g of Multi Walled Carbon Nanotubes (Purity > 96%, outside diameter < 8nm) in powder form are purchased from Nanografi Nano Technology. Then, the powder is taken to Fibermak Composites for the production of the composite plates. The powder is mixed with the epoxy resin (matrix) by an ultrasonic stirrer to ensure that the mixture is homogenous. The plates also have unidirectional glass fiber fabric for additional reinforcement and are produced by using vacuum assisted resin infusion method. The plates have 8 layers and a thickness of 2 mm. The dimensions of the plates are 500 mm × 500 mm × 2 mm. Also the plates contain 0%, 0.25% and 0.5% (weight ratio) CNT powder in the epoxy in order to determine the effect of the reinforcement. Figure3 shows two of the three plates that were for produced.

In order to take the SEM images of the nanocomposite plates, 2 cm × 1 cm samples were cut out from the plates and gold coated in order to increase conductivity for better imaging. The deformations near the edges provided a better view of the fibres and and epoxy-CNT matrix. Figures 4 and 5 shows the SEM images of the % 0.25 and %0.5 samples, respectively. SEM images show the fibres coated with epoxy-CNT matrix which provides additional reinforcement to the fibres. The tubular structure of CNTs also provides additional support similar to rebar in concrete against cracks and fractures, absorbing energy while the crack forms and slowing the advancement of the cracks.

2.3. Experimental set-up and natural frequencies

The test beams are prepared by cutting the plates. The sketch of the beams is shown in figure 6. The length, width, and thickness of the beams are 350 mm, 20 mm, and 2 mm, respectively. The location of the accelerometer near to the free end is shown in figure 6. The weight of the beam and accelerometer are 30 g, and 54 g, respectively. An accelerometer is placed 50 mm away from the free end to record the acceleration response of the beam.

The fibers are at 0° in all of the layers of the composites. 0° and 90° specimens are obtained by cutting the plates in the fiber direction, and in the perpendicular direction to the fibers, respectively, as shown in figure 7. 0° specimens are fiber dominant while the 90° specimens are matrix dominant. The pictures of the specimens are shown in figure 8.

The picture of the experimental set-up is shown in figure 9. The beam is clamped at one end to a highly rigid structure. MicroStrain wireless accelerometer sensor (WAS) is located near to the free end. MicroStrain wireless data acquisition system (WDA) is connected to a personal computer (PC). The sampling rate is 617 Hz for streaming. An initial displacement is given to the free end to excite the first bending vibration mode, and the free vibration responses are obtained. The responses are plotted in 10,11,12. The amplitude decays over time as the result of the damping.

Fast Fourier Transform (FFT) is applied to the time signal. The resulting amplitudes of the FFT signals is shown in figures 10–12. The tests are repeated for the other specimens with different reinforcement ratios and the responses are plotted to compare the natural frequencies of the nanocomposites.
Figure 4. (a) ×200 (b) ×1 k (c) ×5 k (d) ×10 k magnified SEM images of the %0.25 nanocomposite sample.

Figure 5. (a) ×500 (b) ×1 k (c) ×5 k (d) ×10 k magnified SEM images of the %0.5 nanocomposite sample.
2.4. Damping ratios

The logarithmic decrement method [16] is used to find the damping ratios. The logarithmic decrement represents the rate at which the amplitude of a free-damped vibration decreases. It is defined as the natural logarithm of the ratio of any two successive amplitudes.

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

(1)
Equations (1) and (2) are used to determine the damping ratio of a system where $x_1$ and $x_{m+1}$ are the amplitudes of two peaks that are separated by $m$ number of cycles. The peaks of the response are marked in MATLAB and the values are substituted into equations (1) and (2) to determine the damping ratios.
2.5. Results and discussions

Natural frequencies and damping ratios of the $0^\circ$ specimens are listed in table 1. A pure epoxy-glass fiber composite beam is compared to nanocomposite beams with different CNT reinforcement ratios.

