EXPERIMENTAL STUDIES ON THE VIBRATION CONTROL OF EPOXY CLAY NANO-COMPOSITES

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Abstract

Fabrication of nanocomposites for different-clay (alumino-silicate) concentrations (1, 3, 5 and 10 wt%) with the matrix (epoxy) is done by using shear mixer. This paper presents the experimental study of free vibration and damping characteristics. The work also involves vibration control of nanocomposite laminates by reinforcing organically modified montmorillonite clay in the epoxy matrix by resin casting technique. Theoretical study is also carried out to study the vibration and damping characteristics of epoxy clay nanocomposites. Dynamic result shows that the second phase nanoscale dispersion in the matrix significantly enhances the internal damping of nanocomposites. This work also presents the active vibration control of nanocomposite beams. Piezoelectric patches are bonded on the surface of beam and control algorithms are applied to the system. Feed forward (open loop) control algorithms are used to control the vibration. Maximum control is obtained for sample with 3 wt.%OC.

***Keywords**: Vibration, Damping, Vibration Control, Nanocomposite, Organoclay*

Nomenclature

DGEBA	= Diglicidyl Ether Bisphenol-A
ECN	= Epoxy-Clay Nanocomposites
EI	= Young's modulus
OC	= Organo Clay
PCN	= Polymer Clay Nanocomposites
RTC	= Room Temperature Cured
TETA	= Triethylene Tetramine
UC	= Unmodified Clay
ξ	= Damping factor
ω_n	= Natural frequency (rad/sec)

Introduction

Nanomaterials are the class of materials whose dimensions are in the nanometer level (1-100 nm) [1]. Typically nanocomposites are polymeric composites with nanoparticle such as clay as reinforcing agents. Polymer nanocomposites (PCN) are a new class of materials consisting of polymer as matrix and nanoclay as the reinforcement fillers [2, 3]. PNC are polymers (thermoplastics, thermosets or elastomers) reinforced with small quantities (less than 5% by weight) of nano-sized particles having high aspect ratio (L/h > 300). Clay/polymer nanocomposites offer tremendous improvement in physical and engineering properties for polymers with low filler loading.

The increasing demand of high performance requirements has led to the development of smart/ intelligent materials and structures. A smart structure has the capability to respond to changing external environment (such as loads, temperature and shape change) as well as to changing internal environment (such as damage or failure). This has been greatly exploited in applications such as active vibration and buckling control, shape control, damage assessment and active noise control. These structures are used in advanced aerospace, hydrospace, nuclear and automotive structural application.

Piezoelectricity is an electromechanical phenomenon that occurs in certain classes of anisotropic crystalline materials called piezoelectric materials. Due to the internal stiffness, these materials are also found to generate relatively large forces when their natural expansion is constrained. Quartz is an example of a natural piezoelectric material (with relatively low coupling), while lead zirconium titanate (PZT) and polyvinylidene fluoride (PVDF) are engineered piezoelectric materials (with high coupling). Most importantly the electrical properties of

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these piezoceramics can be precisely oriented relative to-their geometry by poling these materials.

Vibration control of any structure can be done by passive, active or combination of these two materials. Controlling any structure in passive manner does not require any external energy but the amount of vibration control is less. Hence active vibration control is adopted where a continuous external energy is supplied to the vibrating system through a smart controller. Two piezoelectric patches are bonded on the surface of the cantilever beam. The piezoelectric patch pasted on the upper side (exciter) excites the beam from an external source. Accelerometer senses the vibration response in terms of voltage. This voltage is multiplied by a gain according to the control law implemented and is fed back to the bottom piezoelectric patch (actuator). The bottom piezoelectric patch in response to the feed back voltage, generates mechanical motion. The motion can be made to oppose the motion of the beam if the feedback voltage is applied 180 degree out of phase and then the vibration attenuation of the beam can be achieved effectively.

In our earlier studies [4], we have successfully synthesized exfoliated epoxy clay nanocomposites by room temperature curing. Improved mechanical, barrier and thermo mechanical properties were obtained by the addition 3 wt% of clay with the epoxy matrix. The effects of hybrid nanocomposite have been studied [5] and performance was discussed. There is improvement in the tensile, impact and DMA properties. Dynamic results show nanoclay dispersion in the epoxy matrix enhances the internal damping of composites up to 3 wt% than neat polymer.

Balamurugan [6] studied the mathematical modeling of the smart beam, plate and shell structure with distributed piezoelectric sensors and actuators and their application used for active vibration control.

A one-dimensional mathematical model for determining the mechanical response of beams with piezoelectric actuators has been proposed by Shen [7]. This model is based on Timoshenko beam theory with the host beam and piezoelectric patches being separately modeled using beam elements.

Devasia et. al [8] have formulated actuator placement and sizing methodologies for vibration suppression in uniform beams. Several closed loop performance criteria were considered as objective functions for optimum placement and sizing of piezoelectric actuators in uniform beams.

Hanagud, Obal and Calise [9] proposed discrete degrees of freedom modal for a structural dynamic system of a linear elastic structure, bonded piezoceramic sensors and actuators and feed back signal conditioning system. In addition to this, they developed an optimal control procedure.

Bailey and Hubbard [10] studied active vibration damper of a cantilever beam by a distributed- parameter actuator and distributed-parameter control theory. They have controlled the first mode of the cantilever beam.

