Chapter 5

Smart Damping Test Results and Benefits

This chapter presents the results of the tests conducted on the vibrations and acoustics test stand described in Chapter 3. The purpose of this chapter is to present and compare the vibration and structure-borne acoustic test results for a plate with and without smart damping. This chapter also discusses the benefits of smart materials when added to existing damping materials, as well as the weight benefits due to smart damping. The tests were designed to compare the smart damping materials with existing damping in terms of vibration and structure-borne noise reduction.

Figure 5.1 illustrates the different test plate configurations used to evaluate the benefits of smart damping. The 'undamped plate,' which is untreated, is the standard plate that was used for the baseline test. The 'shunted plate' refers to the undamped plate with shunted PZTs. As such, the 'unshunted plate' is the undamped plate with PZTs attached to it, but without the shunt circuits. Sections 5.1 and 5.2 compare the undamped plate to the shunted and unshunted plates. The 'damped plate' refers to the test plate treated with passive damping materials, while the 'shunted damped plate' is the damped plate with the shunted PZTs. The benefits of adding shunted PZTs to damped plates are investigated in Sections 5.3 and 5.4. Section 5.4 compares the shunted plate to multiple damped plates to assess the damping benefits of smart materials with respect to added weight.

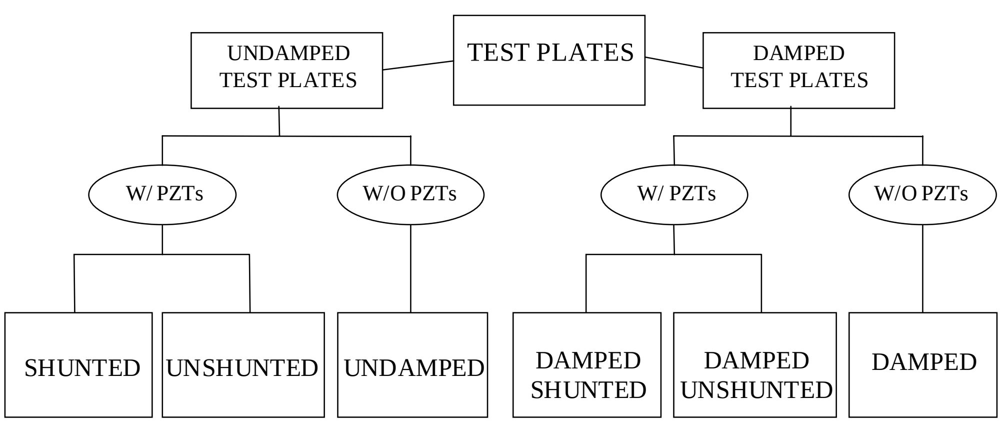


Figure 5.1. Test Plate Configurations Used to Evaluate the Benefits of Smart Damping

5.1 Vibration Benefits of Smart Damping for Undamped Plates

Once the smart damping plate was constructed, initial tests were performed on the shunted and unshunted plates. The shunt circuits were then tuned, as described in Chapter 2, to the resonant frequencies between 50 and 450 Hz for the unshunted plate. Figure 5.2 illustrates the effect of the tuned shunt circuits on the plate vibration response. Peaks 3, 4, and 5 were the most significantly reduced for the shunted plate.

