VIBRATION BEHAVIOR OF NANOCOMPOSITE STRUCTURES

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Abstract. *Damage in composite structures resulting from impact events is one of the most important aspects to be considered in the design and applications of composite materials. This work deals with plates with 16 layers of fiber glass. The fiber glass-epoxy-nanoclay laminate composite 65% fiber volume fraction are manufactured by vacuum assisted wet lay-up. To analyze how the composite overall vibrational behavior is affected by the nanoclay dispertion into the matrix, a set of nanocomposite with 0%, 1%, 2%, 5% and 10% wt were prepared. These plates were tested using Modal Analysis with one excitation point on a grid of 35 response measurement points. This procedure allows extracting the natural frequencies, the associated mode shapes and damping.*

Keywords: *nanocomposite materials, modal analysis.*

1. INTRODUCTION

High performance polymeric composites are a valuable alternative to conventional materials due to their high specific mechanical properties, i.e. stiffness-to-weight and strength-to-weight, tailor-ability, and damage tolerance. These composite materials and/or structures during their service life undergo various loading conditions. Among them, the most critical condition is the impact loadings due to the laminated nature of these structures.

According to Luo *et al.* (1999), the damage in composite structures resulting from impact events is one of the most important aspects to be considered in the design and applications of composite materials. Impact events, can be classified according to the impact velocity, i.e. low and high velocities. As mentioned by Naik and Shrirao (2004), low velocity impact events occur when the contact period of the impactor is longer than the time period of the lowest vibration mode. In high velocity impact, the contact period of the impactor is much smaller than the time period of the lowest vibration mode of the structure. As a consequence, the response of the structural element is governed by local behavior of the material in the neighborhood of the impacted zone, the impact response of the element being generally independent of its support conditions.

Yasmin *et al*. (2003) were among those researchers who studied the effect of nanoparticles (organically modified montmorillonite - Cloisite 30B) into epoxy systems. By varying the amount of Cloisite 30B in weight from 1% up to 10%, they found an increase in the elastic moduli to a maximum of 80%. A more interesting result using nanoparticles into epoxy system was reported by Isik *et al.* (2003). In this case, for use of nanoparticles enhanced both stiffness and toughness. However, for their binary system, resin - diglycidyl ether of bisphenol *A* and cure agent - triethylenetetramine, the maximum impact strength obtained was at 1% in weight of montmorillonite content. The difference between Yasmin *et al.* (2003) and Isik *et al.* (2003) results can be attributed to the mixing process, shear mixing in Yasmin's case and direct mixing for Isik's conditions.

A more comprehensive study on clay-epoxy nanocomposites was performed by Haque and Shamsuzzoha (2003), since they evaluated both mechanical and thermal properties. Their main conclusions were that thermo-mechanical properties mostly increase at low clay loadings (~ 1-2% in weight) but decrease at higher clay loadings ($\geq$ 5% in weight). In addition, the uses of nanoclays also decrease the coefficient of thermal expansion (CTE). They also observed a degradation of properties at higher clay loadings. This phenomenon can be due to the phase-separated structures and defects in cross-linked structures. Furthermore, these problems can be caused by the heating phase during the manufacturing process. It is important to mention that in all the references mentioned previously, heating was present during the nanocomposite synthesis procedure.

Another issue that must be addressed is how the stacking sequence and the boundary conditions affects the natural frequency. One approach to obtain these relations is the finite element method. Ramtekkar and Desai (2002) developed a finite element model based on a six node plane stress mixed element and by applying the Hamilton's energy principle; they were able to obtain the natural frequencies of laminated beams. Their results were in good agreement to data available into the literature. Gubran and Gupta (2005) went further, as they demonstrated that natural frequencies are directly affected by the angle ply formation and the stacking sequence. Moreover, the bending-twisting effect is more evident for the angle ply configuration and associated to the Poisson effect and the shear-normal coupling. The largest reduction, $\approx$ 87 %, on the natural frequency when the bending-twisting effect associated to the shear-normal coupling is considered to a 30 degrees angle ply. When the boundary conditions are considered, the natural frequencies present a higher variation.

According to Aydogdu and Timarci (2003), when the boundary conditions from simple supported-clamped-simple supported-clamped changed to simple supported-free-simple supported-free a decrease of approximately 400% on frequencies is observed. As mentioned by Lam and Chun (1994), when impact loading is considered, the target boundary conditions have direct influence on the materials response to low velocity impact tests. Furthermore, Tan *et al*. (2003) verified that clamped laminate plates undergo deflection and stretching during the impact process, while for simply supported conditions stretching does not occur. In other words, when the stress wave produced outward from the impact region reaches the clamped edges it results in stretching.

The objective of this paper is to study the nanoparticle influence into the plate vibration behavior and tries to correlate it with the impact behavior and published data. To analyze only the nanoparticle influence all manufacturing parameters are kept fixed but the nanoparticle concentration. The modal analysis was made with the objective to determine the modes or the structure shape forms of vibration to compare the frequencies and modal properties for different nanoclay composite plates. This technique allows identifying crossing modes or changes in the vibration frequency sequence of the modes, changing on the frequency and on modal properties for each mode for each nanoparticles in the resin composition.

