OPTIMIZATION IN THE COMPOSITION OF LAMINATED COMPOSITE STRUCTURES

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ABSTRACT

Composite materials are often used in the automotive industry to reduce acoustic vibrations and the sound pressure in a car by the use of damping patches or changing car part fabrication. The material make-up of these composites plays a big role in the effectiveness of damping treatments and is therefore a large focus in the vehicle design process. In this study, a genetic algorithm (GA) is used to test the different configurations of laminated composite structures and is compared with the results of a particle swarm optimization (PSO) and gradient-based algorithms that are performed with the same design variables. Aiming at producing a composite structure containing a high modal loss factor, the design variables are considered as: 1) viscoelastic material thickness, 2) fiber orientation angle, and 3) carbon layer thickness. The ultimate goal of the designed composite structure is to create the optimal balance between minimum vibrations and a minimum mass of the structure.

1 INTRODUCTION

The automotive industry often faces the problem of high vibrations in vehicle structures due to large excitation forces on the body. Fiber-reinforced composites are frequently used in lightweight structures due to their high strength-to-weight ratio as well as good fatigue and corrosion properties versus those of metal alloys. These composites provide better damping properties than those of steel or aluminum but must be paired with a viscoelastic layer to provide more efficient damping. This combination can have a stacking sequence similar to a sandwich, with two composite structures surrounding a viscoelastic layer. This viscoelastic core exhibits high shearing during deformation and, therefore, dissipates vibratory energy more effectively than the composites alone. Mead and Markus [1] developed the theoretical models for the axial and bending vibrations of sandwich beams with viscoelastic cores. Two possible applications exist for these kinds of composite structures: constrained layer damping (CLD) treatment patches and car part fabrication. Car part fabrication is easier to be used in industry than the patches and is the focus in this paper. The laminate is not limited to only three layers, fortunately, and is thus able to be optimized for the best damping configuration. Optimal design of these constrained layer damping treatments has long been a subject of high focus for reducing vibrations in structures by means of the maximization of modal damping ratios and reduction of modal strain energies. This maximization and reduction are achieved by determination of the best material, layer sequence, and laminate make-up, while also aiming at reducing the mass of the treatment.

This paper aims at maximizing the modal loss factor of sandwich structures comprised of varying laminas with respect to their mass as well as to the improvement of their noise, vibration, and harshness (NVH) performance. Multiple optimization algorithms are used to determine the most efficient laminate make-up for damping purposes, as well as the modal strain energy method to calculate strain energies stored and dissipated in the composite layers, and finally these optimization algorithms calculate the modal loss factor for the complete structure, which utilizes a dynamic response in terms of the undamped natural frequencies. A complex modulus approach is used to evaluate the viscoelastic material layers in the given frequency range due to the material experiencing dynamic loading. A comparison between the effectiveness of the different optimization algorithms will also be carried out. Based on the selected best algorithm, the optimal created design will be applied to a vehicle structure in order to validate the efficiency for acoustically problematic automobile parts.

2 OPTIMIZATION ALGORITHM SELECTION

To determine the best optimization algorithm, an extensive literature review was conducted and each different algorithm will be compared based on the results of the literature. The first algorithm is the genetic algorithm (GA) [2] due to its ability to work with large and complicated variable problems. A GA is an evolutionary optimization technique modeled after Darwin's theory of "survival of the fittest" in order to improve each population of solutions. Fortunately, the GA will not be stuck in a local optimum if the population size is significantly large. Araújo et al. [3] maximized the modal loss factor of a structure using single and multiobjective optimizations based on GA. The design variables that they used were fiber orientation angles of laminate face layers and thickness design. Their results showed that this algorithm can substantially improve the modal loss factor for simply supported sandwich beams and plates. Focusing on rectangular plates, Montemurro et al. [4] maximized the first N modal loss factors of the laminate structure through the use of a GA. Their design variables included the number of layers, layer thickness, and fiber orientation, and the results proved GA to be very flexible and applicable as well as able to reach a suitable optimum. According to Rahul et al. [5] the optimization of composite structures using an island model parallel GA method produces a good convergence and a lower processing time, i.e., one tenth of the time of sequential GA.

Gradient-based methods [6], abbreviated to GB for this paper, based on the gradients of the constraints and objectives, can approximate solutions when mathematical closed-form expressions are not available. Therefore, these solutions are only local optima, but the advantage is a faster convergence rate. The research of Araújo et al. [3] proved that the use of GB methods had a computation time fifteen times faster than those of GA for the case of damping maximization of laminated sandwich composite structures. Their design variables were layer thickness and fiber orientation angle. Moita et al. [7] significantly increased the modal loss factor of triangular plates by optimizing fiber orientation angles and layer thicknesses, the design variables, by use of a GB optimization algorithm.