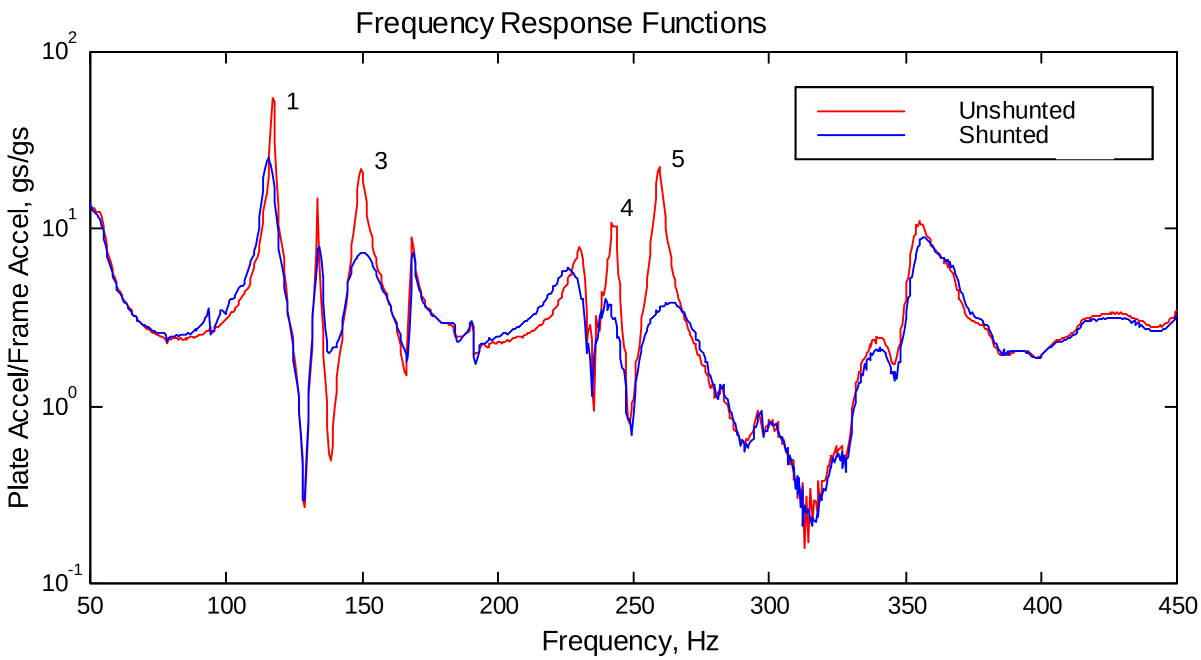


Figure 5.2. Unshunted and Shunted Plate Vibration Response

Before comparing the shunted and undamped plate responses, it is important to first demonstrate how the frequency response of the undamped plate was altered due to the application of the smart materials. As such, the vibration test results for the undamped and unshunted plates are presented in Figure 5.3. The addition of the PZTs caused a shift in some of the resonant frequencies of the unshunted plate, as is particularly evident for peak 1 which is shifted up by approximately 15 Hz. This shift is caused by the structural effects of PZTs, such as adding bending stiffness and slight mass loading.

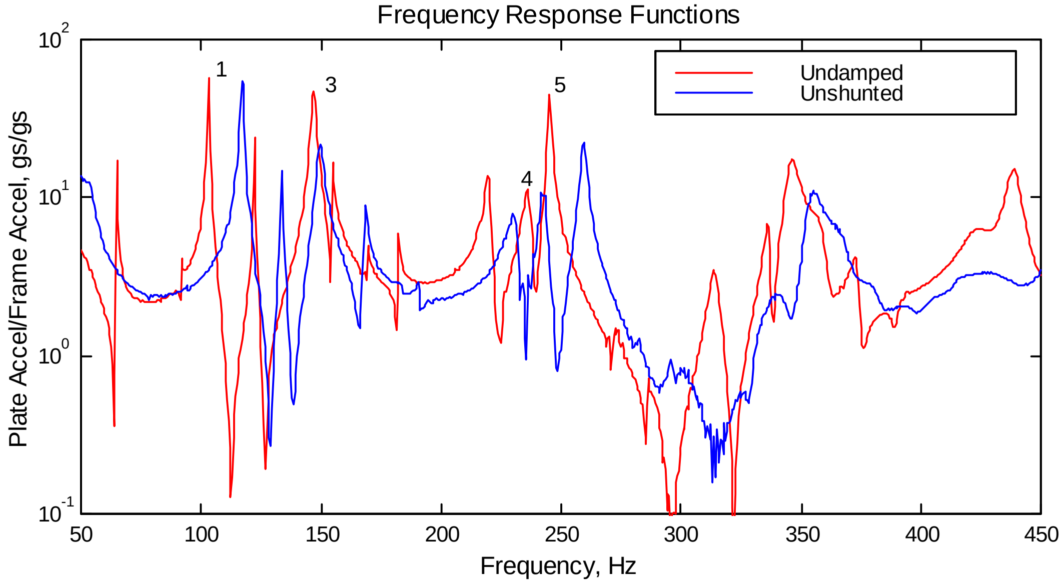


Figure 5.3. Effect of Adding Smart Material to an Undamped Plate

The goal of the testing was to determine the total vibration reduction achieved by the application of smart damping. Table 5.1 presents the decreases in the peak accelerations that were obtained using the tuned shunts. The results indicate that the smart damping significantly reduced the four resonant peak vibrations, with the largest reductions achieved for peaks 3 and 5. The results further show that passive smart damping can add substantial damping for narrow-band frequencies by decreasing peak vibrations by up to 22 dB.