Narayanan and Balamurugan [11] have developed finite element model for laminated structures with distributed piezoelectric sensor and actuator layers. Beam element has been developed incorporating the stiffness, mass and electromechanical coupling effects of the piezoelectric laminates. The piezoelectric beam element is based on Timoshenko beam theory. Constant-gain negative velocity feedbacks, Lyapunov feedback as well as a linear quadratic regulator (LQR) approach have been used for active vibration control with the structures subjected to impact, harmonic and random excitations. The LQR approach is found to be more effective in vibration control with lesser peak voltages applied in the piezo actuator layers.

Jin-Chein Lin and Nien [12] have carried out vibration control of a smart beam by using piezoelectric damping-modal actuators/sensors. Theoretical formulations are based on damping-modal actuator/sensors and numerical solutions.

Rajoria and Jalili [13] have examined the stiffness and damping properties of carbon nanotube-epoxy composites for use in structural vibration applications. The influence of nanotube proportion (weight ratio), nanotube type and frequency dependence is studied by considering both single-walled and multi-walled nanotube-epoxy composites with different proportion of nanotubes. Up to 700% increase in damping ratio is observed for multi-walled nanotube-epoxy beam as compared to the plain epoxy beam.

There is not much work available on the experimental study of vibration control of polymer clay nanocomposites. In this paper special emphasis is given to understand vibration, damping characteristics and vibration control of epoxy clay nanocomposite.

Experimental Procedure

DGEBA Epoxy Resin, Curing Agents and Glass Fibres

DGEBA epoxy resin along with the curing agent, namely Triethylene Tetra amine (TETA) obtained from CIBA, Basle (Switzerland) are used in the present study.

Clays

The organoclay used is alkyl ammonium treated montmorillonite and unmodified clay is the natural Na^+-MMT. The clays are obtained from Southern Clay Products, Texas, USA. The manufacturer data of OC is given in Table-1.

Nanocomposite Synthesis

Room Temperature Preparation of ECN

The schematic representation of the methodology used for the preparation of ECN in this study is shown in Fig.1. The synthesis of nanocomposites involves individual dispersion of OC and UC at different percentages by weight (1, 3, 5 and 10 wt%). After adding the desired amount of clay into the epoxy resin, the mixing of resin-clay mixture was carried out. by high-speed mechanical shear mixer. When the clay was added into the resin, the viscosity of the resin-clay mixture was increased and the amount of air bubbles also increased during mixing. The degassing of mixture was done and then TETA hardener was added to the pre- mixture to initiate the cross-linking. The detailed study of the nanocomposite preparation and the effect of the clay on the resin system has been studied and presented elsewhere [5].

Vibration

Modal Analysis

Modal testing is performed to calculate natural frequency and damping factor ξ. Damping factor is calculated using Impulse Hammer Technique (IHT). A nanocomposite specimen of 250 * 25 * 3mm is prepared, in which one end of the beam is clamped and other end is attached to accelerometer to obtain vibration modes. Fig.2 shows the block diagram of instrumentation used for Free Vibration Technique (FVT). Natural frequency is determined by impulse loading at free end of the beam using impulse excitation (Rion PH 7117, modally tuned hammer). The signal received from frequency is noted down for various modes. Damping factor ξ using IHT is determined using the half-power bandwidth method.

Table-1 : Properties of organoclay

Serial No.	Organoclay (OC)	
	Properties	Values
01	Colour	Off-white
02	Mean dry particle size	4-5 µm
03	Bulk density	Off-white
04	Mineral purity	98.5%

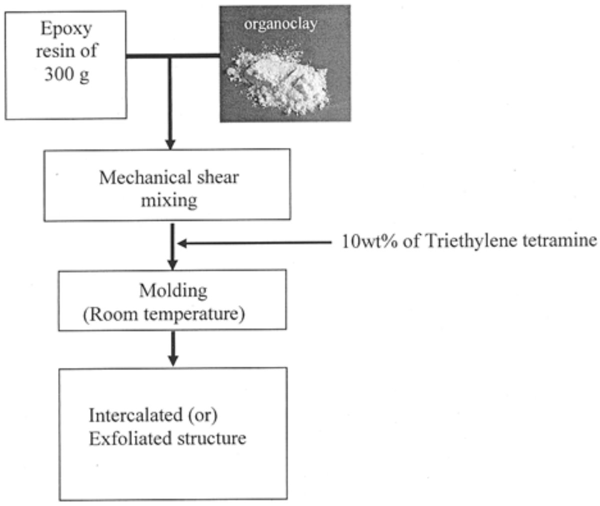

Fig.1 Schematic representation of synthetic procedure of ECN at room temperature

The expression for damping factor ξ by the half-power bandwidth technique is given by Surarez et. al [14].

$$\xi = \Delta\omega/2\omega_n$$

where $\Delta\omega$ = Band width at the hald-power points of resonant peak for nth mode

ω_n = Resonant frequency

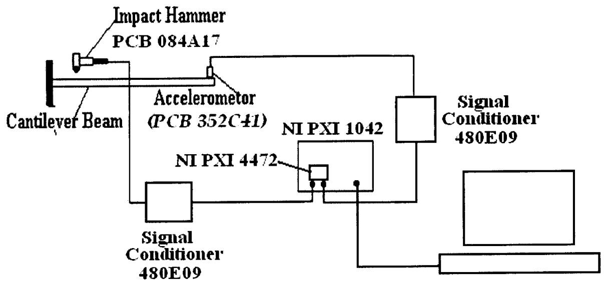

Fig.2 Schematic representation of impulse hammer technique (FVT)