The third optimization algorithm investigated in this paper is the particle swarm optimization (PSO) algorithm [8]. This algorithm is population-based and stochastic, modeled after the flocking behavior of birds. Each solution in the search space of this method is called a particle, resembling one bird out of a flock. The position of this particle in the search space changes based on the best solution in its individual history, resembling the bird's own flying experience, as well as the best solution among all of the particles, i.e., the flying experience of the other birds. From these adjustments, PSO has an optimal potential to benefit from parallel computing. Suresh et al. [9] utilized the PSO method to optimally design a composite box beam for a helicopter rotor blade. They concluded that the use of PSO produced closer results to the optimum values than those produced by GA because PSO produced greater damping values for five different simulations in comparison with GA. However, the computational times were similar with PSO converging after 32.34 minutes and GA after 42.35 minutes. Kathiravan et al. [10] also used PSO in comparison to GB methods for the maximization of failure strength in thin-walled composite box beams. They found that PSO gave superior or equivalent results to the GB methods. The PSO was also used by Bargh and Sadr [11] for the optimization of the lay-up design of laminated composite plates. It was seen that the performance of the PSO was more efficient than the GA. Manjunath and Rangaswamy [12] optimized a ply stacking sequence with the use of PSO. They compared the results from PSO to those of GA and found that PSO produced better results. Fortunately, the PSO algorithm does not need to begin from different initial points as seen in GB methods.

3 VISCOELASTIC MATERIALS: PROPERTIES AND CHARACTERIZATION

Viscoelastic materials can be highly effective in controlling the dynamics of structures in noise control applications. The structural vibrations and the underlying noise radiation can be reduced and controlled by using these materials, whose properties are dependent on the room temperature and the frequency of the applied cyclic load. These characteristics are significant to accurately model viscoelastic materials in numerical simulations. The complex modulus of the behavior of viscoelastic materials was deeply investigated by Jones [13]. For the purpose of this paper, only the frequency dependency is to be taken into account. Also, the properties of viscoelastic materials are defined in a complex domain, having both real and imaginary components. The real component is associated with the elastic behavior of the material and is called the storage modulus $E^{'}$, while the imaginary component is associated with the viscous material behavior and is called the loss modulus $E^{''}$. These properties can be modeled using the following equation:

$$E^{*} = E^{'} + E^{''}, \tag{1}$$

Various measurement methods exist in which mechanical properties of materials can be determined. For example, dynamic mechanical analysis (DMA) [14] provides the characteristics of viscoelastic materials over a large range of temperatures and frequencies. As previously stated, only the frequency dependency is analyzed in this paper.

4 MODAL STRAIN ENERGY METHOD

Throughout literature, the established damping model of fiber-reinforced composites, first developed by Adams and Ni [15], has been adopted by additional authors to improve the analysis of different composite structures with embedded viscoelastic layers [16]. This method is called the modal strain energy method and is used in this paper to simulate the damping in a laminated composite structure with embedded viscoelastic layers. This method defines the damping characteristics of a structure by the ratio of dissipated energy to stored energy during a stress cycle. The total structural damping loss factor can be expressed as

$$\eta = \frac{\sum^{k} \eta_{ij}^{k} U_{ij}^{k}}{\sum^{k} U_{ij}^{k}} \quad (i, j = 1, 2, 3), \tag{2}$$

where η_{ij}^{k} and U $_{ij}^{k}$ are the damping loss factors for the layer *k* of the composite materials and strain energy stored in the layer *k*, and U $_{ij}^{k}$ is the summation of U $_{ij}^{e}$ where *e* represents each element in a layer, related to the stress component σ_{ij}^{e} [17]. This relationship with respect to stress and strain [18] can be written as

$$U_{ij}^{e} = \frac{1}{2} \int \sigma_{ij}^{e} \epsilon_{ij}^{e} \, \mathrm{d}V^{e}. \tag{3}$$

Figure 1 defines the fiber directions, where number 1 is in the fiber direction, 2 is transverse to this direction, and 3 is through the thickness direction. Theta represents the angle between the x-axis and the fiber direction.

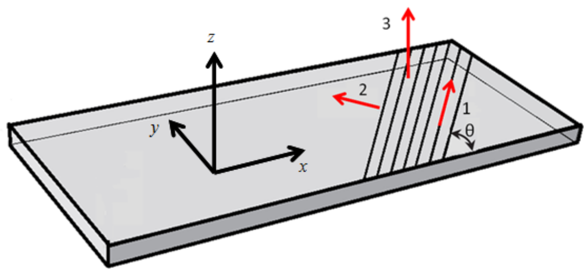

Figure 1. Fiber directions

The modal strain energy method can also be applied for the case of composite materials with embedded viscoelastic layers by considering that the viscoelastic material loss factor can be represented by

$$\eta(f) = \frac{E''}{E'} \quad , \tag{4}$$

where E' and E'' are the storage and loss modulus of the viscoelastic material, respectively, and can be integrated into Eq. 2 for η_{ij}^{k} when *k* is the number of the corresponding viscoelastic layer. This η represents the material loss factor for all directions, as the viscoelastic material is isotropic. See Eqs. 6 and 7 for the loss and storage modulus equations.

