INTER-NOISE 2007

28-31 AUGUST 2007
ISTANBUL, TURKEY

Structural damping optimization using viscoelastic materials

Davut Ayhan Serabatir[a], Faruk Bayraktar[b], and Kenan Y. Sanliturk[c]

Arcelik A.S. Cooking Appliances Plant
Product Development Center
14300 Bolu
TURKEY

ABSTRACT

Vibration and acoustic behaviour of machines are becoming more important for the "quality" of many products in the market. Viscoelastic materials (VEM) are widely used in many structures to reduce vibrations and noise. But these materials bring additional cost and additional weight to the structures. Therefore, engineers are faced with the problem of identifying the maximum benefit using minimum amount of material. The objective of this paper is to establish a methodology that will enable us to determine the optimum distribution of VEM for maximum damping for a given structure. To achieve this objective, the properties of VEM, namely elasticity modulus and loss factor are measured. A reliable method of modeling dynamic behaviour of structures coated with VEM is established and results are validated against experimental data. Then, various optimization methods are examined and a damping optimization method based on Genetic Algorithm is developed. This process involved both developing the code as well as establishing the interfaces between various commercial finite element programs. Damping optimization methodology developed in this paper is applied to various test structures. Experimentally verified results suggest that the method proposed in this paper can be used for real applications for damping optimization using VEM.

1 INTRODUCTION

Vibration and acoustic properties of machines are becoming increasingly more important as these properties are usually linked directly with the "quality" of many products in the market including domestic appliances. Furthermore, the current trend in the design of machines is to provide more functionality, comfort and higher efficiency while reducing the cost. As a result, optimisation at both design and prototype stages is essential in order to produce competitive products. Viscoelastic Materials (VEM) are widely used to provide additional damping to structures so as to reduce excessive vibration and noise levels. In such applications, load carrying structural members are usually coated with VEM, forming composite structures. Although, very substantial amount of work has been done on VEM's and their dynamic properties [1,2]. Optimization of the structures for maximum damping is still difficult due to various reasons, including the temperature and frequency dependency as well as the non-linear behaviour of the properties of the VEMs. E. Boivie [3] considered the elasticity modulus of the material as a design variable for optimization of viscoelastic layer

[a] Email address: davut.serabatir@arcelik.com
[b] Email address: faruk.bayraktar@arcelik.com
[c] Email address: sanliturk@itu.edu.tr

damping on hard disk drives. G.S.H. Pau [4] compared several optimization techniques for constrained layer vibration damping of beams. Jakob S. Jensen and Ole Sigmund [5] used topology optimization for the minimal vibration response of a distribution of two materials on a structure. E.R. Ponslet [6] used genetic algorithm module of a commercial optimization program for the optimization of the location of the steel spring vibration isolator. G. Garay [7] used strain energy based size and location optimization for fan airfoils. G. Locatelli [8] used genetic algorithms to find the optimum placement of actuators. Tim Pühlhofer [9] used genetic algorithm for optimizing mass and stiffness of a clamped beam. Marione Benedicte [10] used genetic algorithm with a commercial finite element program to optimize the thicknesses of solid structures.

The main objective of this study is to establish a methodology that will enable us to determine the optimum distribution (minimum amount) of viscoelastic materials for maximum damping for a given structure. To achieve this objective, properties of viscoelastic materials, namely Young's modulus and loss factor, are measured first using a dedicated measurement system. Then, various optimisation methods are examined and a damping optimisation method based on Genetic Algorithm is developed. This process involved both developing the code as well as establishing the interfaces between various commercial finite element (FE) programs. After that, the performance of the generic algorithm is demonstrated using a few test cases including experimental validations. Finally, some concluding remarks are included.