2. TESTING PROCEDURES

The nanocomposite prepared for this investigation is a S2-glass/epoxy-clay. The resin system was chosen owing to its low viscosity and long gel time (60 minutes) at room temperature. The epoxy formulation is based on two parts, part A (diglycidyl ether of bisphenol A) and part B - hardener aliphatic amine- (triethylenetetramine). The weight mixing ratio suggested by the manufacturer is 100A:20B, and the average viscosity is around 900 cps. The nanoclay particles used in this study are organically modified montmorillonite in a platelet form, while the S-2glass fiber has a plain-weave woven fabric configuration with density of 180 g/m2 from Texiglass. The S2-glass/epoxy-nanoclay composite is a laminate with 16 layers and 65% fiber volume fraction. The nanocomposite synthesis followed the methodology proposed by Ávila *et. al.* (2006a, 2006b).

Once the fiber S2-glass/epoxy-nanoclay is prepared, a sequence of modal analysis test is performed to investigate how the amount of nanoclay intercalated affects the modal parameters. Shape modes and its natural frequency, shape mode amplitude and the damping coefficient are carried out. Some comments are done relating those parameters with impact load and perforation behavior as stated by Cantwell *et al.* (2005).

The vibration analyses were performed using a Laser Doppler Vibrometer, laser model OFV –303.8 and controller model OFV 3001 S from Politec, a Hewlett Packard data acquisition system model 35670A, a nini-shaker, a shaker power amplifier and force transducer from PCB.

The test plates were hanged by a fine nylon wire and excited by a random signal (white noise). A piezoelectric force transducer was used as the reference for the force bonded to the plate and linked to the stinger/shaker exciter, which transform the amplified electrical signal in force. There was only one force excitation point at the same position for all plates. The velocity of the plate surface was measured using a grid of 35 points by the laser Doppler vibrometer. The data acquisition system processed the signal response of the measurement point generating the Mobility (velocity/force) Function Response Frequency (FRF), for each point of the plate.

The rectangular plates had the same dimensions 136mm x 116mm. In order to be able to investigate the nanoparticles influence into vibration analysis, samples with 0%, 1%, 2%, 5% and 10% of nanoclay with respect to the matrix weight were employed. The fiber volume fraction was kept around 65%. A modal analysis program has done the mode shape identification from the 35 FRF for each plate. This modal analysis program is based on polynomial interpolation and employs Chebycheff Orthogonal Polynomials method, Arruda *et al.* (1996).

3. DATA ANALYSIS AND CONSIDERATIONS

The modal analysis was made with the objective to determine the modes or the structure shape forms of vibration to compare the frequencies and modal properties for different nanoclay composite plates. The Fig. 1 shows a sequence of vibration modes with frequencies and damping coefficients for the epoxy resin composite. Figure 2 plots the response shape and modal parameters for the composite plate with 1% nanoclay weight. Fig. 3, Fig. 4 and Fig. 5 shows the same data for specimens with 2%, 5% and 10% of nanoclay in the epoxy resin system. Table 1 brings a summary of the natural frequencies, the associated damping coefficients and Mobility amplitude.

In the Fig. 1, Fig. 2, Fig. 3, Fig. 4 and Fig. 5 the first and the seventh vibration mode, Mode 1 and Mode 7, for all plates is bending-twist mode. The position of the stinger and the piezoelectric force transducer could have some effect on the behavior on the first Mode. The force transducer was bonded in the coordinate 7-5, Fig. 1 to Fig. 5, but all