5 OPTIMAL DESIGN FORMULATION

A common goal in the automotive industry is to improve acoustic performance in vehicles without sacrificing structural dynamic stiffness. One means of improving this acoustic performance is through the use of CLD patches. Another method consists of the development of materials suitable for car body manufacturing, aiming at reducing poor acoustic performance. This paper focuses on the development of efficient composite structures made of fiber-reinforced composite and viscoelastic layers. In order to efficiently design these automobile parts, the design variables are taken as: layer thickness and fiber orientation based on mechanical properties. The objective by means of various optimization algorithms is to improve the acoustic performance of structures. The first improvement can be made through the increase in damping capabilities of the composite structure in order to minimize the resonance vibrations of the vehicle. The optimization work flow can be seen in Figure 2. The pre-processor ANSA is utilized to change the

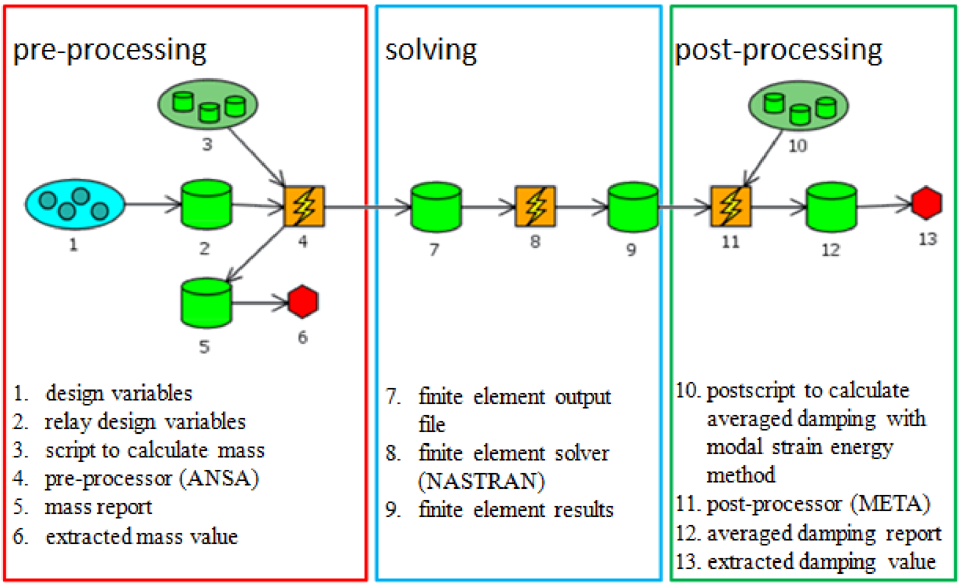

Figure 2. Optimization work flow for one objective value function.

design variables of the optimization and calculate the mass, NASTRAN is used as the solver, and Meta is used to calculate the damping via a post-script. This post-script was developed to calculate the loss factor at a faster rate by reading all of the stresses and strains of every single layer simultaneously.

In a literature review on the effect of damping layers in the laminate, Zhang and Chen [19] found that a laminate sequence of viscoelastic layers between layers of carbon composites had the highest modal loss factor. They found that the shear deformation in the viscoelastic layers is maximized when a central carbon composite layer is inserted between two viscoelastic layers. This, in turn, increases the modal loss factor of the structure. The layer sequence will behave better than one viscoelastic layer inserted between two composite laminates.

The laminate sequence scenario 2 will then be used in several optimization problems with the design variables and the constraints remaining the same. The problem that is solved through these optimizations is the maximization of damping, averaging the damping values at the natural frequencies between 30 and 200 Hz, as well as the minimization of the composite mass. The reason for this low frequency range is that automobile acoustic issues are mainly induced by the automobile panels' vibrations in this range. The damping values were averaged over the natural frequencies in the frequency range to improve the damping of all mode shapes.

However, the damping is dependent on the frequency, and the increase in damping will not be equivalent between all mode shapes. Averaging the damping resolves this issue and allows for a better treatment of mode shapes for all frequencies.

