APPLICATION AND ANALYSIS OF CONSTRAINED LAYER DAMPERS

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Abstract

Constrained layer damping is a technique used to reduce vibrations and noise, widely applied in many applications including appliances or vehicles. These damping materials consist of a viscoelastic adhesive and a stiff backing that is bonded to vibrating structures. Damping works by exploiting the viscoelastic nature of the adhesive via dissipation of the strain energy, turning it into heat. In this work, the viscoelastic damping material is characterized experimentally using Dynamic Mechanical Analysis (DMA). Based on this, a Finite Element Analysis (FEA) model is built. The power injection method is used to conduct system level damping tests to characterize the performance of the constrained layer damper. It is shown that simulations can predict the experimental data well and can be a powerful tool for product design. A numerical design study is conducted to investigate the effect of certain parameters such as the thicknesses of the viscoelastic and constraining layers.

Introduction

Vibration is a critical concern in engineered systems and assemblies, as excessive vibration can lead to structural fatigue, undesirable noise, operational discomfort and even product failure. Engineers are wise to consider the effect of vibration on the systems and assemblies they are designing. There are different methods for controlling or minimizing vibration.

Constrained Layer Damping (CLD) is a widely utilized method for mitigating and reducing vibrations across various applications such as aerospace, transportation including automotive, buses and trains, and general industry sectors as well. CLD involves sandwiching a viscoelastic material between a base structure and a constraining layer, as illustrated in Figure 1. Both the constraining layer and the base layer are typically stiff compared to the viscoelastic layer. When the structure vibrates, shear deformation occurs within the viscoelastic layer, dissipating the vibration energy, turning it into heat and thereby reducing vibration amplitudes.

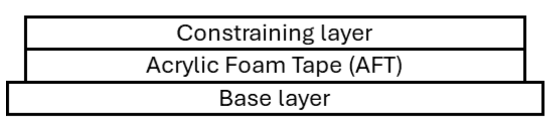

Figure 1. Example of a constrained layer damping system

Acrylic foam tapes have been widely used for bonding assemblies together where vibration is common due to the nature of the application. Application examples where vibrations are present are bonding metal skins to the sidewalls of trailers and box trucks and bonding architectural panels onto buildings. Acrylic foam tapes are effective as a CLDs due to their excellent viscoelastic properties, strong adhesion, and ease of application. Unlike traditional damping materials, acrylic foam tapes enable light-weight designs, allow for bonding with dissimilar materials and offer immediate handling strength, making them ideal for industrial applications.

Damping application examples of acrylic foam tapes

Acrylic foam tapes offer significant damping potential due to their viscoelastic nature. They provide damping by simply using them as a joining technique. Additionally, they can be used solely for the purpose of damping by applying them with a metal cover as part of a constrained layer damper.

Horse Trailer Construction: A common concern among horse owners is the stress their animals endure during transportation due to excessive noise, primarily due to the road-induced vibration of trailers as depicted in Figure 2. Trailers constructed with mechanical fasteners, such as rivets or screws, tend to exacerbate this issue. In contrast, trailers assembled using acrylic foam tape to attach metal skins have been found to be up to 41% quieter at highway speeds and exhibit a substantial reduction in vibration levels by as much as 30%. The application of acrylic foam tapes in this bonding scenario effectively creates a CLD system, significantly enhancing the comfort and well-being of the transported animals.

Figure 2. Horse trailer panel bonding using acrylic foam tape

Appliances: Appliances typically have metal side wall panels for decoration and to conceal the operational assemblies. Glass is also commonly used for washing machine covers and clothes dryer doors (see Figure 3). Vibration occurs in appliances like washing machines and clothes dryers. The metal and glass panels can be mechanically attached, but rattling and sound transmission can be an undesirable effect of using mechanical fasteners. An alternative attachment method for these panels is to use acrylic foam tapes for bonding side wall panels and glass covers on appliances. Acrylic foam tapes provide an invisible attachment method and can play a role in reducing the noise of these appliances. In addition to that, they are often used as part of constrained layer dampers to further decrease vibrations of certain parts such as rotating parts or panels.

Figure 3. Appliance glass cover bonding with acrylic foam tape

Architectural Panels: architectural panels (metal, composite or glass) on building exteriors are subjected to varying wind loads throughout the day, which can cause vibration of these panels. There are also exterior vibrations (noise) from things such as automobiles, trains and buses that can transmit onto building exteriors. Building owners desire quiet buildings for their occupants or renters. Therefore, architects will often specify exterior building materials and components that not only meet aesthetic and performance requirements but also can minimize the sound transmission into the interior spaces of the building. Acrylic foam tapes have been used over the last 40 years as an attachment method for bonding architectural panels to frames and for bonding stiffeners to panels to minimize panel deflection. These tapes not only provide an invisible attachment method but can also play a role in reducing sound transmission into the building when bonding rigid substrates together, such as metal or glass panels to metal frame systems.