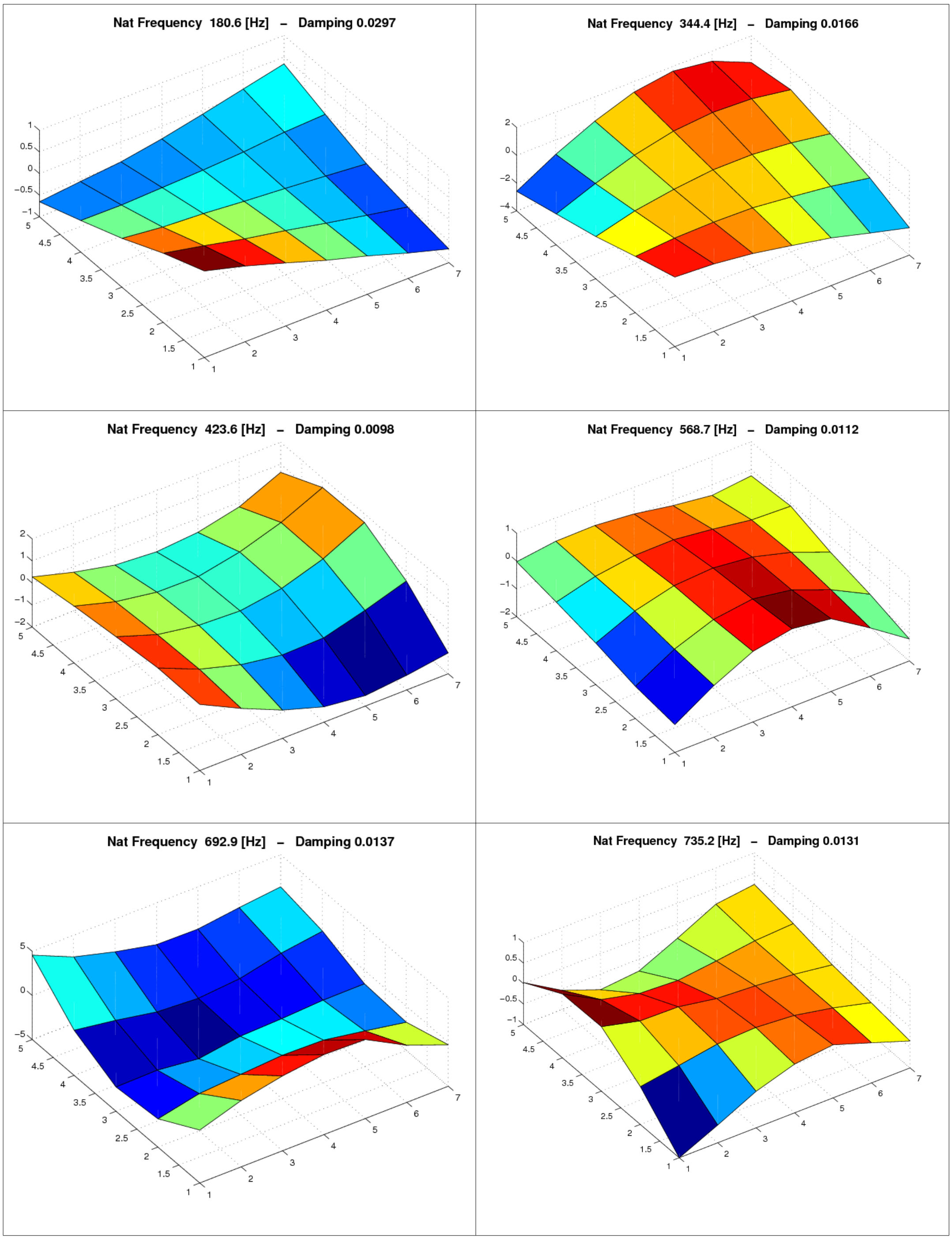

Figure 1. Shape Mode, Frequency and Damping coefficient for epoxy resin plate.

specimens were tested with the same configuration. Other vibration modes 2 to 6 might be classified as predominantly bending.

For plates with 2%, 5% and 10% of nanoclay content appear a new mode identified as Mode 5 in the shape mode sequence, Tab. 1. This mode is not present in the vibration mode sequence for both plates of resin and with 1% of the nanoparticles. The stiffness and the damping conditions on contour or support, the stiffness of the plate can modify the frequencies and the order of the appearance of these modes. Therefore, as the stiffness and internal damping are the only variable, Mode 5 could be present in frequencies above 800 Hertz for those plates and could be not shown, there is a crossing mode too, both Modes 3 and 4 for 5% and 10% of nanoclay content plates appear in changed sequence (Mode 4 with inferior frequency to Mode3).

The difference on frequency values for the same mode, in general, can be associated to mass and rigidity of the plate. As the plates show variations in the mass they can cause changes in frequency, for the same stiffness, low mass