Table 5.1. Effect of Smart Damping on Peak Vibrations

Peak	Undamped (g/g)	Shunted PZT (g/g)	Reduction (%)	Reduction (dB)
1 (101 Hz)	57.79	31.84	56.1	5.2
3 (147 Hz)	47.74	7.53	84.6	16.0
4 (235 Hz)	11.28	4.05	64.1	8.9
5 (245 Hz)	47.97	3.87	91.9	21.9

5.1.1 Third-Octave Analysis

Another convenient method to assess the benefits of smart damping materials is to evaluate their broadband performance using a third-octave band analysis. For the vibration data, 1/3-octave values were determined for each center frequency according to

$$dB(\frac{1}{3}Octave) = 10\log\left[\sum_{n=i}^{j}\left(\frac{Plate\ Acceleration_n}{Frame\ Acceleration_n}\right)^2\right] \quad (5.1)$$

where i and j are the lower and upper third-octave band limits, respectively, and n is the spectral line index. Figure 5.4 shows the vibration response of the shunted and undamped plates, and Figure 5.5 shows the broadband vibration reductions due to smart damping.

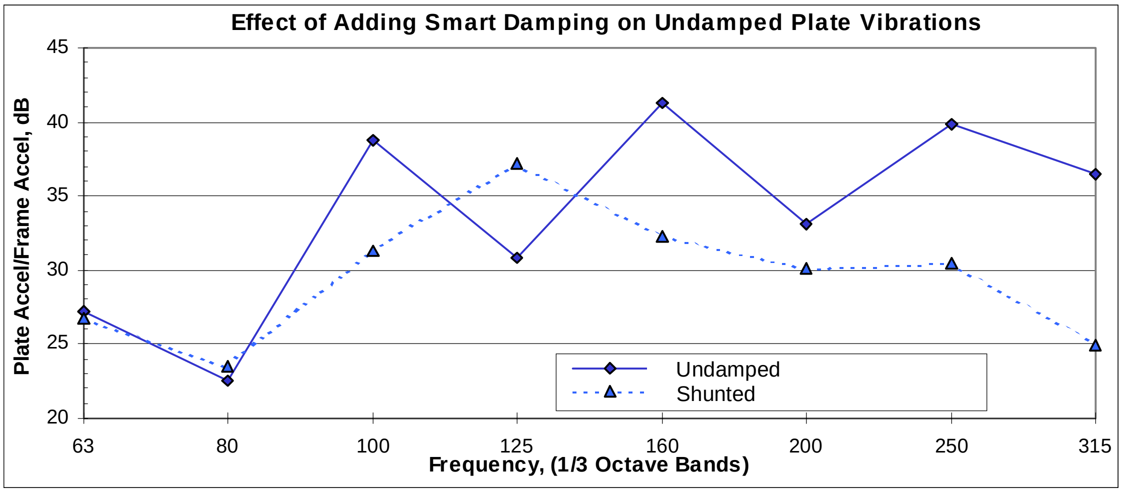


Figure 5.4. Third-Octave Band Analysis of Vibrations for Undamped and Shunted Plates

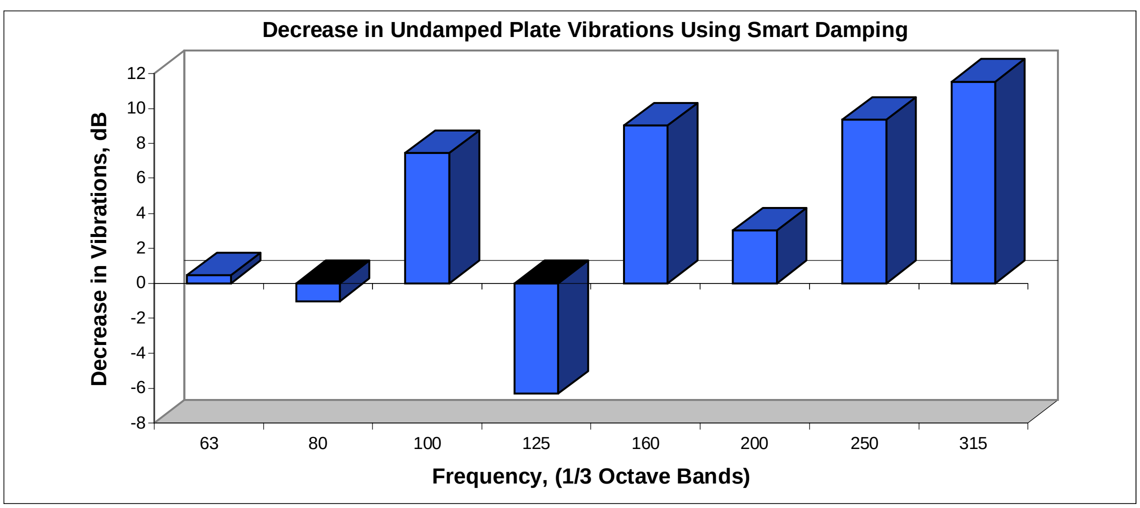


Figure 5.5. Decrease in Undamped Plate Vibrations (Third-Octave Band)