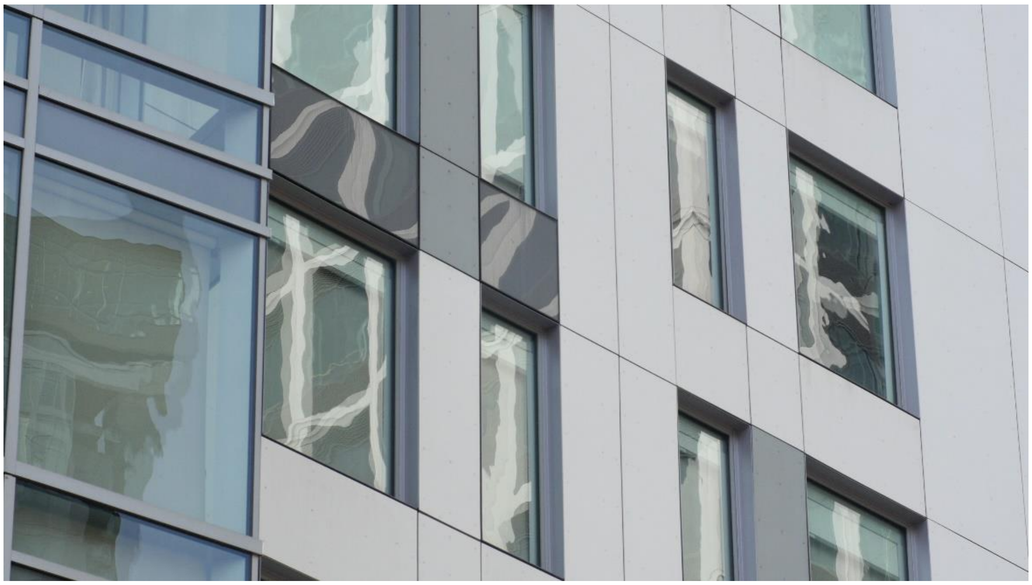

Figure 4. Architectural panels bonded with acrylic foam tape

Electronics/Speakers: Controlling and optimizing vibrations in speaker assemblies is critical to enhance the sound of the electronic device. Acrylic foam tapes are used in speaker assemblies to minimize or isolate vibration in these devices. Understanding the damping characteristics of acrylic foam tapes allows the speaker designers and engineers to choose an appropriate adhesive in different areas of the speaker assembly.

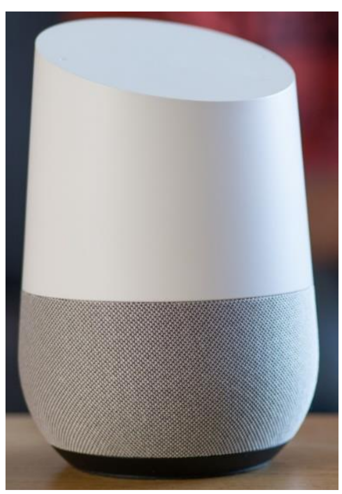

Figure 5. Electronics speaker bonding using acrylic foam tape

In the following, the acrylic foam tape that is used for investigations within this study is characterized experimentally and analyzed in terms of its damping properties. The power injection method is used as a system level test to characterize the loss factor. A finite element model is validated in terms of these results and used to conduct a parametric study to investigate the effect of certain parameters such as layer thicknesses on the resulting damping properties.

Characterization of adhesive foam tape

The adhesive foam tape employed in this study was characterized using Dynamic Mechanical Analysis (DMA), a technique that evaluates viscoelastic properties by applying a sinusoidal stress and analyzing the resulting strain. Key parameters obtained include the storage modulus (reflecting elastic behavior), the loss modulus (indicative of energy dissipation), and the loss factor (also referred to as tan(δ)), which is defined as the ratio of the loss modulus to the storage modulus and serves as an indicator of the material's damping capability. To generate data for the given frequency range, the time-temperature-superposition principle was used. To this end, various measurements have been conducted at constant temperatures between -50 and 120 °C, each with a frequency sweep ranging from 0.08 to 15.9 Hz. These measurements are then superimposed to end up with the master curve, as depicted in Figure 6. In the frequency range of 10 to 2000 Hz, the loss factor varies between approximately 0.8 and 1.0, while the shear stiffness – approximated by the complex modulus – ranges from 0.5 to 7 MPa.