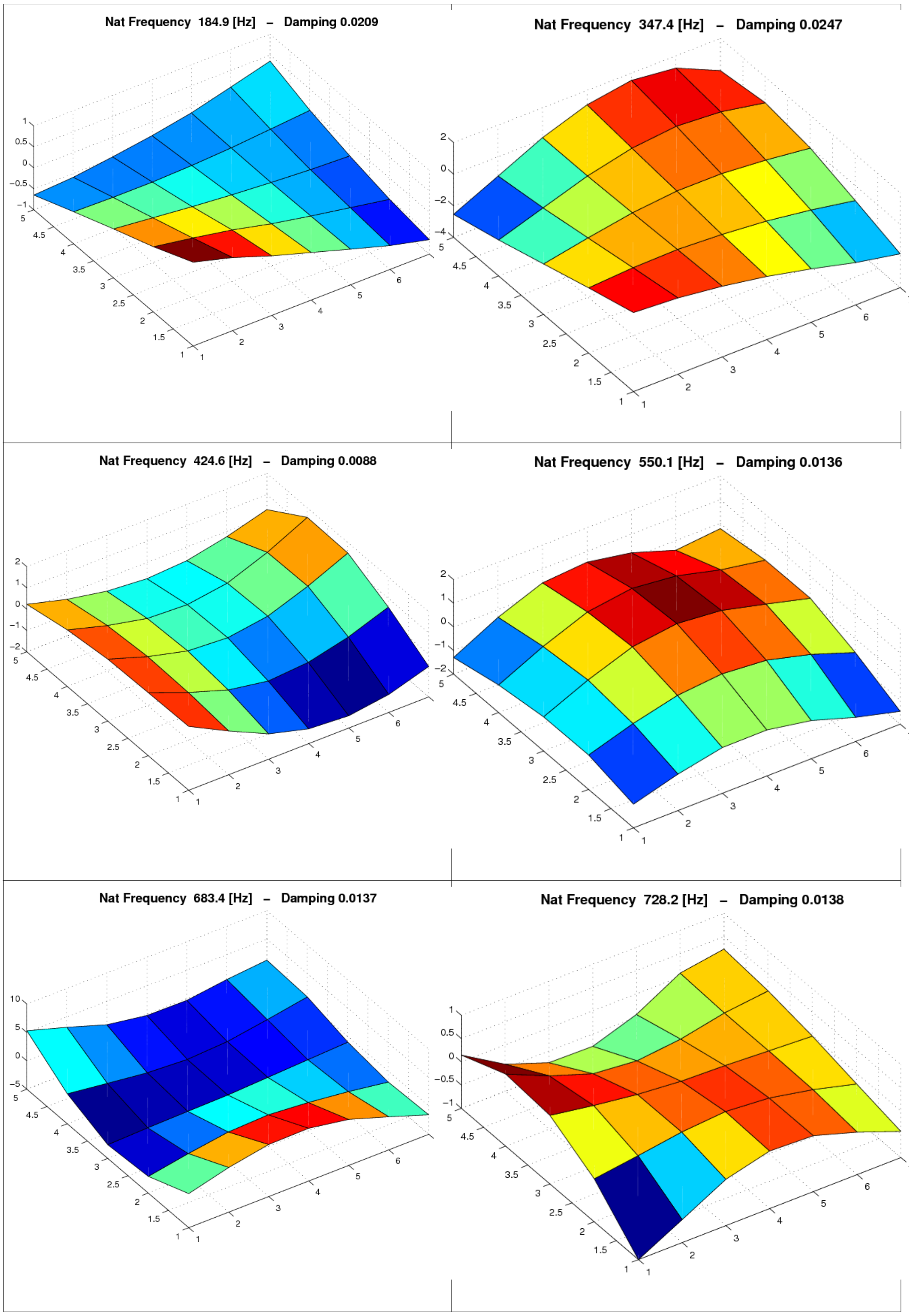

Figure 2. Shape Mode, Frequency and Damping coefficient for 1% nanoclay content plate.

results in higher frequencies. But an analysis of the data indicates that this difference in the mass can not be a decisive factor, the 1% of nanoclay plate is lightest, the frequency in its first mode is greater than of that of pure resin and of the 2% nanoclay composite plate, but inferior to first mode frequencies of the more weighed plates with 5% and 10% nanoclay. In the lightest plate with 1% of nanoparticles the last mode frequency is smaller than those of the pure resin plate, indicating that this mass difference can interfere but can not be the main factor in the frequency mode change.

The change in the inertia is small as the main dimensions have little differences between the specimens, so the improvement in rigidity should be attributed to the bulk modulus. Improving stiffness, as consequence of the increase in