2 MEASUREMENT OF THE PROPERTIES OF VISCOELASTIC MATERIALS

It is essential that the properties of a viscoelastic material (VEM) must be known if it is to be used for structural damping optimization. Here, dynamic properties of VEM were measured using a standard resonant based method (ASTME-756) [3] that is used to determine the material loss factor (η) and modulus of elasticity (E). The temperature and the frequency range of the test method are very often quite limited. However, it is possible to perform the measurements at various temperatures and then project the results to a much wider frequency range using a method called "Shifting Technique". This leads to obtaining the so-called "Master Curve" which describes the variation of the material properties with respect to temperature and frequency [9]. In order to obtain the Master Curve at 25 ˚C, first ASTM measurements are done at -25,0,25,50 and 75 ˚C. Then a set of shifting coefficients is applied for every E and η values. Figure 1 shows the measured material properties of VEM which is used for this study.

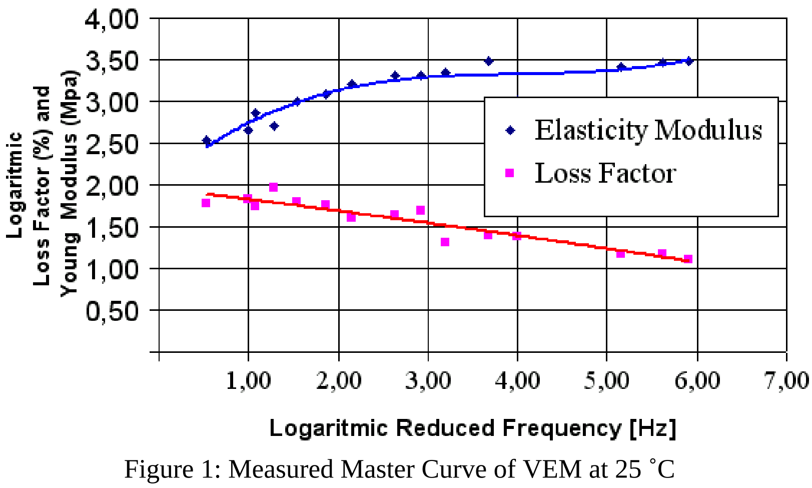


Figure 1: Measured Master Curve of VEM at 25 ˚C

3 DAMPING OPTIMIZATION

3.1 Overview of Optimization Methods

There are various optimization techniques, as mentioned in Figure 2 that may be used for damping optimization. However, some approaches may be more appropriate for certain types of problems. Shape optimization uses nodal perturbations and the main disadvantage of this technique is the probability of re-preparing the numeric model at some steps during the optimization. Topology optimization takes the density of each element as a design variable. Damping matrix implementation to the theory is quite new and rare. As the name implies, material optimization takes material properties as design variables. Using different VEM on different regions of a structure is not an easy way for coating process. Parametric optimization technique takes the dimensions of a structure that are parametrically modeled and aims to optimize them.

Damping level of a structure coated with VEM is very sensitive to the thickness of the VEM coating and different regions of a structure may need different amount (thickness) of VEM. Accordingly, for structures that are modeled using shell type of finite elements, the VEM layer thickness will be the logical design variable. Therefore, parametric optimization based techniques would also be very appropriate way to determine the optimum distribution of VEM. However, setting the thickness of the VEM coating for individual shell elements in a model will easily lead to excessive number of design variables and this will make the optimization process either too costly or impossible to handle. To overcome this problem, finite element (FE) domain can be divided into regions. Each region on the structure may have many finite elements as shown in Figure 3, but each region can have one design variable only. This kind of parametric optimization problem can be modeled with binary string definition.

An important phenomenon takes place when modal analysis is performed for those structures with non-uniform damping distribution, e.g., composite structures with localized damping coating or with non-uniform thickness of the coated materials. In these cases, as the damping is no longer proportional, the mode shapes for these structures will be complex. This will require an appropriate FE solver for during the damping prediction. Furthermore, the objective function for damping optimization appears to be highly non-linear. As a result, it is expected that there will be local minimums during the optimization search. Therefore, a parametric optimization method with a random search technique based on Genetic Algorithm (GA) is selected for this study to avoid local minimums.