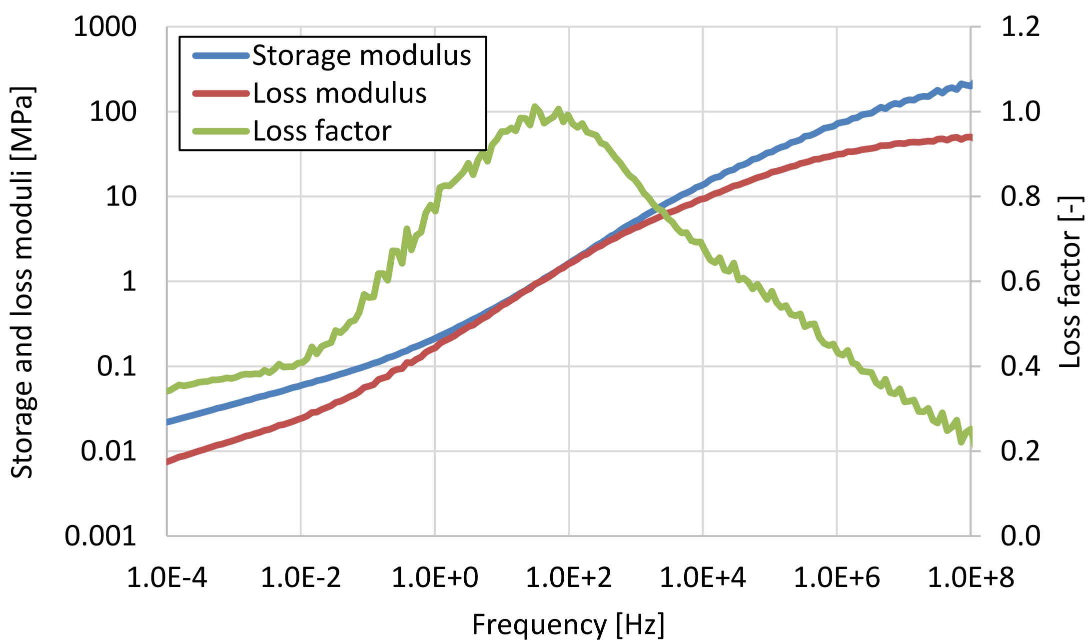

Figure 6. DMA frequency sweep

System level damping measurement

While the damping properties of the adhesive can be measured using DMA on a material level, the Power Injection Method (PIM) is used to measure these properties on a system level for a quadratic steel plate, as shown in Figure 7 [1]. Unlike traditional Oberst beam configurations [2], the two-dimensional structure investigated here undergoes deformations similar to those observed in automotive, railway, and appliance applications, and frequency-resolved measurements prove especially advantageous when evaluating multilayer damping materials with frequency-dependent performance.

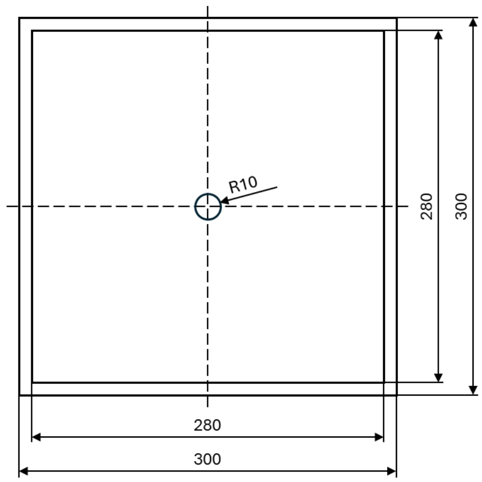

Figure 7. Specimen geometry (units: mm)

A 0.8 mm thick steel plate measuring 300 mm × 300 mm serves as the base layer. The constrained layer damper consists of a viscoelastic adhesive combined with a constraining layer of varying thickness, centrally applied over a 280 mm × 280 mm area with a 20 mm diameter hole for shaker fixation. The viscoelastic layer is comprised of acrylic foam tape (mass density 720 kg/m³) available in several thicknesses, i.e. 0.13 mm (AFT-013), 0.6 mm (AFT-060), 1.1 mm (AFT-110), 1.6 mm (AFT-160), 2.3 mm (AFT-230), 3.5 mm (AFT-350) and 5.0 mm (AFT-500). Constraining layers are fabricated from either aluminum (Young's modulus 70 GPa, mass density 2700 kg/m³) or stainless steel (Young's modulus 210 GPa, mass density 8030 kg/m³).

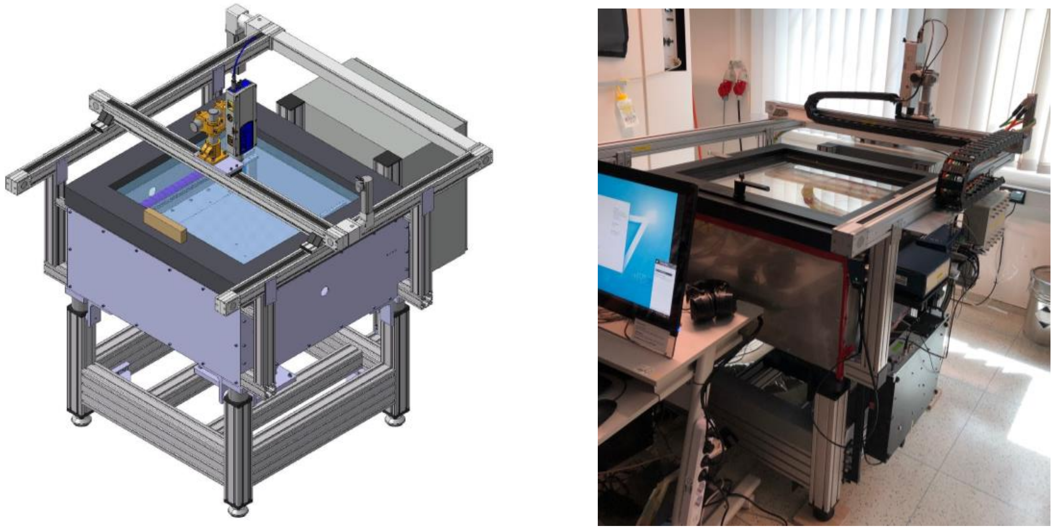

Figure 8. Schematic image of the Power Injection Method (PIM) test setup (left) and real photo of the device in the lab (right) [3]

The experimental equipment is shown in Figure 8, and its implementation is further explained in [3]. Test samples were secured at their corners using pneumatically controlled clamps, while vibrational excitation was provided by a centrally mounted shaker located beneath the test chamber, see Figure 9. Vibrations on the upper surface were captured by a laser vibrometer that traverses the specimen's surface, ensuring full-field displacement measurements. In parallel, an impedance gauge head measured shaker-induced forces and accelerations, and responses from both instruments were compared to validate the measurements. Experiments span a frequency range from 10 Hz to either 1000 or 2000 Hz, with a resolution of 2 Hz. Controlled environmental conditions are maintained at an ambient temperature of 23 °C and 50% relative humidity.