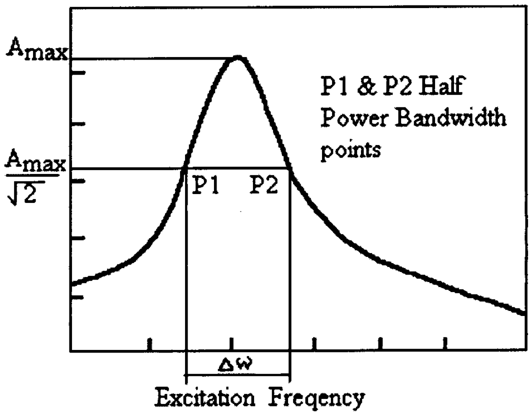

Fig.3 Free vibration test : half power bandwidth damping factor measurement

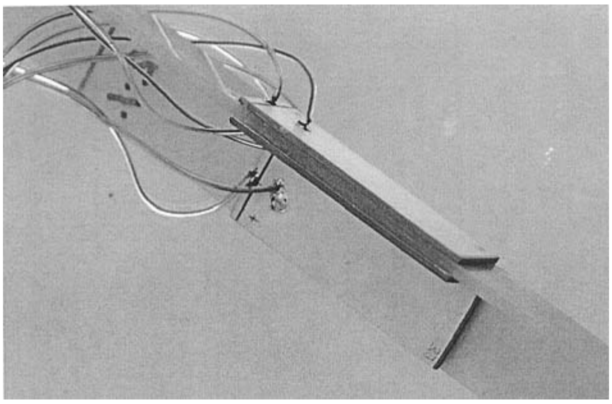

Fig.4 Specimens for vibration control

The half-power points are found at 3 dB below the peak value of the FRF for the particular mode when the logarithmic scale is used or at 1/√2 of this peak value when linear scale is used (Fig. 3).

Vibration Control

Specification of the components

Specimen used for vibration control is shown in Fig.4. The specimens prepared for studying vibration characteristics are used for different composition of clay. The size of the piezoelectric element is 7.61 * 2.54 * 0.2 cm^3 which is SP-5H Plate. The piezo actuator drive amplifier of, range 200 V rms is used. Four Channel Color Digital Phosphor oscilloscope, 100 MHz and 1.25 GS/s has been used for storing the data.

Experimental Set up of Feed Forward Control

Figure 5 shows the experimental set-up of feed forward control system. Here different nanocomposite beams with different composition of the clay (0, 1, 3, 5 and 10 wt%) are pasted with piezo electric patches on the top and bottom surface of the beam, near the fixed support. Upper piezoelectric patch is the exciter and lower patch acts as an actuator. Both patches are connected to the output of the voltage amplifier and the input of the voltage amplifier is connected to the function generator. Accelerator is fixed at the tip of the beam and it is connected to the oscilloscope through the signal conditioner amplifier. The voltage sup-

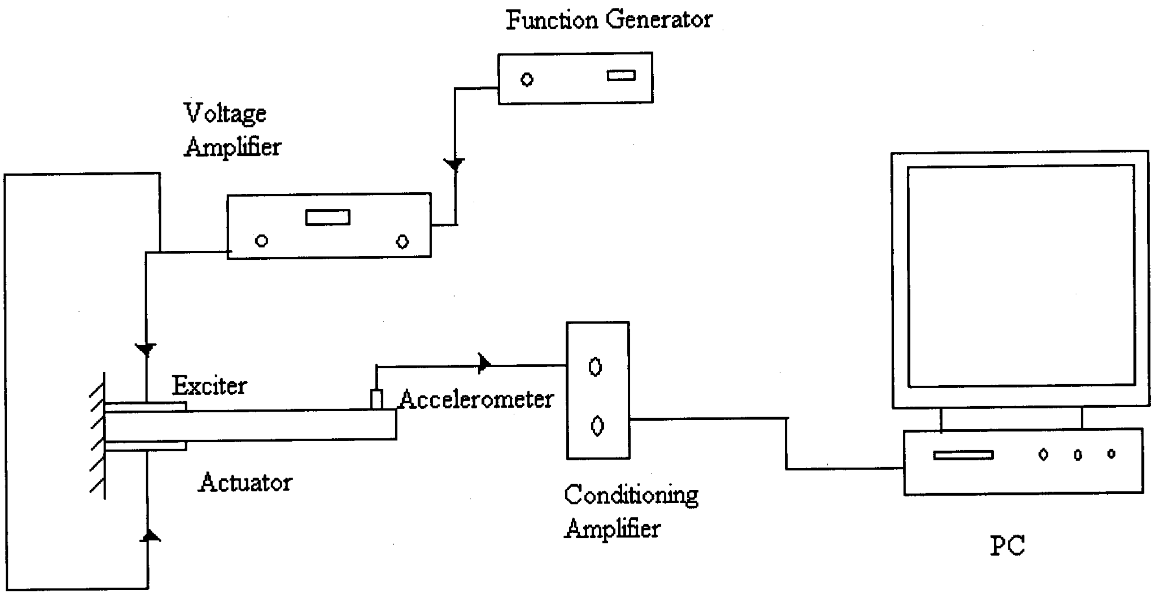

Fig.5 Experimental set-up of the feed forward control system

ply to the exciter patch comes from the function generator, after amplification from the voltage amplifier. Function generator is generating sinusoidal wave at a particular natural frequency of amplifier. Since the size and position of the piezoelectric patches are the same, these patches generate the same amount of the force in the direction, which is parallel to the longitudinal axis, and the moments about the neutral axis of the beam are in opposite direction and hence cancel out each other. Therefore the amplitude of the excitation of the beam decreases to a very low level.