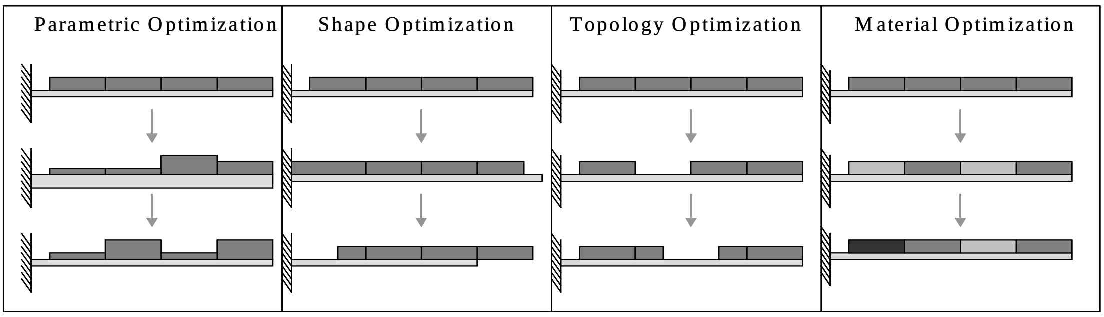
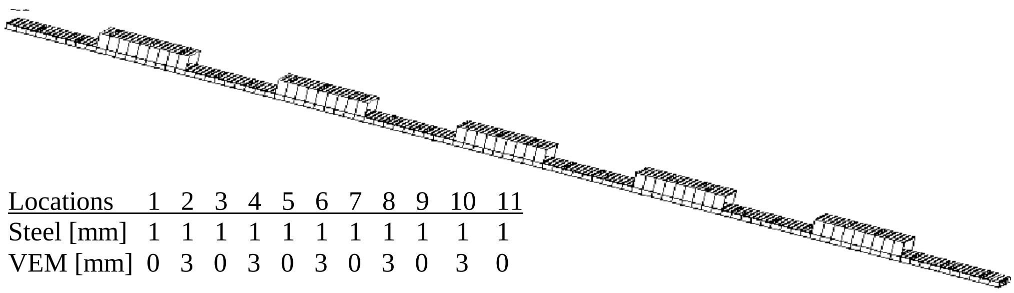


Figure 2: Optimization techniques



Locations	1	2	3	4	5	6	7	8	9	10	11
Steel [mm]	1	1	1	1	1	1	1	1	1	1	1
VEM [mm]	0	3	0	3	0	3	0	3	0	3	0

Figure 3: FE model of a steel beam which has 3 mm thickness of VEM at 6 of 11 VEM regions.

3.2 Genetic algorithm: 'Survival of the Fittest'

Genetic Algorithm is a random search technique that uses some mechanisms of natural evolution theory. This algorithm sets an analogy between the possible design population and the population of the biological creatures in nature. The natural selection rule (survival of the fittest) is replaced by artificial selection based on a computed fitness criteria for individual designs. This fitness is essentially the objective function of the optimization problem and possibly augmented with constraint penalties. The chromosomes that define characteristics of biological beings are replaced by strings of numerical values representing the design variables. When couples of selected individual designs reproduce, they combine portions of their genetic material to create an offspring that shares traits from each parent [6,10].

Genetic Algorithm is selected in this paper for damping optimization and the corresponding code is developed within MATLAB® environment. First, a three dimensional (3D) composite model of a steel structure coated with VEM is prepared parametrically using a commercial finite element program. Figure 4 is a flowchart for the damping optimization process using Genetic Algorithm (GA) that is developed for this study.