6 MODEL VALIDATION

To validate the implementation of an in-house strain energy model a test is developed and compared for glass fiber composites. The strain energy model, previously described, is able to calculate the damping of any geometry and for any boundary conditions through the use of FEM based on the parent material specific damping capacity information resulting from measurement on a cantilever beam. This was described by Berthelot [16]. The specific damping capacities, ψ, and material properties of the layers are taken from Adams and Maheri [20]. The test involves a cantilever beam with one clamped boundary experiencing an excitation at a point near the clamped edge. The material of the beam is considered a glass fiber/epoxy laminate with $E_{11} = 41.5$ GPa, $E_{22} = 10.9$ GPa, $G_{12} = 4.91$ GPa, $\nu_{12} = 0.32$, $\psi_{11} = 1.61\%$, $\psi_{22} = 6.7\%$, and $\psi_{12} = 7.3\%$, where *E* represents the Young's modulus, *G* represents the shear modulus of the material, ν represents Poisson's ratio of the material, and ψ represents the material's specific damping capacity in the directions of tangential and transverse directions, 1 and 2, respectively. The relationship between specific damping capacities, ψ, and modal loss factors, η, [17] is:

$$\eta = \frac{\psi}{2\pi}. \tag{5}$$

The frequency is fixed at 50 Hz to test the effects of the fiber orientation on loss factors. The beam consists of eight unidirectional layers, each of which has a thickness of 0.5 mm, and the width-to-length ratio of the beam is 1:17. The loss factor is tested for various fiber orientations between 0° and 90°. The results will then be compared with those of Bilups and Cavali [21] to show agreement between the results gathered in this test with those of previously developed methods, resembling the curve resulting from the Ni/Adams equation [15].

7 APPLICATIONS

The first application in this paper involves a cantilever beam made from eight symmetric layers of carbon HMS 209. The mechanical properties of the carbon composite is as follows: $E_1 =$ 189 GPa, $E_2 = 6.08$ GPa, $G_{12} = 2.72$ GPa, $\nu_{12} = 0.3$, $\psi_1 = 0.64\%$, $\psi_2 = 6.9\%$, and $\psi_{12} = 10\%$. The aspect ratio of this cantilever beam is 1:17 and the cantilever exhibits a boundary condition of one clamped edge close to the excitation point. The design variables in this scenario involved the fiber orientation angles. The mass is kept constant, 0.1925 kilograms, and the specific damping capacity is averaged over all of the natural frequencies between 30 and 200 Hz and is considered as the objective function to be maximized. The results can be seen in Figure 3.

A validation also to be carried out in this paper, before optimizations, is a simulation and comparison of the stack-up sequence and their damping effectiveness. The first scenario is made of a viscoelastic material with a thickness of 4 mm embedded between two composite material layers of 3 mm. The viscoelastic material exhibits the following mechanical properties [19]

$$E^{'}(f) = 0.0041 + 0.0322 \log(f) \tag{6}$$

and

$$E^{''}(f) = 0.0077 + 0.0433 \log(f) \tag{7}$$

in GPa, where E' and E'' are the storage and loss modulus of the viscoelastic material, respectively.

The second scenario is comprised of a composite material of thickness 2 mm, a viscoelastic material 2 mm thick, another composite material with a thickness of 2 mm, another viscoelastic layer of 2 mm, and lastly, a composite material layer of thickness 2 mm. An improvement of 6% from the original percentage is observed for the second scenario with respect to the specific damping capacity percentage.

Based on the results of this application, the best layer stack-up sequence proved to be the second scenario. This layer sequence is further developed to optimize its damping capabilities for a roof based on the problem solution described in the previous section. In this test, the fiber orientation was chosen to vary between 0° and 90°, and the fiber orientations of the first and last layer were considered as one design variable to be changed similarly in order to guarantee that the laminate would be symmetric. The thicknesses of the various layers were varied between 0.6 mm and 1.4 mm, and the thicknesses of the different carbon composite layers were considered as one design variable to be equally changed together, as it was found in Zhang and Chen [19] that this configuration produced a maximum loss factor. The real-life application is then carried out in this paper for the automotive industry. In one part of the automobile, in this case a car roof, the material is optimized based on the problem solution previously described, with clamped boundary conditions. The results of each optimization solution will then be evaluated for the best material make-up for this roof. The solution will then be applied in the entire roof, and the structure will be coupled with fluid inside the vehicle to compare the sound pressure at the driver's ear position. Lastly, a comparison between each different optimization algorithm will be carried out with respect to convergence time and the performance quality of the optimal result obtained for each algorithm.

8 RESULTS AND DISCUSSIONS

The two previously described optimization algorithms, GA and PSO, were utilized to optimize the damping of a cantilever beam and the GB method for the damping of a car roof. The results of the cantilever beam can be seen in Fig. 3, where the blue dots represent the objective function evaluations, and the red dot shows the optimal result of the PSO algorithm. This simulation

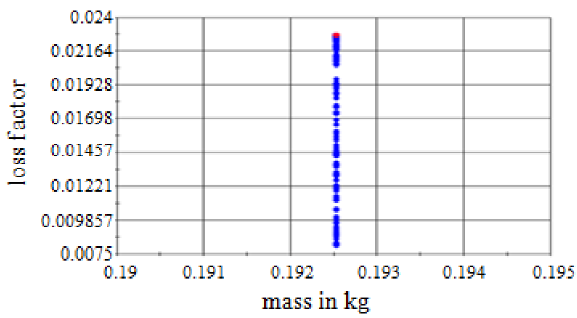

Figure 3. Beam damping maximization using PSO method.