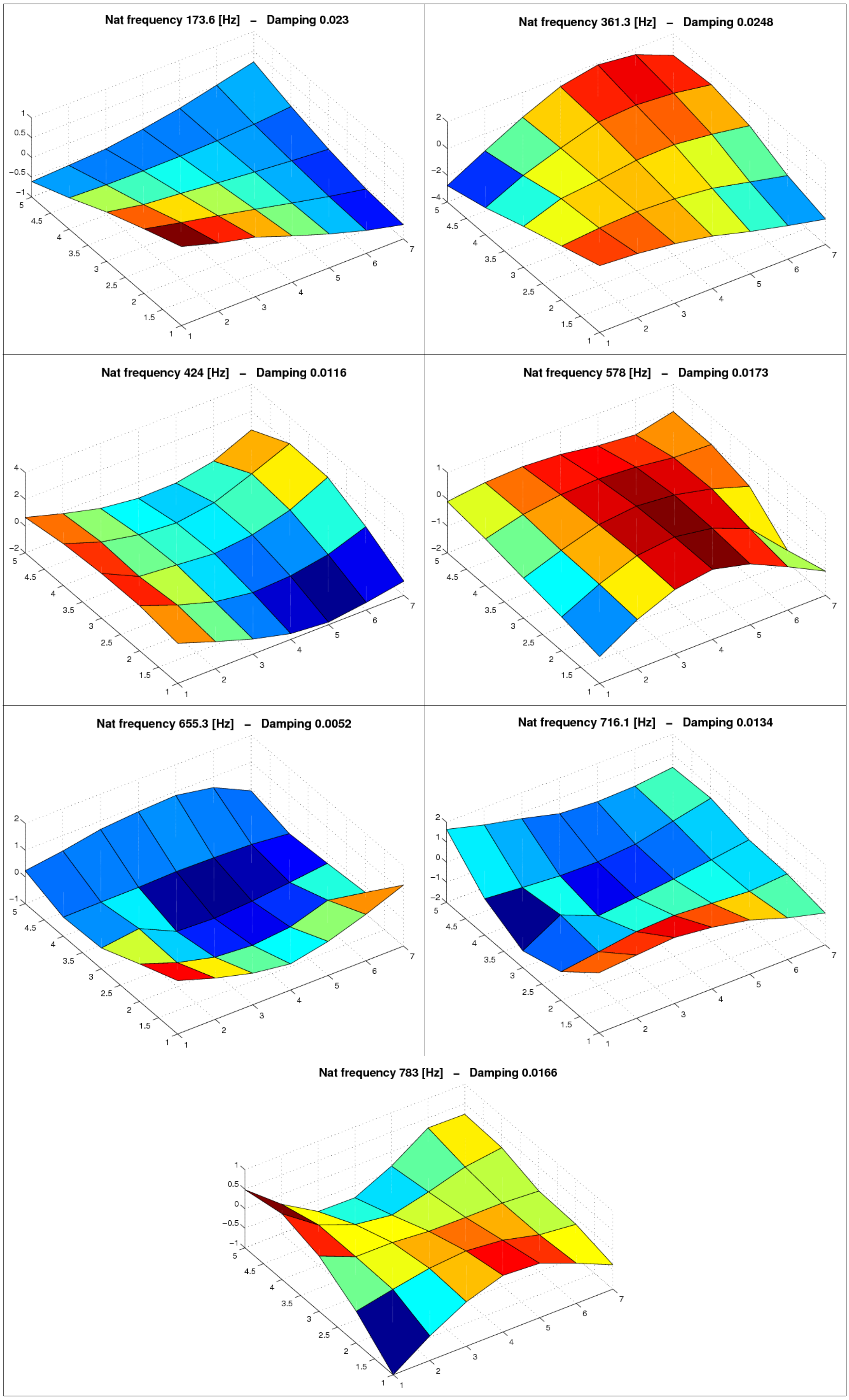

Figure 3. Shape Mode, Frequency and Damping coefficient for 2% nanoclay content plate.

