Shape Optimization of Damping Liners on Vibrating Panels

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Extended Abstract

This paper present a methodology to achieve three dimensional shape optimization of damping liners attached to vibrating panels. It is the initial stage of the development of a flexible CAE design tool to optimize such liners in automotive panels. Noise, vibration and harshness are critical aspects in modern vehicle refinement and passenger perception of quality. Vibration from engine, powertrain and road sources are transmitted through the vehicle structure and excite body panels that add to the tactile vibrations felt by passengers and the noise level. To reduce this, damping materials are commonly attached to panels as uniform layers to absorb and dissipate vibration energy. A redistribution of damping material based on the dynamic response characteristics of the panels constitutes a more efficient damping treatment which would save costs and reduce overall weight. To achieve this in an efficient manner, a CAE approach is used where thickness can be continuously varied and commercial FEA package ABAQUS is used to evaluate the dynamic response. A genetic algorithm is written in python to control the variables and arrive at an optimum configuration. The approach is demonstrated on a simple panel.

The liner covering the panel in the demonstrated example assumes a complex three dimensional shape created by a loft through three cross-sectional sketches. Each of these sketches is composed of three fixed boundaries and one moving boundary. The moving boundary of each sketch is a spline curve that is fitted through 5 control points. The coordinates of these control points are assigned to variables that collectively define a particular model configuration, or population member within the genetic algorithm.

A dynamic simulation is performed in ABAQUS to obtain the vibrational response to a set of loads placed on the panel over a frequency range that contains the first three resonant frequencies. An objective function based on this response is formed from a combination of velocity and acceleration data and a weight penalty factor to disadvantage models with liners of excessive volume. Three different cases are considered. Firstly application of constant amplitude of load over the frequency range is compared for 2 different weight penalty factors, then a loading situation is considered where a sharp peak in amplitude exists roughly midway between the second and third resonant frequency. For all cases the performance of optimized liner shapes obtained is compared with the performance of uniform layers of the same volume. The results showed that considerable improvement was attained by the optimized shape.

1. INTRODUCTION

Damping material has long been used to reduce structural vibration in dynamically excited panels in automotive and aircraft applications (Rao 2003). Recently emphasis is placed on efficient optimized solutions in all forms of design in an effort to reduce weight and cost of materials used. To enable such solutions for the optimal distribution of damping material requires an accurate and efficient method of evaluating performance for a very large number of possibilities and specific control of the variables determining the continuous updating of geometry via an optimization algorithm. Recent rapid developments in processing power of computational hardware has enabled the use of CAE tools such as FEA packages to determine the dynamic response of complex structures within reasonable cost and various design optimization problems such as shape optimization have been successfully approached by the use of evolutionary strategies such as genetic algorithms.

Subramanian *et al* (2004) points out the need for an efficient CAE model that can evaluate large number of possibilities. Traditionally experimental techniques are used in the automotive industry to redistribute damping materials in a manner that would approach optimal arrangement in terms of material type, size and location of the damping treatment. Vehicle structures are excited by electrodynamic shakers and the dynamic response is recorded by transducers e.g. velocity contours generated by laser vibrometer to identify flexible regions of the structure. This procedure must be repeated for many excitation locations (up to 30 for cars and minivans). Subramanian *et al* (2004) point out this is excessively time consuming and expensive. Damping material is then focused on the flexible regions by manual adjustment according to visual inspection of the velocity contours. To overcome the time/cost constraints of the experimental approach Subramanian *et al* (2004) employ a CAE methodology where an FEA model using Nastran was constructed of actual automotive panels. Eigenmodes were extracted over a relevant frequency range and visual inspection of strain energy contours outputted by Nastran was used to determine coverage and thickness of the damping treatment by manual adjustment. The performance of the optimal design arrived at by the CAE method was compared with that of the experimental approach by comparing actual sound pressure levels in the real vehicle between the two solutions.