Finite element model

A finite element model (FEM) was developed using Abaqus, incorporating steady-state dynamics analysis. Pinned boundary conditions applied in each corner with 10 mm distance to the edges, restrict translational displacements while permitting rotations, and a tie constraint accurately represents the bonding between layers. The plate and constraining layer are modeled with linear elastic behavior using shell elements with 5 integration points over the thickness, reduced integration and hourglass control. For the adhesive, viscoelastic behavior is defined using solid elements with reduced integration and hourglass control. Mesh size was determined based on a convergence study. The final mesh is shown in Figure 10. A summary of the modeling details is given in Table 1.

Table 1. Overview of modeling details

	Base layer	Viscoelastic layer	Constraining layer
Material	Steel	Acrylic Foam Tape	Aluminum/steel
Material model	Linear elasticity	Viscoelasticity	Linear elasticity
Element type	Shell (S4R)	Solid (C3D8R)	Shell (S4R)

The system loss factor

$$\eta_{\text{sys}} = \frac{P_{\text{in}}}{E_{\text{tot}} \cdot \omega} = \frac{F \cdot v^*}{2\,\omega\,(E_{\text{strain}} + E_{\text{kin}})}$$

describes the damping properties of a system and is defined as the ratio of power that is put into the system to the total energy put into the system per time, i.e. the higher this value, the better the damping.

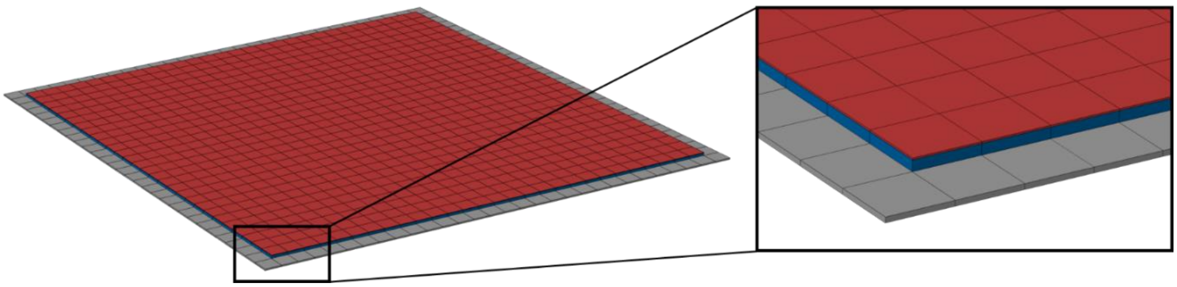

Figure 9. Finite Element Model (shell elements are shown with real thickness)

Model validation

Validation of the numerical model was achieved by comparing simulated results with experimental data obtained using an alternative acrylic foam tape. Direct measurement of the system loss factor is challenging; therefore, the acceleration at the point of loading serves as the basis for comparison, with absolute values presented to facilitate logarithmic visualization (see Figures 11 and 12). Experimental analysis reveals that the damped plate follows the general trend of the undamped configuration, with peak accelerations reduced by up to two orders of magnitude. Although steel substrates typically exhibit negligible damping in practical applications, simulations of undamped steel plates tend to overestimate accelerations due to the assumption of dissipation-free, linear elastic behavior. The frequencies of local maxima are predicted accurately. Discrepancies arise from both experimental factors (e.g., imperfect bonding and geometric tolerances) and simulation aspects (e.g., inaccuracies in the viscoelastic loss factor model or noise in DMA data).