has shown that changing only the fiber orientation, between 0° and 90°, while keeping a similar mass, can improve the loss factor by a factor of approximately 2.9. The optimal fiber orientation, seen in red and coming from PSO, consisted of a fiber orientation of $[90, 7, 90, 90]_2$, starting at layer one, with a loss factor of 0.023. The loss factor as a function of the carbon fiber orientation can be seen in Fig. 4a and Fig. 4b. It can be seen in Fig. 4a that the high loss factor is obtained when the fiber orientation of layers 1, 3, 5, 6, and 8 are oriented at 90° and in Fig. 4b when layers 2 and 7 are oriented at 7°. The high damping value of the optimal design configuration obtained by use of PSO can be explained by the high Young's modulus in the second direction. This high Young's modulus will produce a high strain energy stored in this second direction. As the specific damping capacity of the material, $\psi_2 = 6.9\%$, is much higher in the second direction than the first direction, $\psi_1 = 0.64\%$, a high composite loss factor will be produced, based on Equation 1. By adding the layer with a fiber orientation of 7° between the layers, the inter-laminar strain energies were increased, meaning that the strain energy in the direction 1,2 increased and produced a higher loss factor as the specific damping capacity of the material is very high in this direction, $\psi_{12} = 10\%$. The second beam configuration, from GA, for the cantilever beam consisted of a fiber orientation of $[44, 44, 44, 44]_2$ and a loss factor of 0.018. The results of this GA can be seen in Fig. 4c. The highest loss factor from these results are obtained for all layers oriented at 44°, as seen in the graph. However, for GA, the Young's modulus in the second direction was not high due to the fiber orientation 44°, which produced a loss factor less than that produced by PSO. The PSO converged after 10 iterations with a total of 200 objective function evaluations and the GA after 16 iterations with 340 total objective function evaluations.

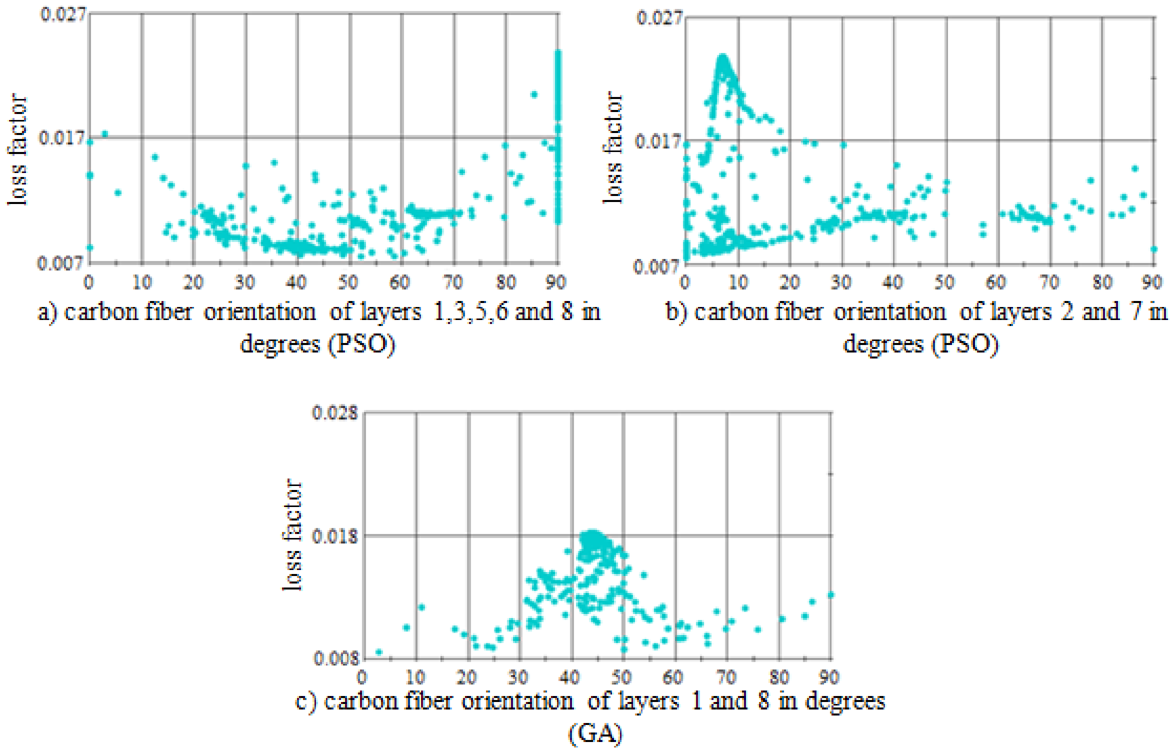

Figure 4. Loss factor as a function of fiber orientation.