There have been several reported approaches at fully automating optimization procedures of damping layers using CAE applied to simple beams and plates (Lumsdaine *et al* 1995, 1998, 2000 and 2002; Pai *et al* 2004). Lumsdaine *et al* (1995, 1998) use a Sequential Quadratic Programming algorithm in conjunction with ABAQUS to optimize unconstrained damping layers on dynamically excited beams and plates. The structures were always fully covered by the damping material but thickness at different regions was allowed to evolve to give an optimum material distribution. In contrast Bandini et al (2002) optimized the coverage of constant thickness damping treatment on a flat plate. Nastran was used to evaluate the performance of the configurations while a genetic algorithm written in MatLab controlled the evolution. Thus the use of commercial FEA packages in evaluating the effectiveness of damping layers on vibrating panels has been well demonstrated. In particular ABAQUS, in the references mentioned above and also Tomlison (2000) has been used in simulating the widest range of liner types from unconstrained, partially constrained to fully constrained damping layers. It also has the capability to later expand the model and include more complex analysis involving the absorptive linings such as trim and carpet for air-borne noise (DeSouza 2004).

In real automotive panels, the design variable space is limited by not only the physical space required to house the liner but also the manufacturability, particularly if complex 3D shapes are to be considered. For example no one will strive to reduce thickness in a specific small region of a liner by half a millimetre if it will cost huge sums of money in developing new manufacturing processes or tooling. Likewise no one will develop a material or process to match the effectiveness of any given optimization algorithm. New materials and processes are continuously being developed based on their own inherent objectives applications (Rao 2003) and thus an intelligent design application tool should have the flexibility of allowing the designer to modify such constraints through a user-friendly interface without having to re-program the optimization algorithm. This paper presents a methodology to initiate such conceptual design where commercial code ABAQUS will be used to evaluate the dynamic response while programming in python will be used to employ a genetic algorithm with flexible constraints. Such an approach will be demonstrated by optimizing the liner on a simple plate while varying some constraints. This study is a work in progress where eventually the methodology will be applied to real panels under current existing constraints.

2. FINITE ELEMENT MODEL

Consider a flat steel panel with a liner attached that can assume a complex 3D shape. The geometry of the liner can be achieved by creating a loft through a number of cross sectional sketches as shown in figure 1 below.

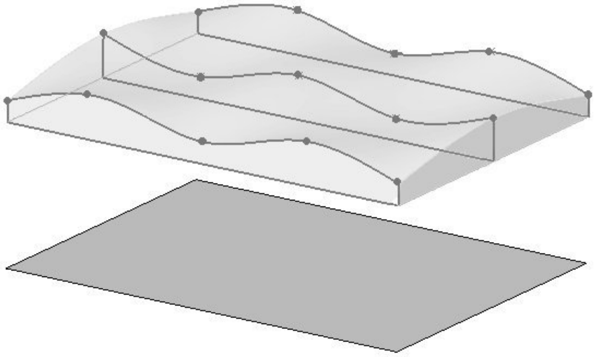


Figure 1. Steel plate with damping liner (separated)

Each cross section has four boundaries, three of which are fixed and one which is moving. The moving boundary is created by fitting a spline through a number of control points (Zhang *et al* 2004, Cerrolaza *et al* 2004). The coordinates of these control points are assigned to variables used in the genetic encoding of each configuration (population member) within the genetic algorithm.

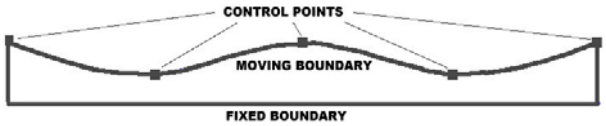


Figure 2. Cross sections contain a moving boundary created by fitting a spline through control points

The simple example has 3 cross-sections each of which has one variable boundary. A symmetry plane has been used to reduce the number of variables. The greater the number of cross-sections, the more precisely the shape can be controlled in the loft direction (perpendicular to plane of cross-sections). Within each cross-section there is one boundary created by spline-fitting through five control points. Thus there are only 10 variables in the whole model. Once again the greater the number of control points, the more precisely the shape can be controlled in the plane of the cross-section. Figure 3 below shows the finite element mesh of one possible configuration of the liner volume.

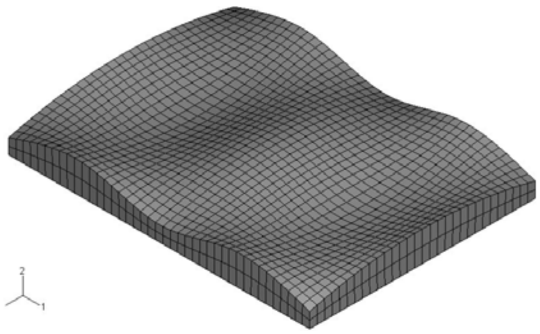


Figure 3. Finite Element mesh of a complex 3D volume

The panel and liner surfaces are constrained to each other by a surface TIE constraint in ABAQUS. This represents the situation where a vibration absorbing liner would be attached to the panel by the very common method of surface adhesion. Another possibility is the use of clips to fasten the liner to the panel which may be accomplished in FEA by the use of MPC's.