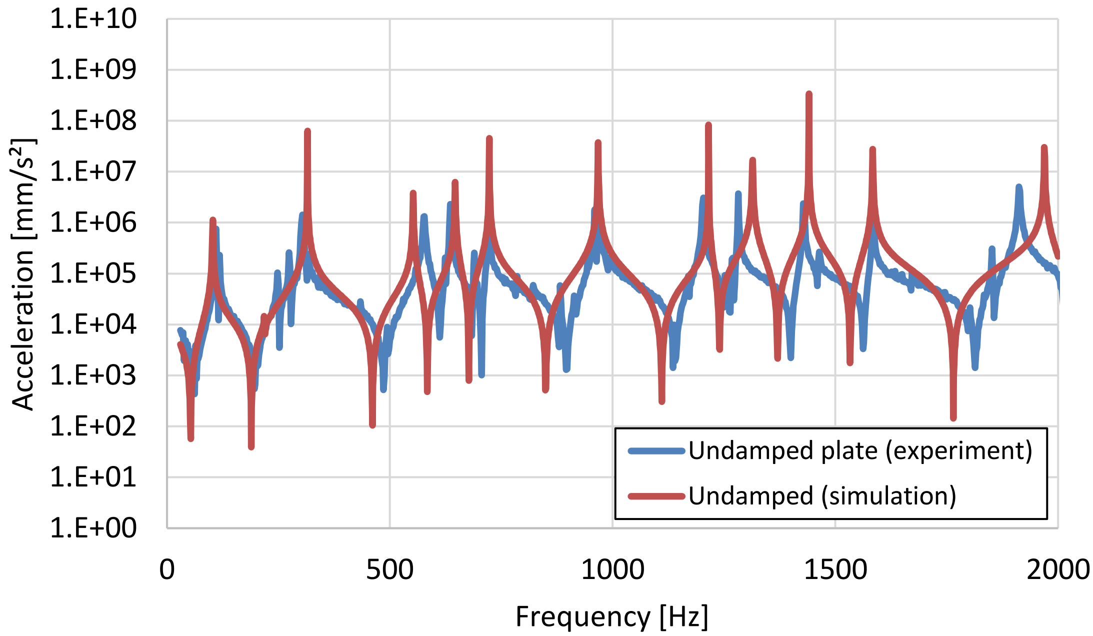

Figure 11. Experiment and simulation results of undamped steel plate

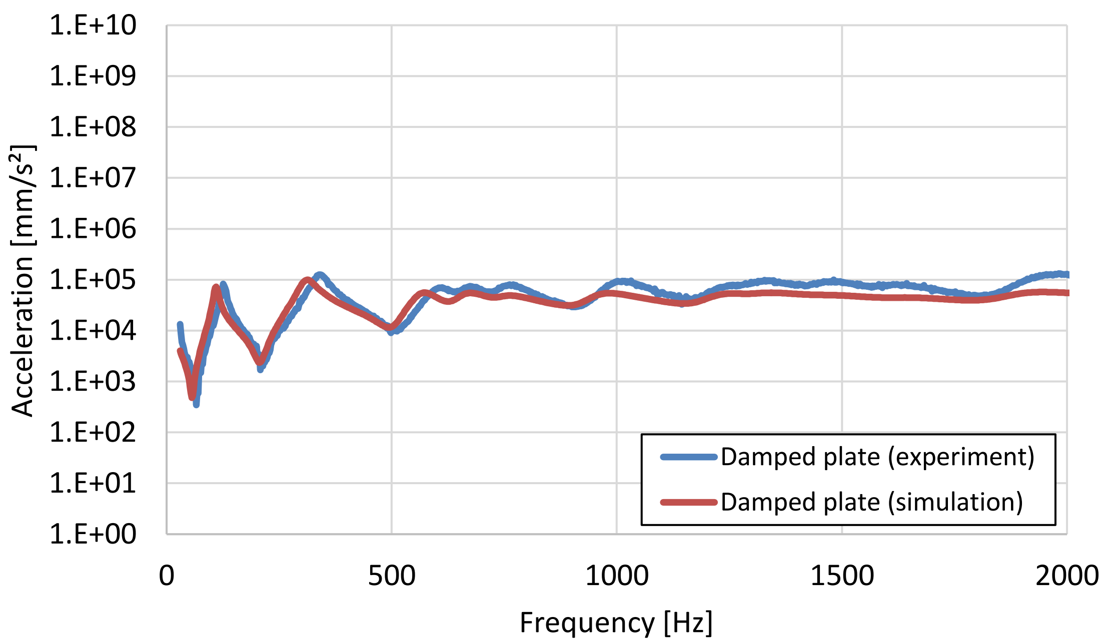

Figure 12. Experiment and simulation results of damped steel plate

Parameter study

Simulations were conducted to investigate the response of the damped plate, focusing on the overall system loss factor as a representative metric of damping performance. Given the importance of mass in automotive, aerospace, and rail applications, damping performance is also evaluated per specific mass, defined as the mass of the damping tape (adhesive plus constraining layer) per unit area.

Influence of tape thickness

Figure 13 illustrates the system loss factor for a constraining layer damper with varying acrylic foam tape thicknesses and constraining layer of 0.25 mm aluminum. Figure 14 shows the average system loss factor and average system loss factor per specific mass for the same damping tapes. The average loss factor over the whole frequency range is used to have a quantity representing the damping over the whole frequency range.
Resonance frequencies, associated with high deformations and energy dissipation, yield increased system loss factors at approximately 30, 150 to 200 and 350 to 450 Hz. Towards higher frequencies, damping decreases with increasing frequency. This reflects the material's intrinsic loss factor declining from approximately 1.0 at 10 Hz to 0.8 at 1000 Hz. Although a thicker tape enhances energy dissipation, the rate of improvement decreases at higher thicknesses. Best damping performance per specific mass is achieved with tape thickness between 0.6 and 1.6 mm for an aluminum constraining layer with 0.25 mm thickness.