**Figure 11.** Acceleration and frequency responses of the 0.25% CNT-reinforced nanocomposite beam.

**Figure 12.** Acceleration and frequency responses of the 0.5% CNT-reinforced nanocomposite beam.
The experiments show that the natural frequencies of the beams increase as the weight ratio of CNT-reinforcement increases. The CNT increases the stiffness of the composite as a result of its high elasticity modulus which increases the natural frequency of the beam. The increase in natural frequency is 5.1% from 0% CNT to 0.25% CNT. On the other hand, the increase in natural frequency is less (1.4%) from 0.25% CNT to 0.5% CNT. This is due to CNT agglomeration because the mixing of the epoxy with CNT homogeneously becomes more difficult as the weight ratio increases, and CNT accumulates in some small areas. Damping ratio also increases as the weight ratio increases because the fibers strength against bending also increase and absorb more energy which increases the damping ratio because the specimens are fiber dominant. These results show that adding and mixing small amounts of CNTs to composites homogenously can improve the damping and natural frequencies of beams.

Natural frequencies and damping ratios of the $0^\circ$ specimens are listed in Table 1.

In the case of $90^\circ$ specimens the natural frequencies are lower than the $0^\circ$ ones as expected because the fibers are perpendicular to the direction of bending. However, the increase in natural frequency is much higher (23.8%) from 0% CNT to 0.25% CNT. Another difference between the $0^\circ$ and $90^\circ$ specimens is that the damping ratio decreases in the $90^\circ$ case. The adhesion between the epoxy and CNTs cause less slippage and less energy dissipation and a decrease in damping ratio because the $90^\circ$ specimens are matrix dominant.

### 3. Conclusions

This study investigates the effect of CNT reinforcement on the natural frequencies and damping ratios of nanocomposite beams. Free vibrations tests are performed on the specimens. Natural frequencies and damping ratios are determined by applying FFT and logarithmic decrement method to the acceleration response of the specimen. A pure epoxy-glass fiber composite beam is compared with two CNT reinforced epoxy -glass fiber nanocomposite beams with different CNT ratios. The results are as follows:

- The natural frequencies increase with CNT reinforcement as expected because the rigidity of the beam is increased.
- The increase in natural frequencies is less for higher ratio of CNT. The reason for this result is because mixing CNT homogeneously is more difficult for higher ratio of CNT and CNTs tend to agglomerate in the epoxy.
- The increase in natural frequency is higher for $90^\circ$ specimens as compared with $0^\circ$ specimens. The reason for this result is because $90^\circ$ specimens have matrix dominant material properties and the effect of CNT is higher.
- Damping ratios of the $0^\circ$ specimens increase with the addition of CNTs and the pattern of increase is similar to natural frequencies. This is because the fibers strength against bending also increase and absorb more energy which increases the damping ratio because the specimens are fiber dominant.
- Damping ratios of the $90^\circ$ specimens decrease with the addition of CNTs although the natural frequencies increase. The adhesion between the epoxy and CNTs cause less slippage and less energy absorption and a decrease in damping ratio because the $90^\circ$ specimens are matrix dominant.

### Table 1. Comparison of natural frequencies and damping ratios ($0^\circ$).

|                | Natural frequency (Hz) | Damping ratio |
|----------------|------------------------|--------------|
| 0% CNT         | 7.1928                 | 0.0023       |
| 0.25% CNT      | 7.5649                 | 0.0026       |
| 0.5% CNT       | 7.6071                 | 0.0027       |

### Table 2. Comparison of natural frequencies and damping ratios ($90^\circ$).

|                | Natural frequency (Hz) | Damping ratio |
|----------------|------------------------|--------------|
| 0% CNT         | 4.1048                 | 0.0048       |
| 0.25% CNT      | 5.0839                 | 0.0041       |
| 0.5% CNT       | 5.1592                 | 0.0037       |
These results show that adding small amount (0.25%) of CNT rather than larger amount (0.5%) is more effective to observe the increase of the rigidity of beams which results in an increase in the natural frequencies. This also means that nanocomposite beams are a good alternative to the regular composite beams. This may be beneficial for the applications such as robotic manipulators where rigidity and lightness are desired qualities. Further studies are planned for industrial structures.

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