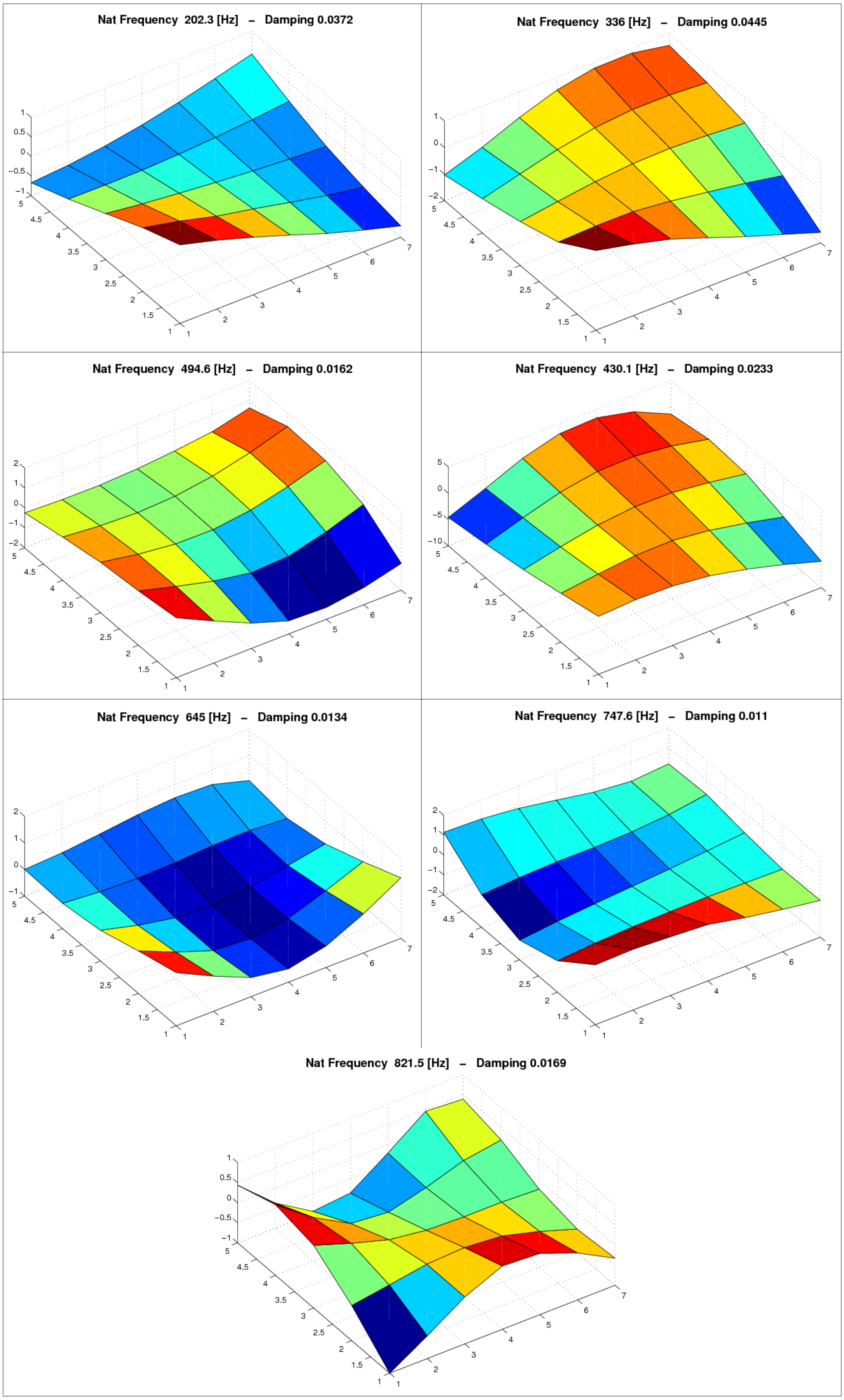

Figure 4. Shape Mode, Frequency and Damping coefficient for 5% nanoclay content plate.

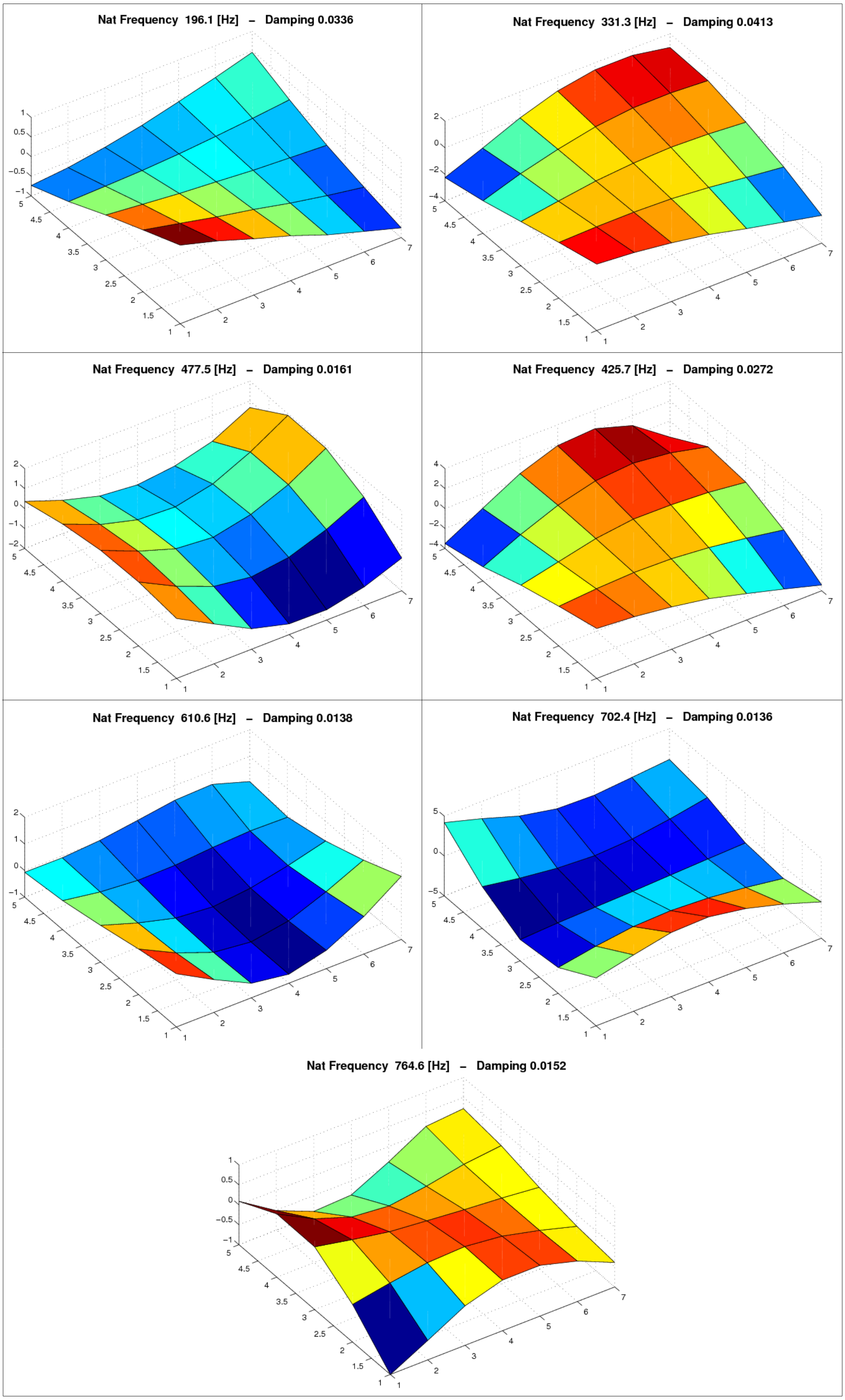

Figure 5. Shape Mode, Frequency and Damping coefficient for 10% nanoclay content plate.