Results and Discussions

Vibration characteristics

By considering the nanoclay composites as quasi-isotropy the natural frequency of the cantilever beams is obtained as follows. The equation of motion of Euler-Bernoulli for beam is given by

$$m\,(x)\left(\frac{\partial^2 w}{\partial t^2}\right)+c\left(\frac{\partial w}{\partial t}\right)+EI\left(\frac{\partial^4 w}{\partial x^4}\right)=f\,(x\,,\,t) \qquad (1)$$

Where, *m* is mass per unit length of the beam defined as $m = \rho A$, ρ is the density of composites, E is Young's Modulus and *A* is area of cross-section of beam. If no damping and external force are considered then $c = 0$ and $f\,(x, t) = 0$. By assuming $EI\,(x)$ and $m\,(x)$ as constant, the equation (1) can be rewritten as,

$$\left(\frac{\partial^2 w}{\partial^2 t}\right)+\frac{E\,I}{m}\left(\frac{\partial^4 w}{\partial x^4}\right)=0 \qquad (2)$$

Assuming steady state vibration in harmonic form, we have

$$w\,(x\,,t)\;=\;W\,(x)*\;\sin\,(\omega\,t-\phi) \qquad (3)$$

Introducing equations (3) in (2), we have

$$\left(\frac{\partial^4\,W\,(x)}{\partial\,x^4}\right)+\beta^4\,W\,(x)\;=\;0 \qquad (4)$$

where,

$$\beta^4\;=\;\frac{\omega^2\,m}{E\,I} \qquad 0 < x < l$$

The solution of the equation (4) is

$$W(x)=c_1\,\sin\,\beta\,x+c_2\,\cos\,\beta\,x+c_3\,\sin\,\mathrm{h}\,\beta\,l+c_4\,\cos\,\beta\,l \qquad (5)$$

The constants of equation (5) are obtained by applying boundary conditions (cantilever type) and the expressions for natural frequency of the first four modes are given by,

$$\omega_1\;=\;1.875^2\;\sqrt{\frac{E\,I}{\rho A\,L^4}}\;\;rad/sec$$

$$\omega_2\;=\;4.694^2\;\sqrt{\frac{E\,I}{\rho A\,L^4}}\;\;rad/sec$$

$$\omega_3\;=\;7.854^2\;\sqrt{\frac{E\,I}{\rho A\,L^4}}\;\;rad/sec$$

$$\omega_4\;=\;10.995^2\;\sqrt{\frac{E\,I}{\rho A\,L^4}}\;\;rad/sec \qquad (6)$$

where ω_1, ω_2, ω_3 and ω_4 are the natural frequencies corresponding to mode 1, 2, 3, and 4 respectively. The theoretical values obtained by Euler-Bernoulli Beam theory are given in Table-2. The natural frequencies thus obtained have good agreement with the experimental values in most of the cases.

The experimental results of the natural frequency of epoxy-clay nanocomposite specimens with different percentage by weight are given in Table-2. It is seen that the reinforcement of OC clay shifts the natural frequency of pure epoxy polymer to higher values for all modes of vibration. The maximum increase is observed at low clay content (2-3 wt% OC) and at higher clay content natural frequency starts decreasing but higher than the value of pure epoxy polymer. Good dispersion and stiffness at low clay content has increased the natural frequency. The decrease of stiffness at higher clay content and existence of agglomeration have decreased the natural frequency of composites. Epoxy filled with UC shows slight increase in natural frequency; however the rate of increase in natural frequency value is very much lower than OC filled composites. The trend is similar for both experimental and theoretical values.

Damping Factor

Damping factor of epoxy filled with OC and UC series corresponding to first four modes and the values are given in Table-3. It is observed that damping factor is higher for OC than that of UC filled polymer, which is observed for all the four modes. The damping factor of pure epoxy shows different values for the four different modes and also there is no clear trend in the change of damping factor. In general the addition of clay (both OC and UC) has increased the damping factor of epoxy polymer. However, the rate of increase in damping factor of OC is higher than that of UC filled composites.

Suraraz et. al [14] and Moser and Lumasseger [15] suggested that the increase in damping of composites is mainly due to the stiffness mismatch at the fibre-matrix interface that serves as high damping medium. Since OC dispersed in the matrix at nano level which is not seen for UC filled composites, the effective modulus of OC is higher than that of UC. Since internal damping at OC/matrix interface is higher than that of UC/matrix interface, high damping factor is observed in OC filled composites. The decreasing trend in damping factor at higher OC content (> 3 wt%) possibly has decreased the effective modulus of OC, which is due to the existence of intercalated and agglomeration.

The addition of clay increases the damping factor of pure epoxy polymer as observed in the case of impact hammer method. This suggests that OC acts as good vibration absorption medium and serves as high damping material.

Vibration Control

The control values in percentage (%) are given in Tables 4 and 5. Individual feed forward control graphs for 1, 3 and 10 wt% OC and UC for all mode of epoxy beam are shown in Figs.6-11.