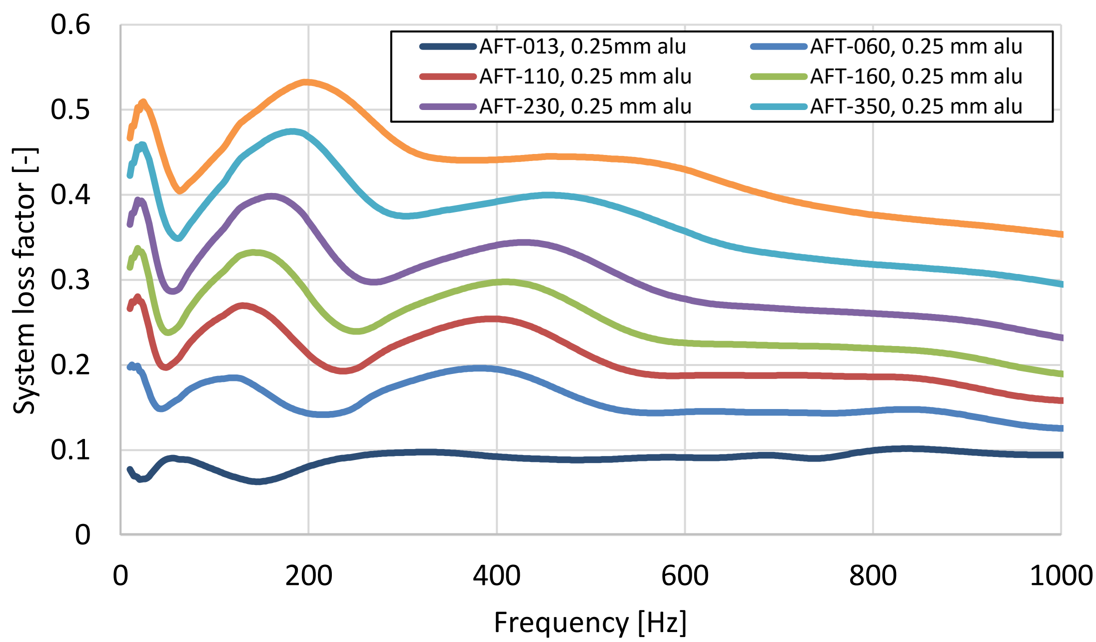

Figure 13. Simulation response of system loss factor for a constraining layer damper with varying acrylic foam tape thicknesses and constraining layer of 0.25 mm aluminum (alu)

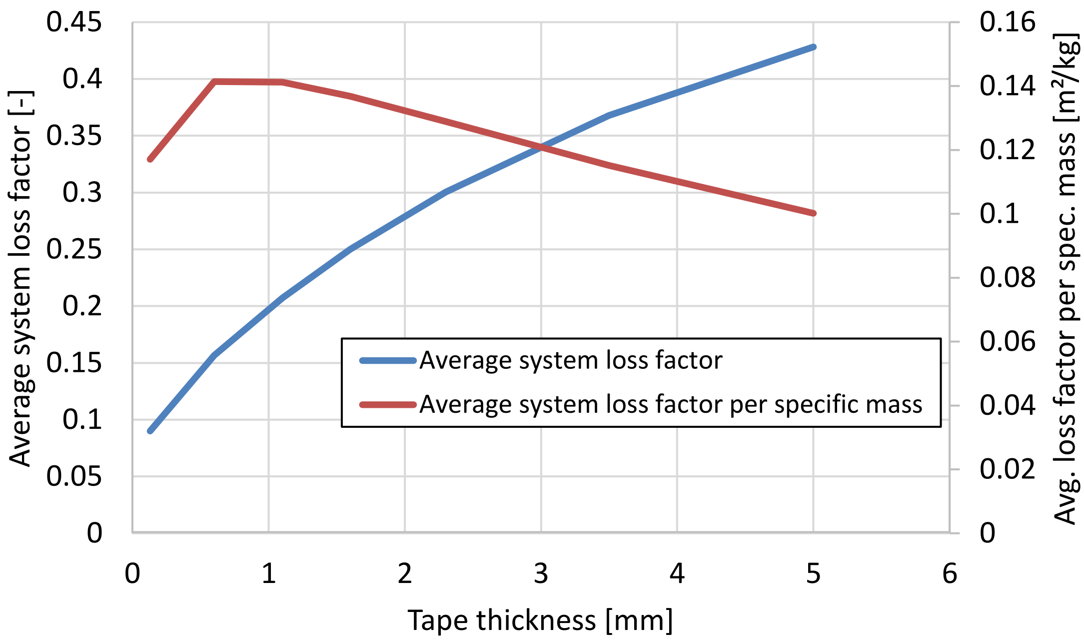

Figure 14. Simulation response of average system loss factor and average system loss factor per specific mass for a constrained layer damper with varying tape thickness and constraining layer of 0.25 mm aluminum

Influence of constraining layer stiffness and thickness

The constraining layer's primary role is to induce shear stresses within the viscoelastic layer, a requirement for effective energy dissipation. Its stiffness may be adjusted by altering either its thickness or material properties. In this study, aluminum and steel were chosen for their availability and favorable stiffness-to-mass ratios. Enhancements in stiffness improve the system loss factor until a saturation point is reached – approximately 1.0 mm for aluminum and 0.5 mm for steel – beyond which additional stiffness yields negligible improvements. Although both materials can achieve similar loss factors, aluminum offers a superior loss factor-to-specific-mass ratio.