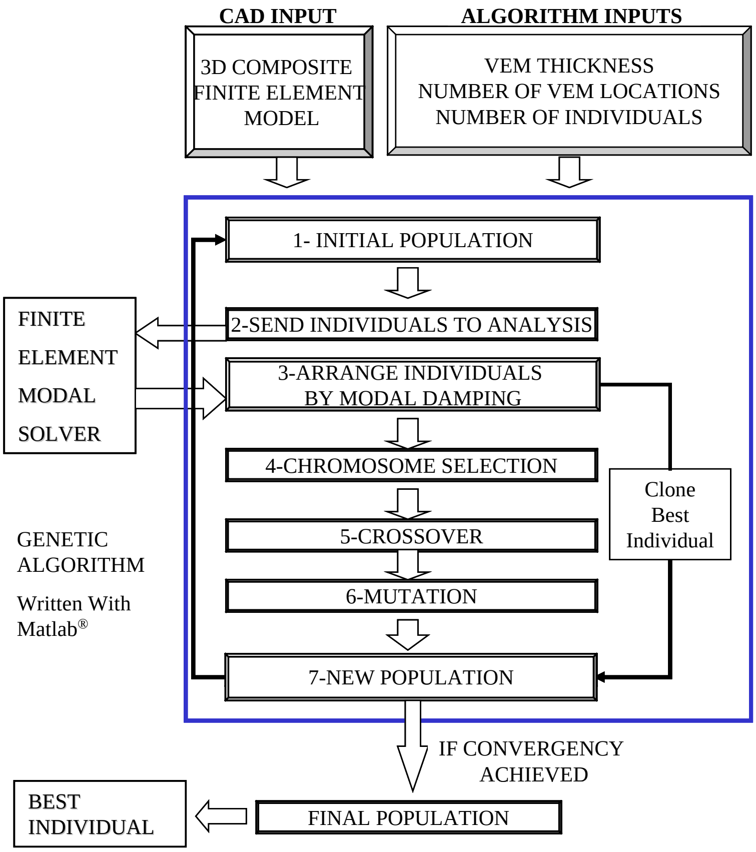


Figure 4: Flowchart for structural damping optimization using Genetic Algorithm

The first and the most important step in preparing an optimization problem for a GA solution is that of defining a particular coding of the design variables and their arrangement into a string of numerical values to be used as the chromosome by the GA. This numerical string is called “Chromosome” in GA literature. If there is a VEM on a region of the steel surface, The “gene” that represents this region takes the value 1. Otherwise the value of the gen individually set to 0. Figure 5 demonstrates the use of chromosome and genes on a VEM coated cantilever beam finite element model.

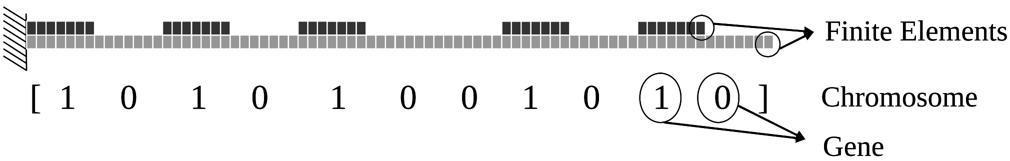
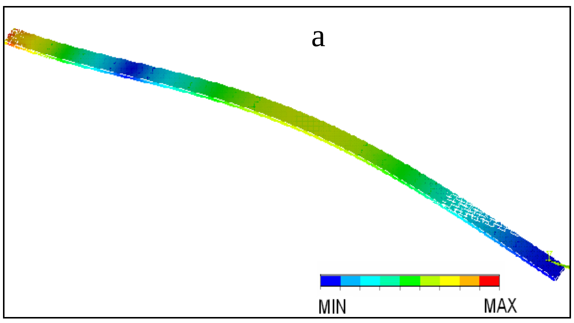


Figure 5: Demonstration of the chromosomes and genes for an individual design

Composite finite element modeling begins by creating the 3D sheet model of the structure. Then, the sheet model is divided into regions, which are suitable for VEM coatings. These regions are meshed with shell finite elements. Shell element thickness of each VEM region is defined parametrically. The algorithm can assign VEM thickness to each region on the FE model of the structure Then, modal analysis is performed by a commercial finite element program, and the algorithm reads the modal damping ratio from the output of the FE program. Additionally, there are three input parameters that must be defined before GA optimization begins. The first parameter is the thickness of the VEM (T), the second parameter is the “number of locations” (L) that algorithm can allocate the VEM. Each population have a limited number of designs, which is called as “individual number” as a third parameter. These individuals (designs) are changed from generation to generation. Figure 5 illustrates an example of VEM distributions with 1 mm thickness on 5 separate locations of 11 regions.

In this study, vibration modes and modal damping ratios of structures are calculated using commercial Finite Element (FE) programs. Therefore, number of degrees of freedoms of a structure in a FE model can be quite large. However, the number of design variables needs to be chosen carefully and this number need to be as small as possible but should be sufficient for the purpose. For example, the second mode shape of a clamped beam in Figure 6a can be obtained using an FE model with a large number of degrees of freedoms. However, if the damping for this mode is to be optimized, the number of design variables (the thickness of the viscoelastic coating in various regions) can be chosen to be a very small number. Figure 6b illustrates the relationship between the number of regions and the number of design variables.