Composites are high damping materials when compared to isotropic material (steel, aluminium, etc.) and

Table-2 : Natural frequency values of RTC epoxy-clay series (IHT)

MATERIAL	EPOXY WITH OC SERIES								EPOXY WITH UC SERIES							
	I mode		II mode		III mode		IV mode		I mode		II mode		III mode		IV mode	
	Theory	Exptl	Theory	Exptl.	Theory	Exptl.	Theory	Exptl.	Theory	Exptl	Theory	Exptl.	Theory	Exptl.	Theory	Exptl.
Epoxy	22.44	16.03	140.66	126.44	407.12	380.12	797.46	747.33	22.44	16.03	140.66	126.44	407.12	380.12	797.46	747.33
E + 1% clay	24.50	17.14	153.69	136.45	430.50	400.69	843.25	798.56	23.65	16.92	148.23	133.68	415.21	387.86	813.33	767.26
E + 3% clay	25.83	20.30	161.92	157.12	453.54	419.41	888.40	855.21	24.76	19.02	155.20	150.88	434.72	403.91	851.52	810.90
E + 5% clay	24.73	30.03	155.02	151.75	434.21	412.19	850.53	832.14	23.18	20.03	145.33	144.04	407.07	401.23	797.37	783.21
E + 10% clay	23.72	18.53	148.74	140.34	416.61	405.09	816.06	800.32	22.73	19.02	142.20	133.12	399.14	398.24	781.84	770.21

Table-3 : Damping factor of RTC epoxy-clay series (IHT)

Material	E + OC Series				E + UC Series			
	I Mode	II Mode	III Mode	IV Mode	I Mode	II Mode	III Mode	IV Mode
Epoxy	0.0540	0.0080	0.0070	0.0050	0.0540	0.0080	0.007	0.0050
1%	0.0590	0.0090	0.0080	0.0058	0.0560	0.0070	0.0076	0.0058
3%	0.0630	0.0130	0.0100	0.0074	0.0600	0.0100	0.0088	0.0074
5%	0.0590	0.0097	0.0084	0.0058	0.0560	0.0091	0.0076	0.0058
10%	0.0560	0.0085	0.0076	0.0053	0.0550	0.0083	0.0071	0.0053

hence to give the excitation to the beam (by using piezo-electric patches high amount of voltage (60-70 V rms.) is required. For open loop control, graphs are in sinusoidal and control implementation is only for the control of vibration amplitude. For OC-RTC series, the control value increases from 82% to 93% for mode I, 83% to 97% for mode II, 80% to 97% for mode III and 77% to 96% for mode IV up to 3 wt. % OC but for higher clay content the control value decreases to 84%, 82%, 92% and 93% but higher than the pure epoxy beam. The increase in control values up to 3 wt% OC is due to the increase in stiffness. The large improvement in stiffness observed in our earlier studies [16] suggests that exfoliation/intercalation of nanoscale particle in the matrix restrict the mobility of polymer chains under loading. This is also due to the good interfacial bond between particle and the epoxy matrix.

Table-4 : Control valaues (%) if RTC epoxy-clay series

% clay	Control values in %			
	Mode I	Mode II	Mode III	Mode IV
0	82.31	83.23	80.17	77.45
1	88.57	95.71	95.29	94.54
3	93.33	96.87	96.87	96
5	91.17	86.47	91.46	94.28
10	84	82.38	90	92.72

Table-5 : Control valaues (%) if RTC epoxy-clay series

% clay	Control values in %			
	Mode I	Mode II	Mode III	Mode IV
0	82.31	83.23	80.17	77.45
1	84.30	90.40	89.12	88.31
3	84.40	91.20	90.60	91.60
5	84.00	90.60	85.71	88.50
10	80.88	79.33	75.00	78.00