The panel is modeled out of steel while liner material properties (modulus E=0.5GPa, Poisson's ration ν=0.4 and material loss factor η=0.7) are taken from similar studies (Bandini *et al* 2002).

The linear perturbation step 'Steady State Dynamics, Modal' is used in ABAQUS to sweep through the frequencies in the range to encompass the first three natural frequencies. The panel is loaded at 4 locations as shown in figure 4 below. Boundary conditions are also applied at these locations so that the points can only move in one direction (vertical). Preliminary testing has shown that if all the loads are in phase, the condition fails to excite unsymmetrical modes of resonance. Therefore a phase difference is applied between all the loading points to ensure significant response. For real automotive panels, the excitation signal can be obtained via accelerometer data at mounting points. For this initial application, a unit load is applied at each corner.

Figure 4. Loading points

To be able to include possible variations in input force across different frequencies while using this type of analysis, an amplitude function can be specified. Further details of this are given in the section Evaluating Performance.

3. GENETIC ALGORITHM

Below are the steps executed by the genetic algorithm written in python. The use of the ABAQUS CAE environment has the distinct advantage that it itself is written in the modern language python and the python compiler is immediately available to implement any custom developed code. Modules and functions already exist that can be called to create and alter geometry, use the meshing algorithm, process the simulation job and obtain results.

PROCEDURE**:**
Generate an initial population of 8 models (individuals) at random;

*Perform FEA evaluation of objective function
*Select top 4 performers
*Generate 4 new members via cross-over from the top 4. Cross-over positions are determined by random generator.
*Apply mutation operator (1 in 8 chance) to all individuals except top 2 performers (elitism)
*Repeat procedure until convergence is satisfied.

Such algorithms have been successfully used for a variety of engineering application and are adequately described by Coley (1999).

4. EVALUATING PERFORMANCE

The various works of Lumsdaine *et al* (1995,1998) use a very simple measure of performance for the optimization algorithm (minimizing midpoint displacement at first frequency) since the works focus on other issues such as defining viscoelastic material properties and the use of discrete multilayered continuum elements. Bandini *et al* (2002) has presented the only detailed method of evaluating performance of a vibrating panel that is of practical relevance. Velocity was summed of over all FE nodes on the panel and over a frequency range that contains several resonances. Penalty factors are applied to disadvantage solutions which use more material than others and those exhibiting excessive roughness in the velocity spectrum.

Bandini *et al* (2002) points out that to obtain the velocity information over the entire frequency range in 1 Hz increments is excessively computationally expensive and thus certain regions should be focused on with greater resolution depending on relevance. Their focus is on resonant frequencies since this is where the structure is dynamically the weakest. This is the appropriate approach for optimizing a structure's inherent dynamic performance in a general sense. However for an object's performance within *specific* operating conditions, the resolution of data gathering should focus on both the inherent dynamic properties and any significant peaks in the excitation signal. The final forced response of a structure is a product of its Frequency Response Function and the excitation signal spectrum as shown below in figure 5.

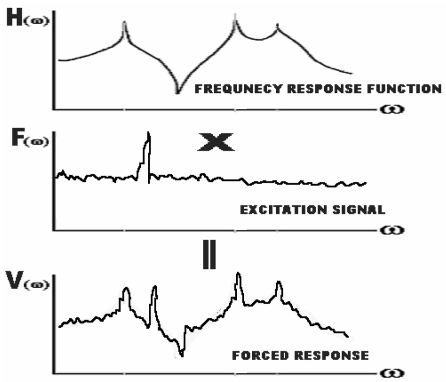


Figure 5. Response Function Constituents

This study adds capability to this type of analysis by allowing the influence of varying amplitudes in the excitation signal to have a bearing on the result. The user is able to specify in table format the magnitude of loads at different frequencies which will be read by the program and specified in the amplitude function of the loading. The resolution of data gathering is concentrated around any peaks in the loadings in the same manner as near resonant frequencies. It is envisaged in future developments that users be able to refer to a data file obtained from experimental testing to specify load amplitudes in the frequency domain.