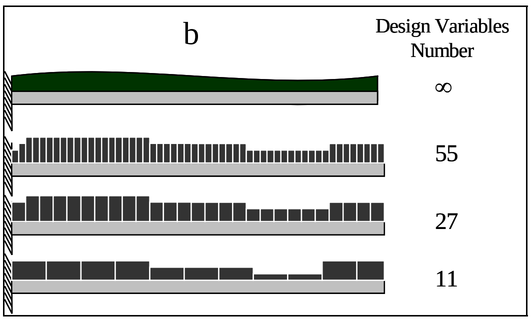


Figure 6: a) Numerical strain energy distribution on a cantilever steel beam
b) Demonstrating the number of design variables.

An initial population (initial guess) must be generated for the genetic optimization algorithm to start the process. In this step, the algorithm generates specified number of chromosomes randomly. For the purpose of damping optimization, chromosomes are the specific composite structures that have specific number of VEM locations. The optimization process using GA is explained for using a simple example in Figure 7. Here, the possible number of VEM location is set to 4. In this manner the amount of VEM is set to be the same for all chromosomes. Then, as illustrated in Figure 7, the program generates 5 random different composite structures having the same amount of VEM. At this stage the FE code computes the modal damping (for selected vibration mode) corresponding to those initial five initial chromosomes of composite structures and the results are sorted in descending order. Then, the selection operator is in charge of picking individuals for reproduction.

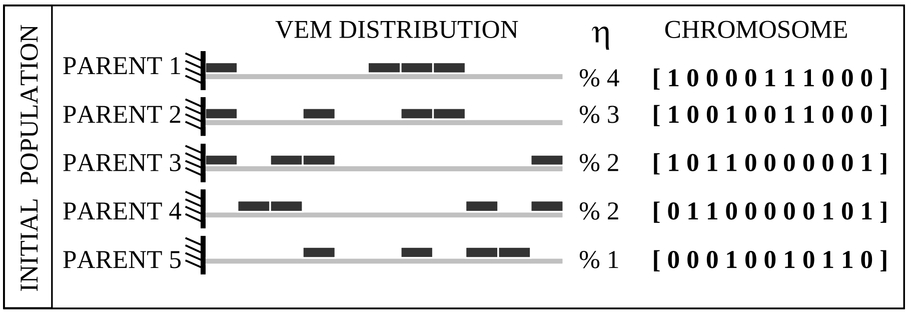


Figure 7: Demonstration of an initial population of the algorithm

The individual which has better damping value is selected as the parent number 1. The second parent is selected by using "biased roulette wheel" where fitter individuals get a larger (not full) portion of the wheel and therefore have a better chance of reproducing and transmitting their characteristics (genes). As a result, the classical problem of creating the super-individual is avoided. Once two parents are selected, their chromosomes undergo a crossover operation that generates offspring chromosomes (children). The operator selects some random regions on the structure; the genes of two parent chromosomes exchanged between these regions and create the chromosomes of two children with providing the probability of changing the amount of VEM for each individual. Figure 8 demonstrates the meaning of the crossover of chromosomes.