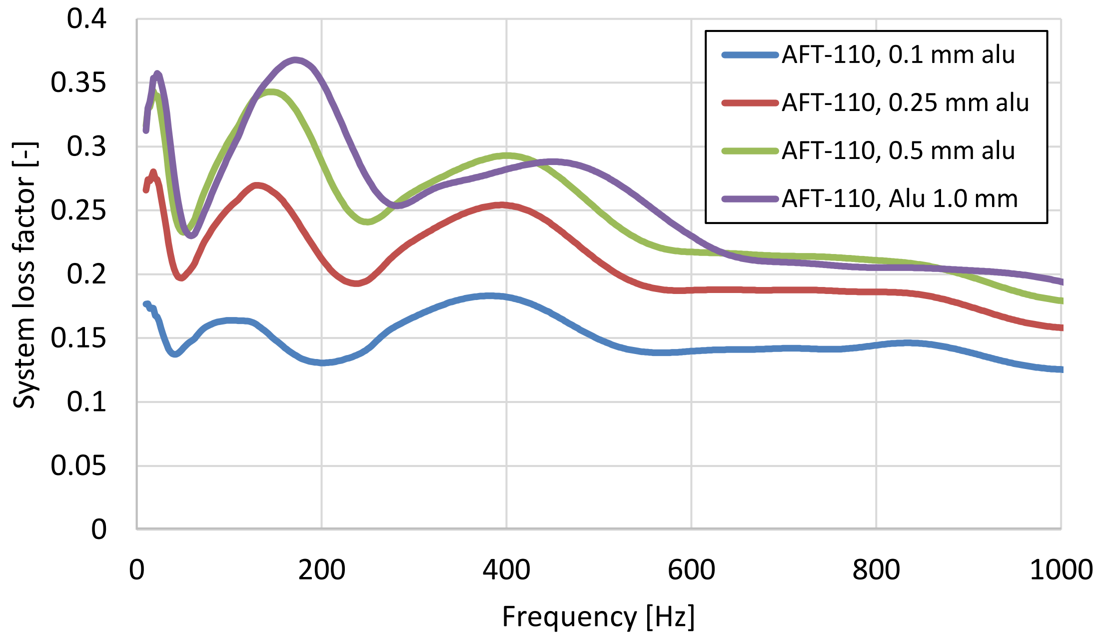

Figure 15. Simulation response of system loss factor for a constraining layer damper with AFT-110 and aluminum constraining layer with varying thicknesses

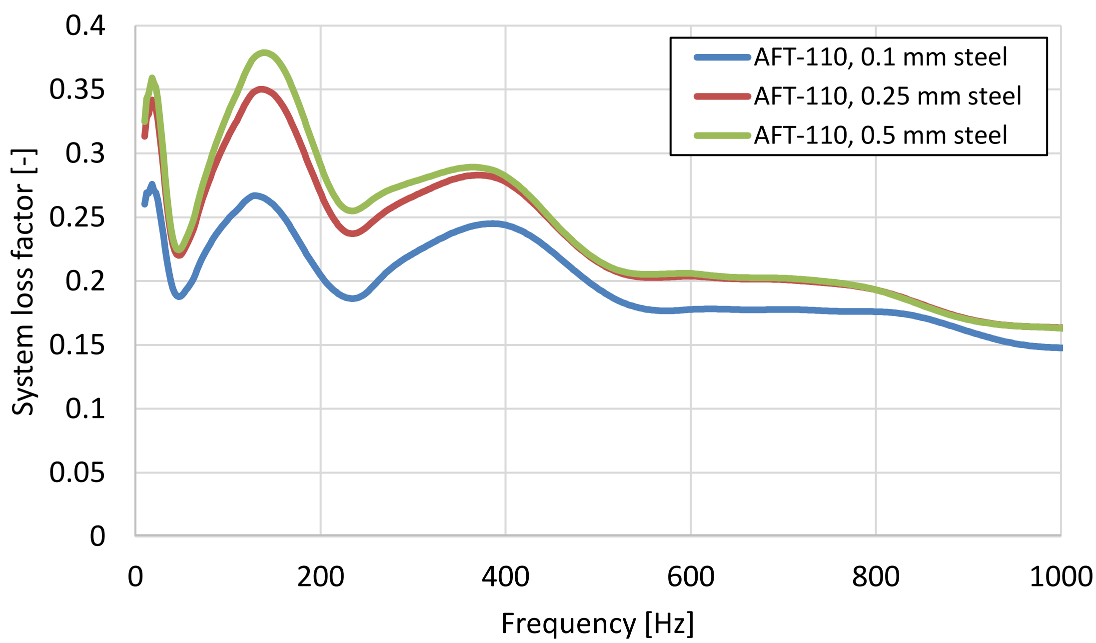

Figure 16. Simulation response of system loss factor for a constraining layer damper with AFT-110 and steel constraining layer with varying thicknesses

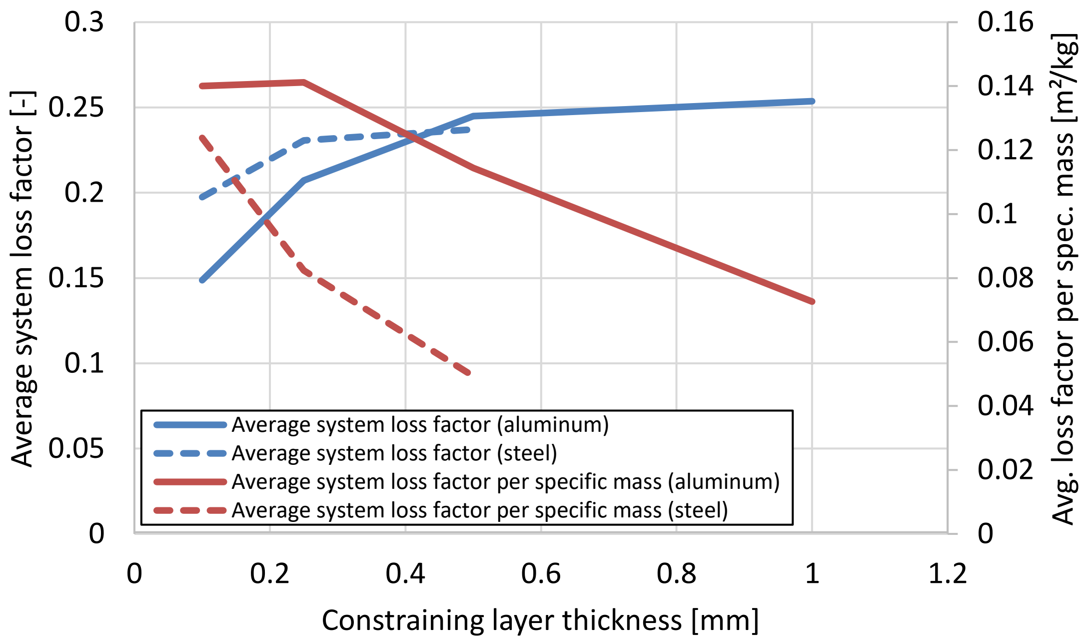

Figure 17. Simulation response of average system loss factor and average system loss factor per specific mass for a constrained layer damper with AFT-110 and different constraining layers