As stated earlier Bandini *et al* (2002) uses an objective function based on a summation of velocities across the FEM nodes of the vibrating panel. Using velocity information has the inherent advantage that it's proportional to both the energy contained within the vibrations and also the sound pressure level of any resulting noise. However acceleration has also been used in the past to quantify the magnitude vibrational response. Several methods around the world that are used to evaluate ride comfort, or human response to vibration (Els 2005, Song 2003) consider acceleration at frequency ranges up to 100Hz for structural vibration. Such data have been considered in the study of car seats, steering columns and arm. This study employs a fitness function that uses a combination of acceleration and velocity data with a parameter to control the relative importance of each. The intention is to have a fitness function that can eventually be applied to different automotive panels depending on their location. For example the inside of a passenger door may have more relevance in tactile (felt) vibrations due to the arm rest being in contact with the passenger, thus the objective function favoring acceleration is more appropriate. On the other hand, panels further away from the passenger, say the bonnet have more relevance in terms of sound radiated from them, and thus velocity is more important. In all cases, a weight penalty factor is to be applied, with the designer having the flexibility to adjust the parameter depending on relative importance. For example in a luxury car model, the vibration performance aspect is more relevant than weight reduction, while the opposite holds true for an efficient economy model.

Therefore, a grid of 15 evenly spaced points is created on the base panel. The nodes corresponding to these points are placed in a set and absolute magnitudes of both velocity and acceleration data are requested. This data is summed over all these nodes and across all frequencies of simulation. The parameter α controls the relative weighting of acceleration while the parameter β controls the relative weighting of velocity. The parameter γ is the weight penalty factor. ABAQUS has a python method called getVolume(…) which returns the volume of any complex 3D volume.

$$O.F. = \gamma\,(0.1V) \text{ x } [\alpha\,[\Sigma \mathbf{v}] + \beta \text{x} 0.005\,[\Sigma \mathbf{a}]] \ldots. (1)$$

where **v** is magnitude of complex velocity at each grid point at each frequency interval; **a** is magnitude of complex acceleration at each grid point at each frequency interval.

The factor of 0.005 is used to bring unscaled magnitudes of acceleration in the same order as those of velocity data. This factor is expected to depend on the model and loading type.

Thus superior performing models return lower values of this objective function.

5. FLEXIBILITY

In addition to the adjustable parameters of the objective function discussed in the previous section, the user has other opportunities to adjust various aspects of the optimization procedure. At the start of the code script a table allows the user to enter many more parameters. The values of these are assigned to variables within the code which are then referred to in the rest of the optimization program. Maximum and minimum permissible values are entered for the acceptable range of thickness at each control point to address potential issues of available space and manufacturability. The speed of solution can be controlled by entering the number of iterations. For quick preliminary studies, less iterations can be chosen. Also the frequency range in this type of FEA analysis step is divided into intervals between resonant frequencies. The number of data points taken within each interval is also determined by adjustable parameters to allow more weight in particular frequency ranges. A greater number of solution points within each frequency band will lead to greater accuracy but incur longer simulation times.

6. RESULTS

A 2000x1500mm rectangular plate was used for the example, loaded across a frequency range to encompass the first 3 resonant frequencies. Possible thickness of liner material ranged from 3mm to 130mm. Three cases are considered. In case 1 the magnitude of loading is constant across the entire frequency spectrum as shown on figure 6. Case 2 is as case 1 except the weight penalty factor γ is doubled.

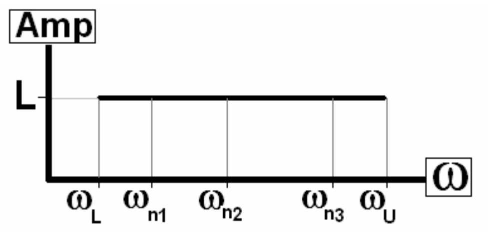


Figure 6. Case 1&2 loading is constant across spectrum

In case 3, a sharp peak in loading is introduced at a frequency roughly midway between the second and third resonances as shown in figure 7. The resolution of data gathering points was increased around this peak in similar fashion as near resonant frequencies.