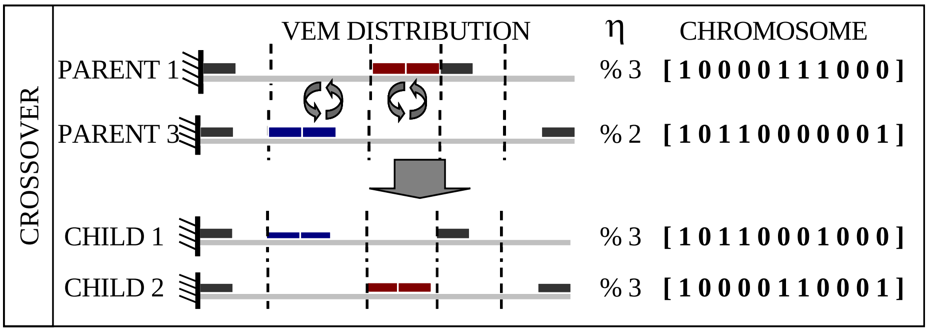


Figure 8: Demonstration of a crossover step of the algorithm

The role of the mutation is to prevent loss of genetic diversity by introducing design features that may have never been present in the population or may have been lost over time. Mutation is applied with a small probability to a gene in the chromosome. If mutation occurs, the current value of the gene is replaced with another gene, uniformly distributed in the range of that particular design variable. After crossover and mutation steps are completed, the two new individuals are created. Figure 9 demonstrates the mutation process.

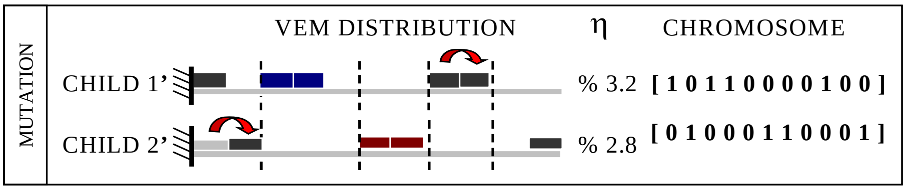


Figure 9: Demonstration of a mutation step of the algorithm

These individuals and the best of the previous population take place on the next population. Again, the modal damping corresponding to these new individuals are computed and sorted. Figure 10 shows the population (set of individuals) at the end of the generation 1.

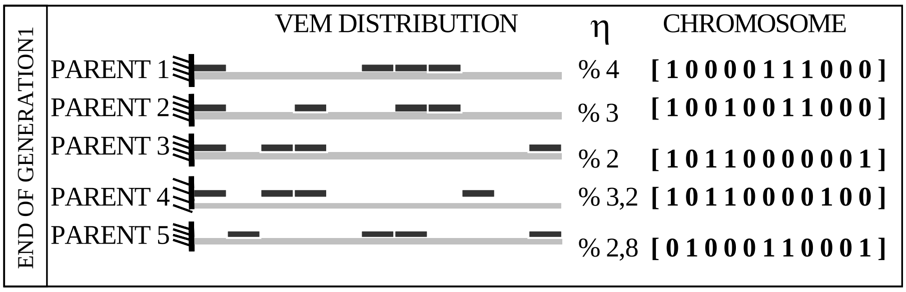


Figure 10: Demonstration of the population at the end of the generation 1

Note that the population size is limited to 5 individuals in this example and the “worst” individual (VEM arrangement resulting in minimum level of damping) is expelled from this new population, guaranteeing the the weakest to perish. This optimization program runs for many generations (many crossovers and mutations) until convergence –optimum arrangement of VEM for maximum damping- is achieved.

4 CASE STUDIES WITH EXPERIMENTAL VALIDATION

Damping optimization using GA is used to predict the optimum locations of VEM for maximum damping and the results are validated using experimental modal testing [13]. In each case, the predicted (result of optimization) optimum configuration is physically created and the damping is measured via processing the measured Frequency Response Functions (FRF). A typical set-up for measuring FRFs is shown in Figure 11. The measured FRFs are processed using the Line-Fit option in ICATS [14] software.

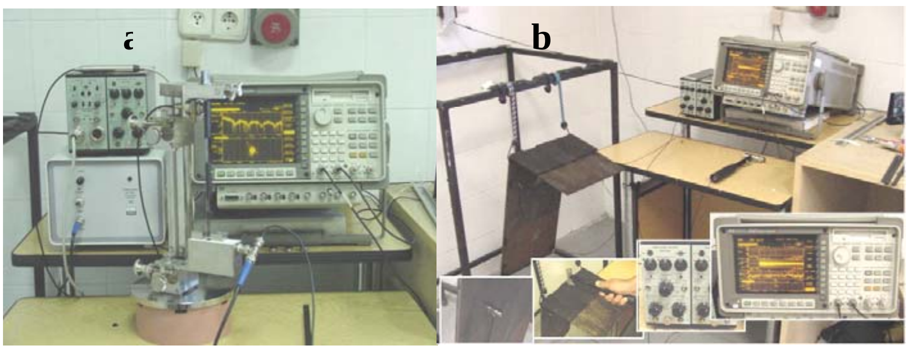


Figure 11: Set-up for frequency response function measurement a) Beam set-up b) L plate set-up