The same procedure is applied to the roof of a car. By constraining the mass between 11 and 13 kg, the averaged damping over the natural frequencies between 30 and 200 Hz was considered as the objective function to be maximized in the optimization process. The PSO algorithm converged to the best damping value, the GA converged second best, followed by the GB method. The results can be seen in Fig. 5. Also, the GA optimization required many more iterations than the GB optimization method, while the GA and PSO were similar and required more iterations than the GB method.

The green dots in Fig. 5 are the accepted objective function evaluations and the pink dots are the rejected objective function evaluations due to the mass constraint defined by the user.

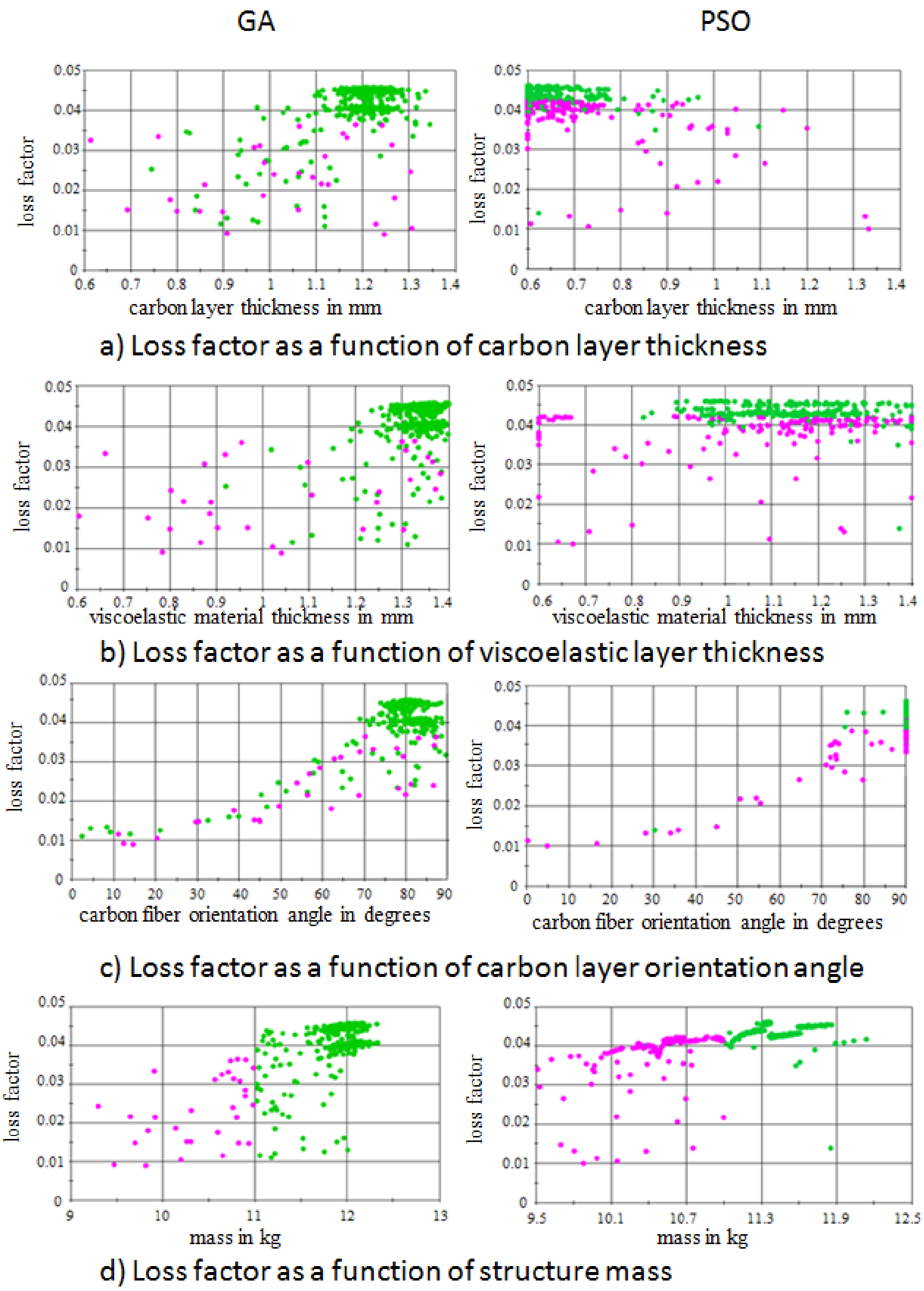

Figure 5. PSO and GA optimization results for the composite roof structure.