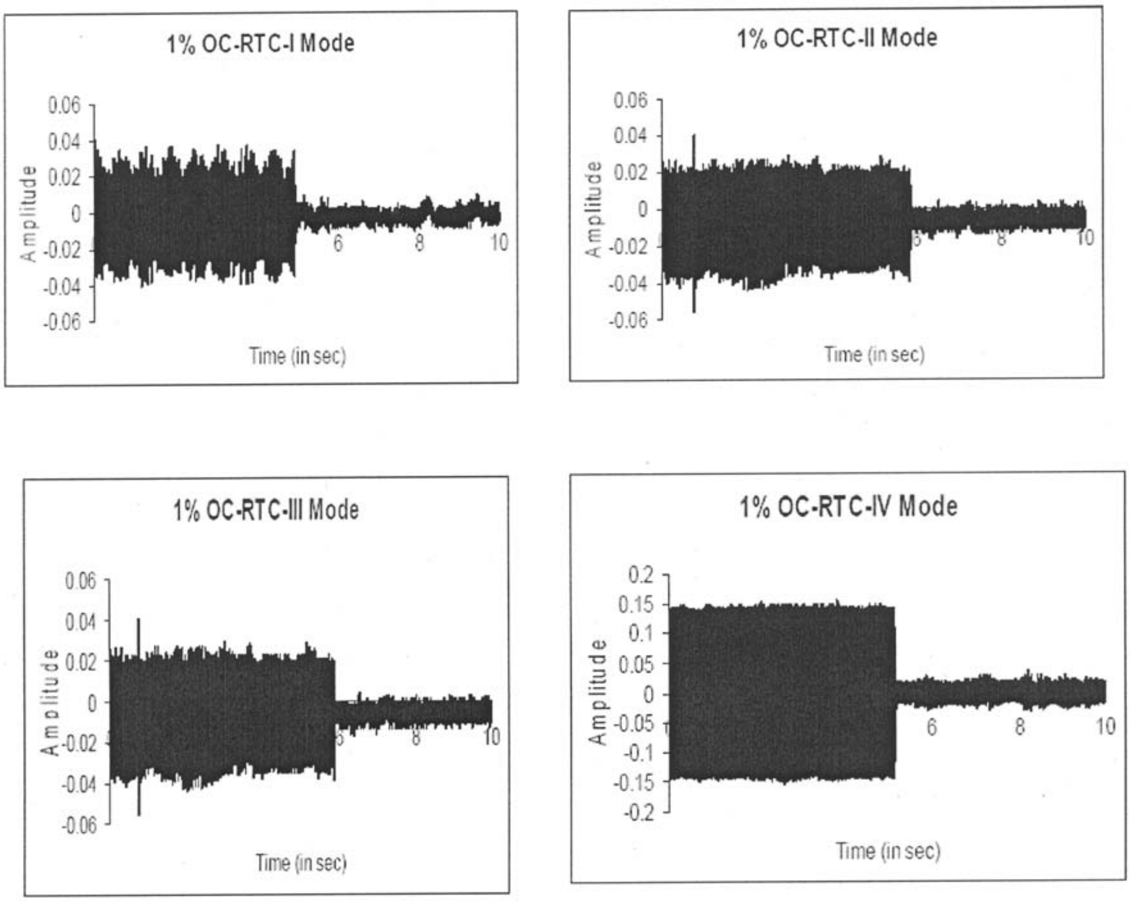

Fig.6 Control graphs of epoxy with 1% OC-RTC

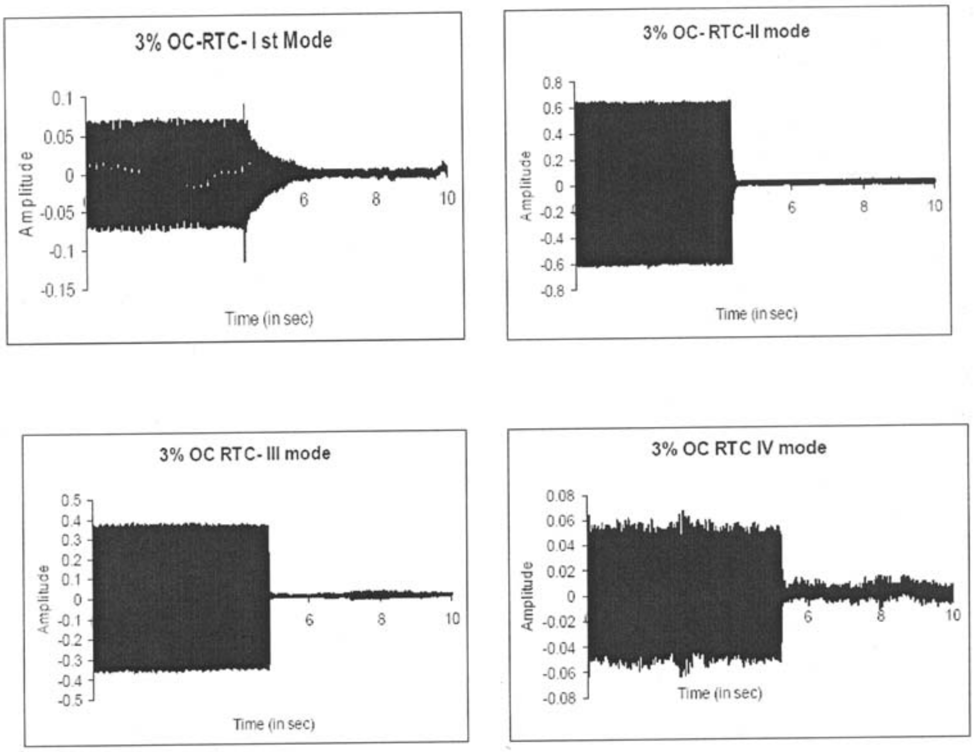

Fig.7 Control graphs of epoxy with 3% OC-RTC

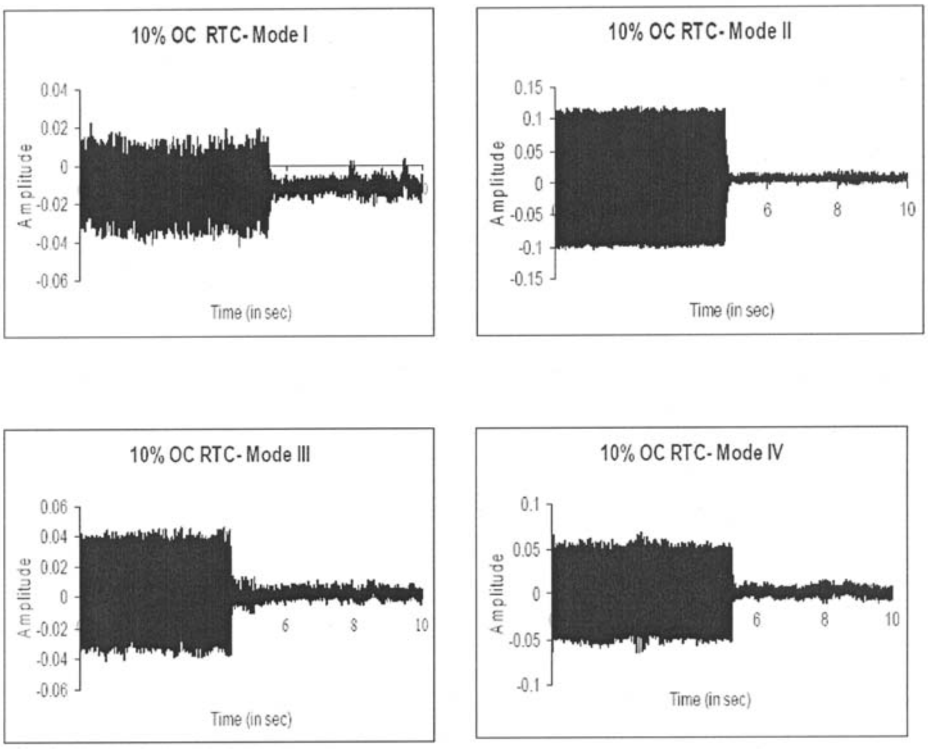

Fig.8 Control graphs of epoxy with 10% OC-RTC

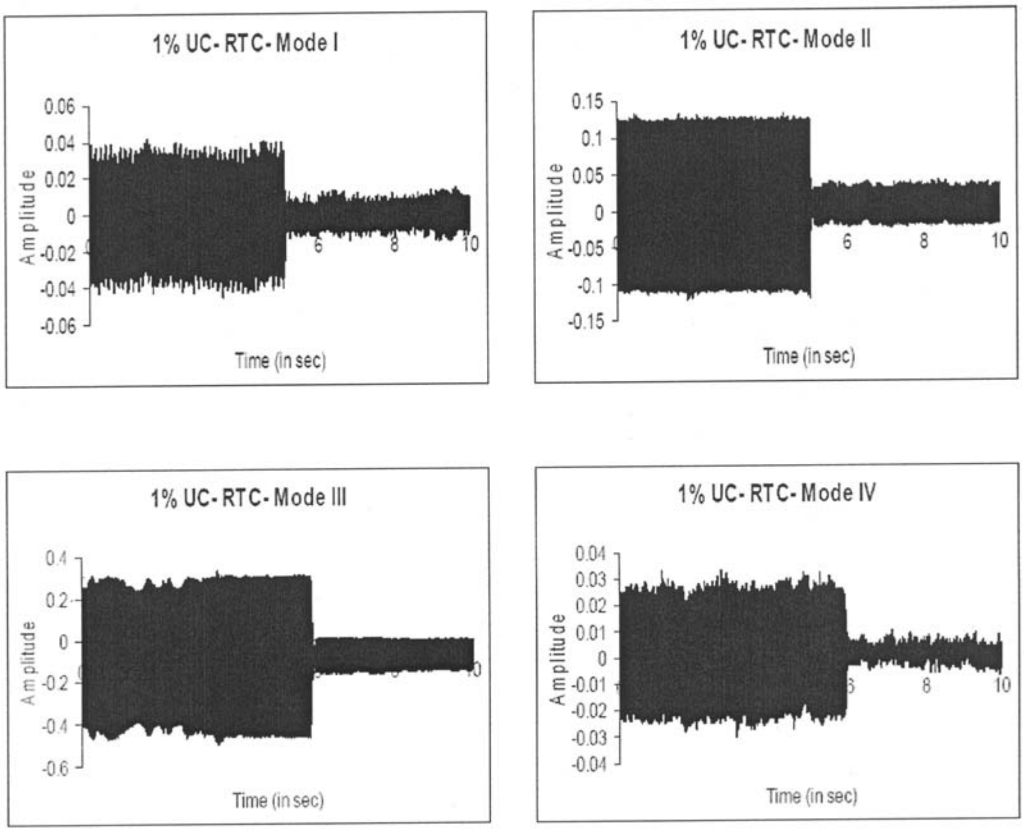

Fig.9 Control graphs of epoxy with 1% UC-RTC

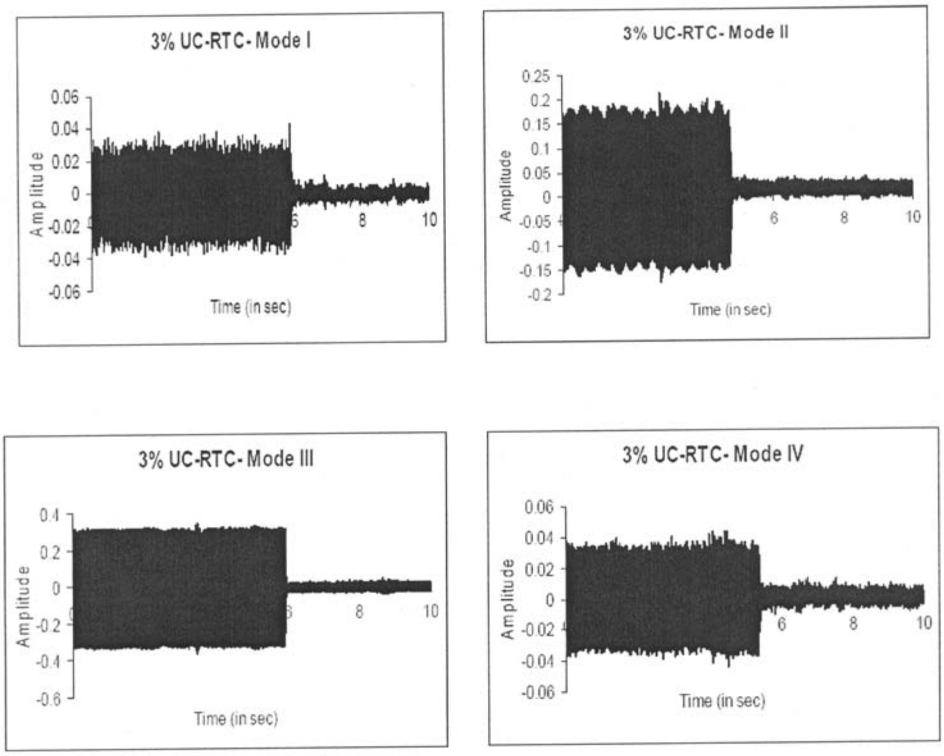

Fig.10 Control graphs of epoxy with 3% UC-RTC

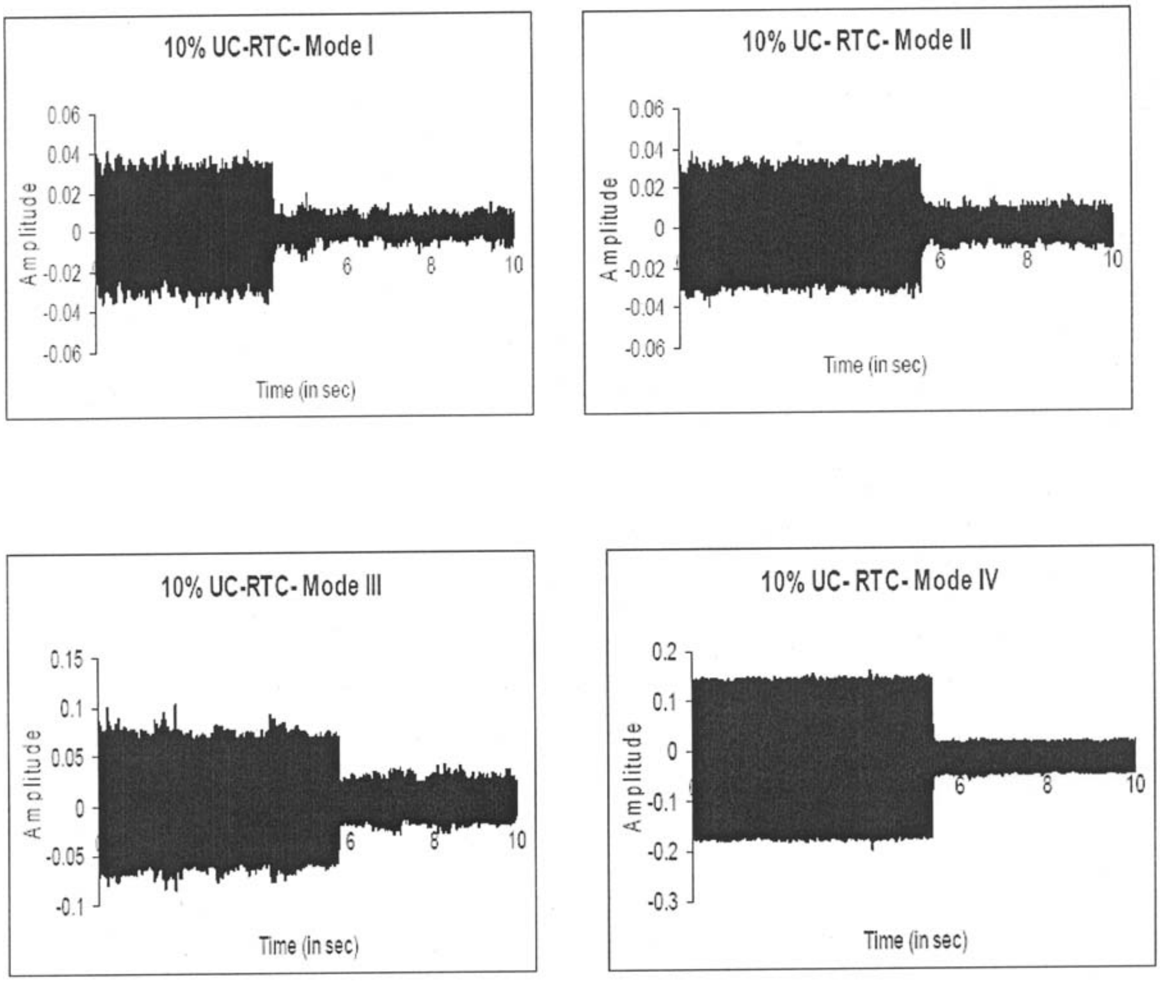

Fig.11 Control graphs of epoxy with 10% UC-RTC

The nanoclay reinforcement enhances the surface area of contact to the matrix and thereby enhancing the stress transfer between both parts and results in improved modulus. The orientation of clay platelets and polymer chains with respect to the loading direction can also contribute to the reinforcement effects, however, the decreasing rate of elastic modulus improvement with higher clay