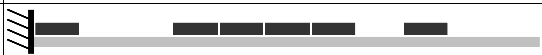
4.1 Optimization of a Damped Cantilever Beam

In this case study, the aim of the optimization process is to maximize the modal damping for the second mode of a damped steel beam. The results for the fully VEM coated steel beams with different thicknesses are listed in Table 1. Optimization is performed for various combinations of the Thickness (T) and the number of Locations (L) of VEM along the beam axis and the best locations for maximum level of damping are determined. Results are summarized in Table 2 where each row shows the best locations for maximum damping for a given T and L combinations, noting that M is an indication of the quantity of VEM used. The results in Table 2 should be compared with those in Table 1 to appreciate the benefits of using the same amount of material at most sensitive and profitable locations.

Table 1: Fully coated beam predicted and measured modal damping values.

T [mm]	L [#]	M [TxL]	Fully Coated Beam	Predicted η [%]	Measured η [%]
1	11	11		1,9	2,1
2	11	22		8	9
3	11	33		18	20

Table 2: Optimum VEM distributions for various combinations of T and L, and predicted and measured modal damping values.

T [mm]	L [#]	M [TxL]	Optimum VEM Distributions	Predicted η [%]	Measured η [%]
1	3	3		1	1
1	6	6		3	3
1	9	9		2	2
2	3	6		4	4
2	6	12		5	5
2	9	18		7	8
3	3	9		8	7
3	6	18		10	8
3	9	27		15	17

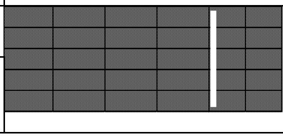
Inspection of the results in Table 2 reveals that:

- The algorithm mostly finds the best VEM locations to be those of maximum strain energy regions for the mode of vibrarion considered.
- Measured damping values are very close (or the same) to the predicted values. Thus, the accuracy of numerical composite modeling is also validated.
- When the results of the optimization are examined, it is seen that local and dense coating of VEM (at only a few areas with thick coating) appears to be more efficient way of optimizing damping that allocating the same amount of VEM material over a larger area.

4.2 Optimization of a Damped Plate

L-shaped steel plate with 3 mm thickness is used in this case study. Again, results for fully VEM coated L-plate with different thicknesses are shown in Table 3. Optimization run is done for maximizing the modal damping for the first mode of vibration of the plate. Figure 12 illustrates the optimization search as the generation (iteration) number increases. It is seen that modal damping is increasing gradually as better locations are found. This result demonstrates the evolution of the locations for coating VEM for maximum damping.. Results are summarized in Table 4.

Table 3: Fully coated L shape steel plates predicted and measured modal damping values.

T [mm]	L [#]	M [TxL]		Predicted η [%]	Measured η [%]
3	30	90		1,7	1,6
4	30	120		2,9	2,6

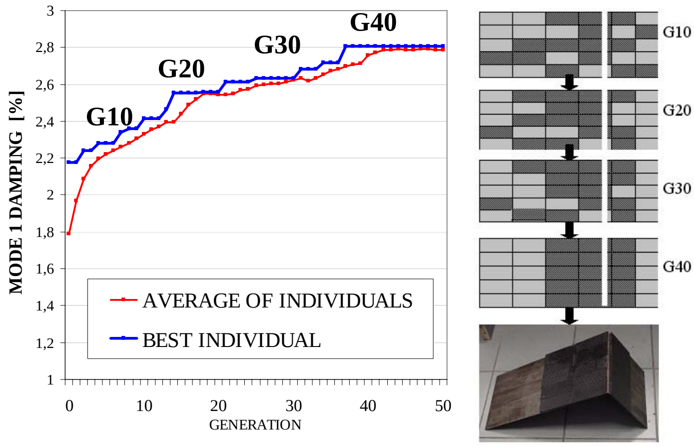
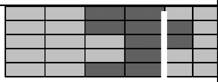
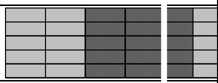
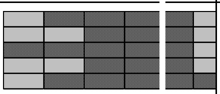
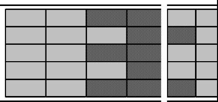
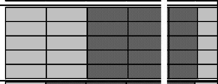
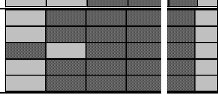