Each algorithm performed in different ways. The carbon layer thickness converged to 1.2 mm in GA, shown in Fig. 5a, left, and the PSO carbon layer thickness converged to the minimum allowable thickness, 0.6 mm, in Fig. 5a, right. The viscoelastic layer thickness converged to 1.35 mm in GA, shown in Fig. 5b, left, and the PSO viscoelastic layer thickness started to converge at 0.9 mm, in Fig. 5b, right. In terms of fiber orientation angles, the GA converged to 85°, Fig. 5c, left, while the PSO fiber orientation angles converged to 90°, Fig. 5c, right. The GA converged to a mass of 12 kg while the PSO converged to a mass of 11.3 kg, Fig. 5c left and right, respectively. This difference of mass is a result of the fact that the PSO carbon composite thickness converged to a lower value, as the carbon is heavier than the viscoelastic material. All convergences were considered as the thickness, angle, or mass that produced the highest loss factor value.

To compare the performance of each optimization method, the results of each method are recorded and are displayed in Table 1.

Table 1: Layer properties and loss factor of optimization results for the composite roof structure.

	carbon angles 1 and 6	carbon angle 3	carbon layer thicknesses	first viscoelastic layer thickness	second viscoelastic layer thickness	loss factor percentage
PSO	90°	90°	0.60 mm	1.34 mm	0.98 mm	4.6%
GA	85°	81°	1.22 mm	1.39 mm	1.23 mm	4.5%
GB	81°	70°	0.8 mm	1.4 mm	1.3 mm	4.4%

In addition to these results, the objective function evaluations, which occur within each iteration, were observed. The PSO was observed to have the best convergence performance in terms of reaching their optimum values, followed by GA and GB, respectively. The difference between the PSO optimum value and the GB optimum was only around 0.2%. However, the GB converged with 3.2 times fewer objective function evaluations in comparison with PSO. PSO converged after 300 objective function evaluations over 15 iterations, GA performed with 250 objective function evaluations over the course of 9 iterations, and lastly, the GB optimization performed with 94 objective function evaluations over the course of 10 iterations.

A mass of 11.8 kg was further considered to be able to compare two different results for the same mass. The optimal of PSO observed an averaged damping of 0.046, and a similar-mass scenario observed an averaged damping of 0.013. The two different layer compositions can be seen in Table 2. The layer thicknesses are more or less the same, with the only differences being the carbon fiber orientation angles, which performed best for 90°. This best performance for 90° comes from the fact that a high strain energy is stored in the material in the second direction, which is produced by a high Young's modulus in the second direction, in conjunction with the high specific damping capacity of the material in this direction and agrees with the results found in [19] for their study performed on beam structures. According to Zhang and Chen [19] the fiber orientation angles of compliant layers played a crucial role in improving the dissipation capacity of the complete composite. They observed that the stiffer the constraining layers were, the higher the shear deformation in the viscoelastic layers will be and the higher the loss factor of the composite. The second design has more energy stored in the first direction, causing a lower total loss factor due to the lower specific damping capacity of the material in this direction.

Table 2. Comparison for same-mass and optimal PSO design results.

	carbon angles 1 and 6	carbon angle 3	carbon layer thicknesses	first viscoelastic layer thickness	second viscoelastic layer thickness	loss factor percentage
optimal design	90°	90°	0.62 mm	1.39 mm	1.16 mm	4.5%
same-mass design	2°	30°	0.62 mm	1.37 mm	1.18 mm	1.4%

Considering these two scenarios, the averaged strain energy between 30 and 200 Hz was calculated for the roof of the car. As expected, the strain energy values were efficiently reduced in the optimal composite in comparison with the composite of similar mass but less damping.

The strain energy was used in this case to compare two different roof configurations, as it has been previously proven by Jaber et al. [22] that placing damping treatments on locations of high strain energy is able to greatly reduce the vibratory energy in an automobile part. The optimal design has a minimum strain energy value and shows that it does not require any further damping treatment.

The strain energy on the roof of the car for the two scenarios, along with a reference strain energy of the aluminum roof, can be seen in Figure 6. Through optimization, the laminate roof caused an reduction of the strain energy in the structure, even with the most poorly performing objective function evaluation from PSO. Moreover, the strain energy was better reduced by the optimum objective function evaluation laminate structure make-up created by the PSO method.

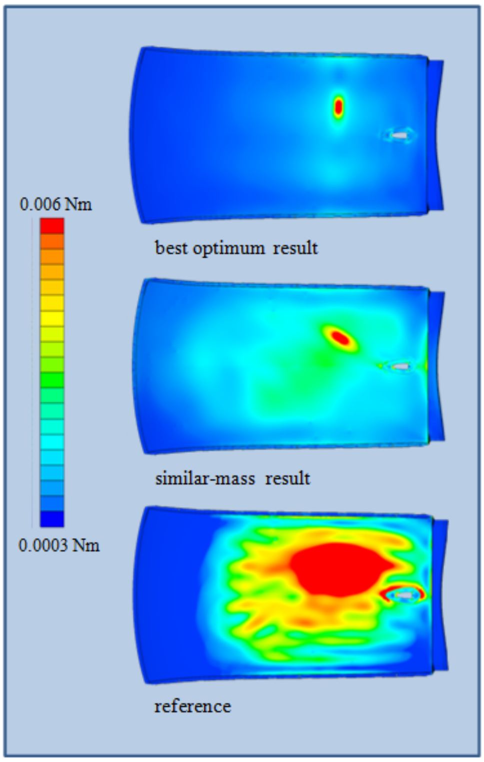

Figure 6. Strain energy comparison for PSO results with the same mass.