These figures show that smart damping can decrease the 1/3-octave accelerations by up to 11 dB. The accelerations were not reduced in the 125-Hz octave band because this octave band contains peak 2 at 121 Hz. As explained in Chapter 4, this peak was not selected to be damped because it was an even mode and, therefore, an inefficient noise radiator. Another element that contributes to the apparent lack of vibration reduction in this band is the stiffening effect of the PZTs, as discussed in Section 5.1. As shown in Figure 5.3, peak 1 for the undamped plate occurs at 101 Hz. When PZTs are applied to the plate, however, this peak occurs at approximately 118 Hz, which is in the 125-Hz 1/3-octave band. For this reason, the levels are higher for the PZT-treated plate in this frequency band as compared to the undamped plate. For the higher peaks, the shift in resonant frequencies is relatively smaller and the frequency bands are wider. Therefore, the higher resonant peaks are not shifted out of the 1/3-octave bands by the addition of PZTs.

The vibration test results show that passive smart damping can effectively reduce vibrations for both narrowband and broadband frequency ranges by reducing acceleration peaks by up to 22 dB, and reducing 1/3-octave values by up to 11 dB.

5.2 Acoustic Benefits of Smart Damping for Undamped Plates

To determine the effect of smart damping on structure-borne noise, the radiated acoustic pressures were first measured for the shunted and unshunted plates and then compared to the undamped plate. The narrowband noise levels are presented here as sound pressure normalized with respect to frame acceleration in Pascals over g's (Pa/g). This normalization is performed in order to account for any frame acceleration changes that occur from one test to another and from the addition or elimination of different materials. Since the frame is excited by a constant force from the shaker, its acceleration changes as the effective mass of the test plate changes.

As shown in Figure 5.6, the noise levels at the four peaks have been significantly reduced with the most reduction occurring at peaks 3, 4, and 5. Figure 5.7 compares the narrowband noise levels for the shunted plate with the undamped plate. The figure clearly shows that there is a substantial reduction in noise levels due to the addition of smart damping. The most significant reduction occurs for peak 5, where the noise levels are reduced by 20.3 dB.

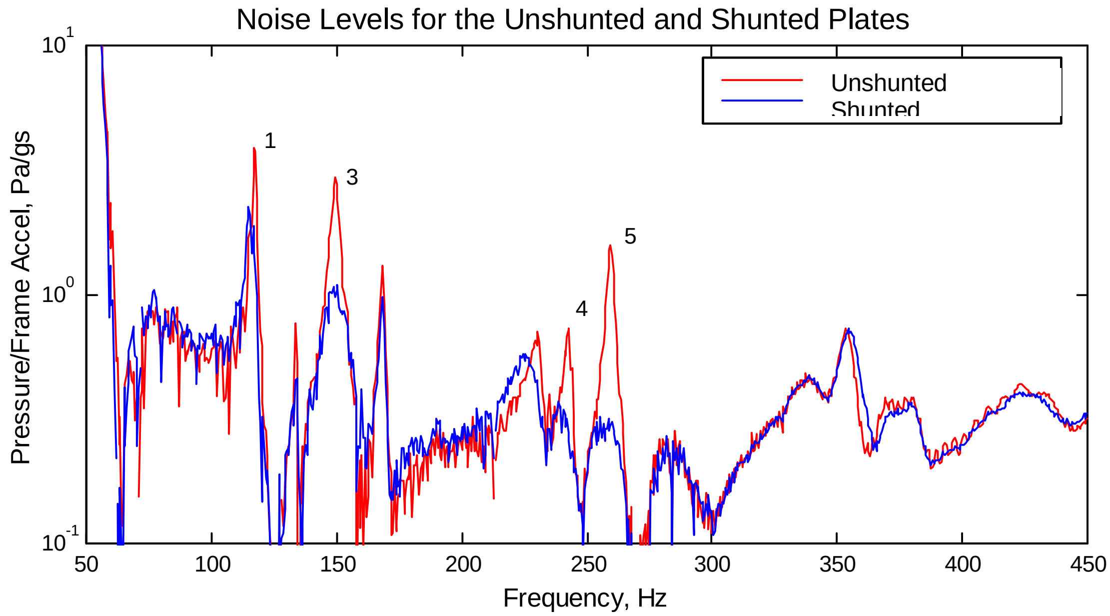


Figure 5.6. Effect of Smart Damping on Structure-Borne Noise for an Undamped Plate