Conclusion

A comprehensive analysis of various damping configurations was conducted, with a particular focus on system loss factors (see Figure 18 and Table 2). Increasing adhesive thickness up to 5 mm enhances the system loss factor, though efficiency decreases with increasing thickness. Similarly, improvements in constraining layer thickness and stiffness yield increased damping until a saturation threshold is reached. The highest damping performance per specific weight was observed for viscoelastic layer thicknesses between 0.6 and 1.6 mm combined with aluminum constraining layers of 0.1 to 0.25 mm. For instance, an AFT-110 configuration with a 0.25 mm aluminum layer exhibits comparable damping properties to an AFT-060 configuration with a 0.5 mm aluminum layer, while offering a reduced specific mass. Likewise, AFT-160 with a 0.25 mm aluminum layer provides a weight-efficient alternative to AFT-110 with a 0.5 mm aluminum layer.

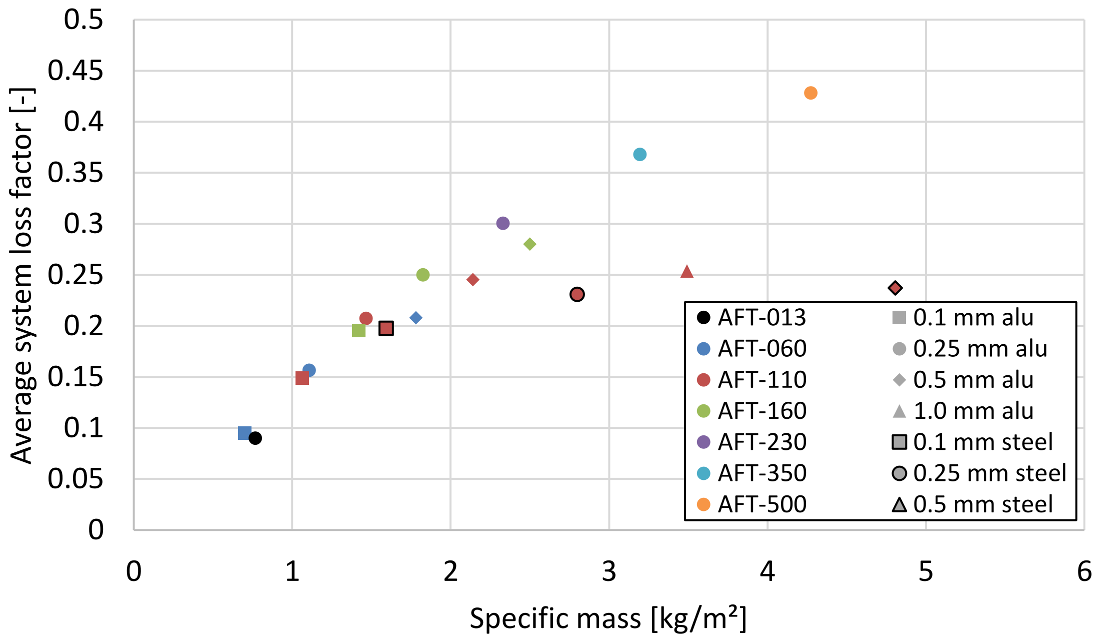

Figure 18. Overview of all constrained layer damper compositions that have been analyzed within this work

Table 2. Overview of all constrained layer damper compositions that have been analyzed within this work

Damping tape	**Average system loss factor [-]**	**Specific mass [kg/m²]**	**Avg. loss factor per specific mass [m²/kg]**
AFT-013, 0.25mm alu	0.090	0.769	0.117
AFT-060, 0.1 mm alu	0.095	0.702	0.135
AFT-060, 0.25 mm alu	0.156	1.107	0.141
AFT-060, 0.5 mm alu	0.208	1.782	0.117
AFT-110, 0.1 mm alu	0.149	1.062	0.140
AFT-110, 0.25 mm alu	0.207	1.467	0.141
AFT-110, 0.5 mm alu	0.245	2.142	0.114
AFT-110, 1.0 mm alu	0.254	3.492	0.073
AFT-110, 0.1 mm steel	0.197	1.595	0.123
AFT-110, 0.25 mm steel	0.231	2.800	0.082
AFT-110, 0.5 mm steel	0.237	4.807	0.049
AFT-160, 0.1 mm alu	0.195	1.422	0.137
AFT-160, 0.25 mm alu	0.250	1.827	0.137
AFT-160, 0.5 mm alu	0.280	2.502	0.112
AFT-230, 0.25 mm alu	0.300	2.331	0.129
AFT-350, 0.25 mm alu	0.368	3.195	0.115
AFT-500, 0.25 mm alu	0.428	4.275	0.100

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