In order to better illustrate these damping solutions in a real-life application, the newly designed roof was put in place of the original aluminum roof of a car. The structure was coupled with the fluid within the vehicle chassis, and the sound pressure was calculated at the driver's ear position. The results can be seen in Figure 7.

Observed from these results, the sound pressure at the driver's ear position was reduced by around 5 dB (SPL) for some frequencies. The reduction was not similar for all frequencies due to the fact that the increase in the damping is not similar over all frequencies due to its dependance on the mode shape of the structure. This reduction shows that this optimization of the material make-up of the structure itself is able to effectively improve the NVH performance of an automobile and provides a more feasible solution than using CLD treatments because the part is previously controlled in terms of acoustic issues through production, rather than cutting and placing CLD treatments after production. Furthermore, the mass of the automobile roof was effectively reduced from 14.17 kg to 12 kg. It is suggested that further studies be conducted to investigate if this newly designed roof will affect other testing requirements such as crash testing and dynamic stiffness testing, as well as a cost comparison between designs should be

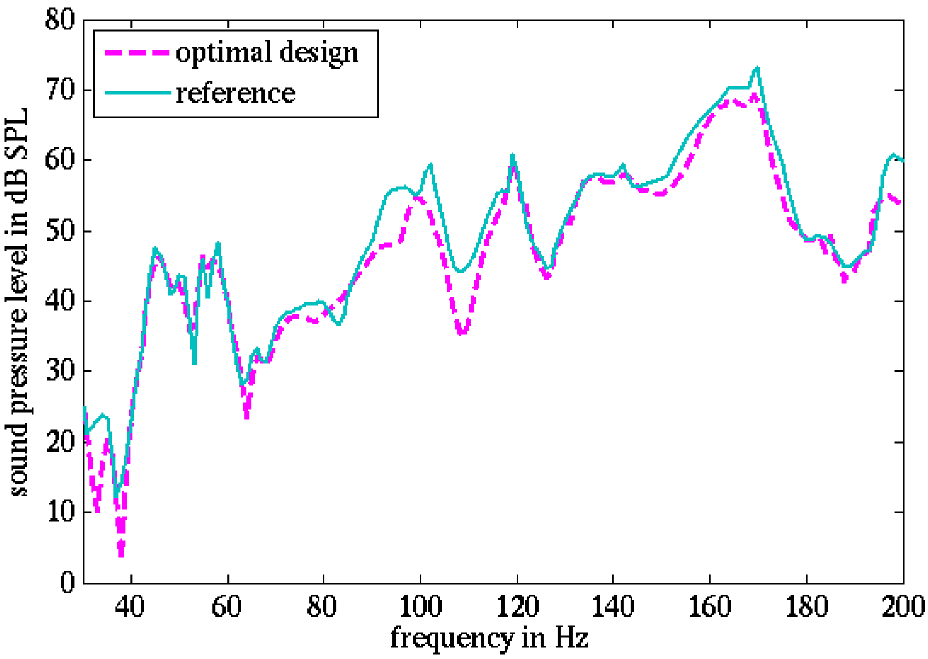

Figure 7. Sound pressure level comparison at driver's ear position.

conducted.

9 CONCLUSIONS

In order to design a vehicle with a good lightweight structure, carbon composite materials with embedded viscoelastic layers can be a potential solution to improve NVH performance levels. Unfortunately, carbon composites do not always have a reliable performance and require a very accurate design. Many parameters, such as fiber orientation, layer thickness, and laminate stack-up sequence, can play a crucial role in the design of these NVH-improving, lightweight structures. The modal strain energy method has been used to predict the loss factor of carbon composites with embedded viscoelastic layers in conjunction with optimization algorithms, and as well the frequency dependence of the viscoelastic material has been taken into account. Optimization algorithms can be an efficient way to optimize the design of these structures, such as GA and PSO. The PSO proved to be more efficient and faster than the GA, followed by GB optimization algorithms. It has been shown that changing the composition of a car roof can effectively reduce the strain energies of said roof as well as reduce the sound pressure at the driver's ear position within a vehicle chassis. For this PSO, the damping value was calculated as improving by a factor of four when compared between the best and worst optimization results for the same mass. Also, the GB optimization method is a better optimization method in situations of large automobile parts due to the optimum varying only slightly from the PSO optimum, and is observed to converge at a faster rate than that of PSO. Changing the material itself in structural parts of an automobile can provide an effective means of improving the acoustic behavior of cars, as well as create a more efficient car part fabrication for passive control purposes. Further investigations should be carried out to verify other requirements during design, such as crash testing and dynamic stiffness testing.

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