Table 1. Damping coefficient, Amplitude and natural frequencies for vibration shape modes between 100 and 800 Hertz.

Compósito	Mass [gr]		Shape Modes						
			1th	2th	3th	4th	5th	6th	7th
Pure epoxy Resin	66.37	damping coefficient	0.0297	0.0166	0.0098	0.0112		0.0137	0.0131
		natural frequencies [Hz]	180.6	344.4	423.6	568.7		692.9	735.2
		Amplitude [m/s / kgf]	57.0	17.0	6.5	4.8		12.1	8.5
Nanoclay 1% weight	65.27	damping coefficient	0.0209	0.0247	0.0088	0.0136		0.0137	0.0138
		natural frequencies [Hz]	184.9	347.4	424.6	550.1		683.4	728.2
		Amplitude [m/s / kgf]	79.9	14.0	24.1	2.6		17.9	9.6
Nanoclay 2% weight	66.92	damping coefficient	0.023	0.0248	0.0116	0.0173	0.0052	0.0134	0.0166
		natural frequencies [Hz]	173.6	361.3	424.0	578.0	655.3	716.1	783.0
		Amplitude [m/s / kgf]	32.9	5.8	4.7	21.5	44.3	15.0	8.1
Nanoclay 5% weight	67.46	damping coefficient	0.0372	0.0445	0.0162	0.0233	0.0134	0.011	0.0169
		natural frequencies [Hz]	202.3	336.0	494.6	430.1	645.0	747.6	821.5
		Amplitude [m/s / kgf]	33.3	4.4	2.2	5.0	8.4	10.0	14.7
Nanoclay 10% weight	67.89	damping coefficient	0.0336	0.0413	0.0161	0.0272	0.0138	0.0136	0.0152
		natural frequencies [Hz]	196.1	331.3	477.5	425.7	610.6	702.4	764.6
		Amplitude [m/s / kgf]	7.6	0.9	1.3	0.8	1.5	4.2	2.8

the elasticity modulus, results in increasing shape mode frequencies. This increase in the elasticity modulus in principle can also modify the sequence of the mode shapes.

The nanocomposite elasticity modulus greatly depends on the mesh material, the effect of the resin as "agglutinant" element between the layers is secondary, and due to small percentage of the nanoclays there is no expectation that its effect is very marked. Observing the behavior of the first mode frequencies for different plates a moderate increase of the frequency with the increase of the nanoclay percentage is perceived.

Modal properties on Tab. 1 and mode shapes on Fig. 1 to Fig. 5 allows to conclude that increasing nanoparticles inside the matrix/resin does not lead to a definite behavior of the natural frequency for each mode. The only statement that can be done is that the 5% weight nanocomposite plate shows the highest frequencies for each mode. At same time, the nanoclay presence increases the matrix damping coefficient as a general rule, mainly at low frequencies, Fig. 6.

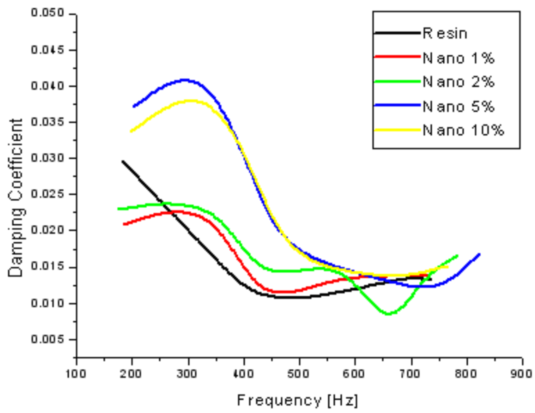

Figure 6. Damping Coefficient for plate composites.

There is a reduction on the frequencies between the shape modes as the nanoclay concentration increases. The higher number of shape modes on the selected frequency band for the highest concentration nanoclay composite plates is a confirmation of this tendency. But, as previously stated increasing the elasticity modulus should improve the frequencies between shape modes sequence. The only explanation for this behavior is that damping coefficient improvement is more significant than is the stiffness improvement. The evidence of the cross shape mode between the third and four modes for 5% and 10% nanoclay composite plate supports this proposition,

The impact energy is absorbed by waves generated from the disturbance. These structural waves are the only way to transmit the energy from the impact area to remain structure and supports. This energy can be dissipated by the structural or support damping or by damage/failure of the structure or support. The flexural wave velocity is not constant and the interaction between wave and the structure dimensions and contour properties determines the mode shape and frequency vibration sequence. The same structure, clamped or not, free or pinned with or without damping can has distinct shape modes and frequencies. The flexural wave propagation depends on the frequency and usually its velocity is called phase velocity so it has different value for each natural frequency.