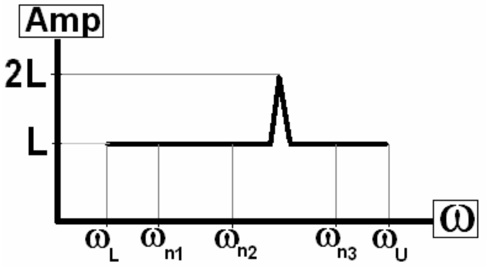


Figure 7. Sharp peak given for Case 3 loading

Equal weighting is given to velocity and acceleration information at this stage since the example is too geometrically simple to warrant a valid comparison. Figure 8, 9 and 10 show the optimized shape after 75 iterations of the algorithm. *NOTE*: thicknesses are made to appear greater than they actually are - images have been stretched in the thickness direction so that material re-distribution is more clearly displayed. Recall that no thickness can exceed 130mm.

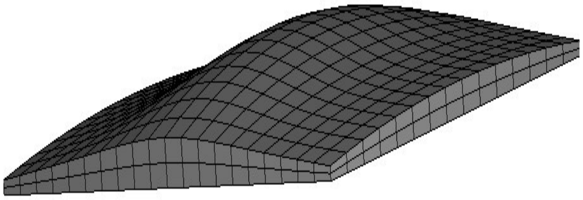


Figure 8. Case 1 optimized liner shape

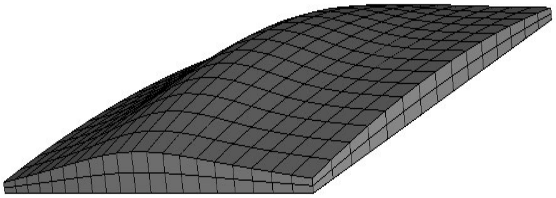


Figure 9. Case 2 optimized liner shape

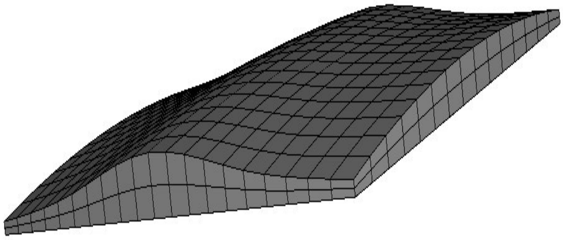
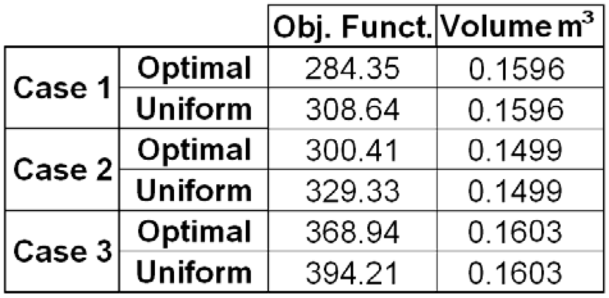


Figure 10. Case 3 optimized liner shape

In case 1 the material is concentrated highly in the centre of the plate, moderately toward the middle of the edges, and low in the corner regions. In Case 2 the shape is very similar but overall volume is reduced. In Case 3 the greatest thickness is still in the middle of the plate but more material was concentrated toward the mid-edges relative to cases 1 & 2. To compare the effectiveness of the optimized shape for each case, a comparison is made with the value for the objective function of the same volume of material that is uniformly distributed across the plate.



		Obj. Funct.	Volume m^3
Case 1	**Optimal**	284.35	0.1596
	Uniform	308.64	0.1596
Case 2	**Optimal**	300.41	0.1499
	Uniform	329.33	0.1499
Case 3	**Optimal**	368.94	0.1603
	Uniform	394.21	0.1603

Figure 11. Results comparison

The results show the benefit from redistributing damping material.

7. CONCLUSIONS AND RECOMMENDATINS

The simple example shows how redistributing damping material offers significant improvement in the reduction of structural vibration in panels. Combining CAE with genetic algorithm optimization proved very effective even when only a small number of variables were used. Future development will be towards applying this methodology to increasingly more complex geometric shapes and eventually actual automotive panels enforcing manufacturing constraints of the liner type considered. Although this will involve considerably greater number of variables, the ever increasing computational power of hardware will make this viable. Also a fitness function will be developed that is directly comparable to experimental validation.

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