content (> 3 wt%) is due to the presence of unexfoliated aggregates. Similarly for UC-RTC series, the control value up to 3 wt% UC is higher but for higher clay content the control value decreases. Since there is a little difference in the size of the piezoelectric patch, the difference between the control force and disturbance force is large. Therefore there is not enough control for the UC-RTC series. Here the best control is obtained for second and third mode of the beam with 3 wt% clay. The possible reason for the decrease in control values for UC series when compared OC series is due to the poor interfacial property owing to their micron scale filling, high stress concentration which paved the way for less load transfer from the matrix to the filler.

Conclusions

Epoxy clay nanocomposites have been prepared for different concentration (1, 3, 5 and 10% by weight) by resin casting method. Vibration test is performed to study the natural frequency and damping phenomenon of ECN. It is observed that considerable increase in natural frequency is seen on OC in the epoxy polymer and maximum value is obtained for clays in the range of 3% by weight in RTC conditions. For higher clay concentrations, natural frequency decreases. The increased modulus of ECN over pure epoxy polymer causes such increase in natural frequency. The addition of OC and UC has increased the damping factor of epoxy polymer. However, the rate of increase in damping of OC filled composites is higher than that of UC filled epoxy composites. The feed forward control has provided very good control over the amplitude because the disturbance level are known and hence we can give the control force same as the disturbance force. Here maximum control is obtained for mode II and III for OC-RTC series at 3 wt.%.

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