The specific kinetic energy of vibration for a single mode $\mathbf{e}_v$, could be estimated by $\mathbf{e}_v \propto (A_M)^2$, where A_M is the amplitude of Mobility (velocity/ excitation force) for the mode frequency ω and the total energy of vibration could be evaluated by the sum of the energy modes $E_v \propto \sum_i (A_M)_i^2$. So the shape mode with a big amplitude stores a great vibration energy since the kinetic and elastic have the same maximum value if there is no damping. The energy dissipated by cycle for a shape mode can be evaluated by $\mathbf{d} \propto \xi(A_M)^2$ where ξ is the damping coefficient, supposed to be viscous damping, so the dissipated energy by cycle is $\mathbf{D_E} \propto \sum_i \xi(A_M)_i^2$.

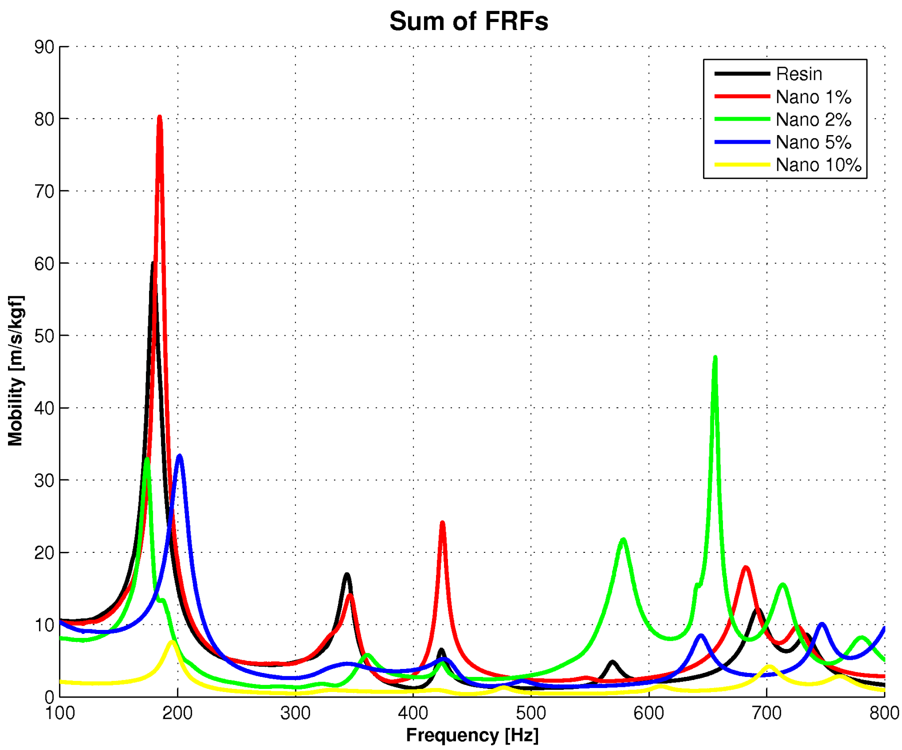

Figure 7. Absolute Mobility Amplitude, A_M , for plate composites.

In the Fig. 7, the 1% nanoclay plate shows an increase in the amplitude when compared to the resin plate for almost all modes in the frequency band. The 2% nanoclay plate has a big amplitude increase for the high shape mode frequencies and except for the Mode 1 there is a strong reduction for the shape mode amplitude on the lowest spectrum frequencies. As the vibration elastic energy is proportional to $(A_M)^2$ then the capacity to store vibration energy moves toward the highest shape mode frequencies for 1% and 2% nanoclay content specimens. For 5 % and 10 % nanoclay plates there is a reduction in the shape mode amplitude for practically all observed modes, greater the content of nanoclay particles bigger seems to be the reduction in the shape modes amplitude.

As mentioned by Naik and Shrirao (2004), low velocity impact events occur when the contact period of the impactor is longer than the time period of the lowest vibration mode. By this way there is enough time to generated waves that are carrying energy from impact zone.

If the impact generate waves have high frequencies the energy will be spread to structure and its supports at high speed. A great energy level will be carried by high amplitude waves. These two aspects explain the improvement on the capacity of the nanocomposite plate to support impact loads, the amplitude of the natural waves of this composite material are improved at high frequencies of the spectrum with the nanoclay content until 2%. Probably its is true for 5% and 10% nanoclay plates for highest frequencies, but the chosen frequency spectrum superior limit do not permit to verify this affirmation.

3. CLOSING COMMENTS

As this research deals with two different levels of reinforcement, one at nanoscale, nanoparticles inside the matrix/resin, and another at microscale, fiber reinforcement with plain weave configuration, it is possible to conclude that coupling between nano and micro effects can be a key issue in the impact phenomena. The fibers can be assumed as a primary “road map” for wave propagation without great changes in natural frequency for the same shape mode. At same time, the nanoclay presence can be associated with the molecular links creating a matrix less brittle than the original one, which can lead to increases the matrix toughness, stiffness and damping coefficient. The increase content of nanoclay in matrix resin system improves the structure capacity to bear impact loads.

This work shows increasing amplitude shape mode frequency toward the high frequency spectrum with the nanoclay presence. This behavior allows the structure to spread fast a great fraction of the impact energy, so reducing the local damage probability.

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