Figure 12: Optimization survey by generation number of an optimum design

Table 4: Optimum VEM distributions for various combinations of T and L, and predicted and measured

T [mm]	L [#]	M [TxL]		Predicted η [%]	Measured η [%]
3	10	30		1,2	1,0
3	15	45		1,5	1,2
3	20	60		1,7	1,6
4	10	40		2,1	1,9
4	15	60		2,8	2,6
4	20	80		3,0	2,8

Inspection of the results in Table 4 reveals again that: The results of optimization studies for L-shaped plate confirm the results of the optimization of the beam example. It shows that GA can be used for optimizing damping for more general and complex structures.

5 CONCLUDING REMARKS

An optimisation methodology based on genetic algorithm is developed to find the best locations of VEMs for maximum damping. The methodology developed in this paper is applied to various test structures coated with viscoelastic materials, including; a simple beam and an L-shaped plate. In all cases, the results are validated by using experimental data. Findings from this study suggest that the method adopted in this paper has the potential of being applicable to real applications for damping optimisation using viscoelastic materials.

6 REFERENCES

[1] Eric Michael Austin, “Influences of higher order modeling techniques on the analysis of layered viscoelastic damping treatments”, *Phd. Thesis*, Virginia Polytechnic Institute and State University (1998).

[2] R. L. Lakes, “Viscoelastic solids”, CRC Press, New York (1998).

[3] Ethan Boivie, “Optimization of viscoelastic damping for hard disk drives”, *Msc. Thesis,* Binghamton University (1998).

[4] G. S. H. Pau, “A comparative study on optimization of constrained layer damping for vibration control of beams”, *HPCES Symposium Singapore* (2003).

[5] Jakob S. Jensen and Ole Sigmund, “Phononic band gap structures as optimal designs” *Proceedings of the IUTAM Symposium on Asymptotics, Singularities and Homogenisation in Problems of Mechanics. Klüwer Academic Publishers,* 2003, pp. 71–81.

[6] E. R. Ponslet and M. S. Eldred, “Discrete optimization of isolator locations for vibration isolation systems: An analytical and experimental investigation”, *Technical Document,* Structural Dynamics Department, Sandia National Laboratories (1996).

[7] G. Garay, “Design and subcomponent testing of a viscoelastic constraint layer damping system for fan airfoils”, *9thNational Turbine Engine HCF Conference* (2004).

[8] G. Locatelli, H. Langer, M. Müller and H. Baier, "Simultaneous optimization of actuator placement and structural parameters by mathematical and genetic optimization algorithms", *Proc. of IUTAM Conference Smart Structures and Structronic Systems*, Magdeburg (2000).

[9] Tim Pühlhofer, “Vom werkstoff zum bauteil die prozesskette bei der optimierung werkstoffhybridermetall faserverbundbauteile”, *18th Cad-FemUsers’ Meeting, Internationale FEM Technologies* (2000).

[10] Marion Benedicte, “Methods for the optimization of dynamic behavior of machine tools”, *Phd. Thesis*, Swiss federal Institution of Technology, Zurich (2002).

[11] ASTM-E 756,. “Standard test method for measuring vibration damping properties of materials”, *American Society for Testing and Materials*.N.Y. (1993).

[12] G.M. Rowe and M.J. Sharrock, “Development of standard techniques for the calculation of master curves for linear-visco elastic materials”, *The 1st International Symposium on Binder Rheology and Pavement Performance*, Calgary (2000).

[13] D.J. Ewins, “Modal testing: theory and practice”, John Wiley & Sons, NY. (1995).

[14] ICATS *Reference Manual*, Imperial College, London (1996).