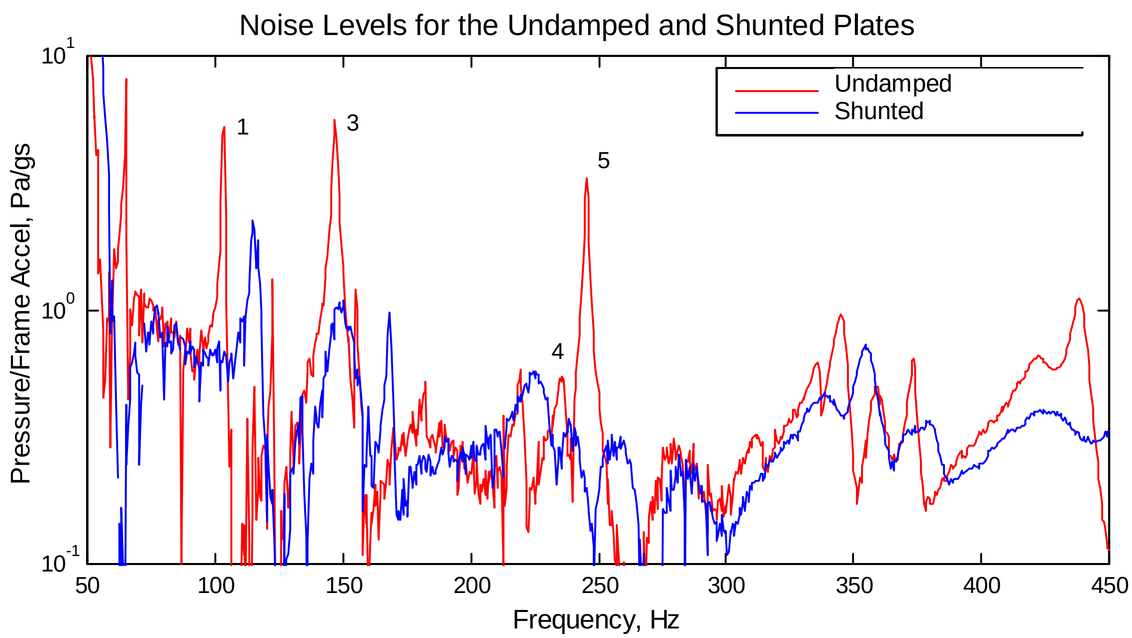


Figure 5.7. Noise Reductions Due to Smart Damping of an Undamped Plate

Table 5.2 presents the decrease in the peak noise levels that were obtained using the tuned shunts. As with the vibration test results, the table indicates that the smart damping significantly reduces the four acoustic peaks, with the most reduction occuring at peaks 3 and 5. The results also show that passive smart damping can add a substantial amount of damping for narrowband frequencies by decreasing peak noise levels by up 20.3 dB, or nearly 90%.

Table 5.2. Normalized Noise Level Reductions Due to Applying Smart Damping to an Undamped Plate

Peak	Undamped (Pa/g)	Shunted PZT (Pa/g)	Reduction (%)	Reduction (dB)*
1 (101 Hz)	5.27	2.26	57.1	7.4
3 (147 Hz)	5.59	1.09	80.5	14.2
4 (235 Hz)	0.55	0.37	32.7	3.4
5 (245 Hz)	3.32	0.32	90.4	20.3

*Note: Decibel scale is determined as $20\log\left(\frac{Undamped\ Acoustic\ Level\ (Pa/g)}{Shunted\ Acoustic\ Level\ (Pa/g)}\right)$

5.2.1 Third-Octave Analysis

As with the vibration test results, a 1/3-octave band analysis was performed on the acoustic test results to assess the broadband acoustic benefits of smart damping materials. For acoustic analysis, it is common to present sound pressure on a decibel scale as

$$L_p = 20\log\left(\frac{P_{rms}}{P_{ref}}\right)(dB) \tag{5.2}$$

where L_p is referred to as the sound pressure level, or SPL, and

$P_{ref} = 20e^{-6}$ Pa [28].

This decibel calculation, which is performed on the microphone pressure measurements of the reception chamber, discounts the mass-loading effect of the added PZTs on the input frame acceleration. This analysis is, therefore, only valid for evaluating the acoustic effects of adding the shunt circuits to the unshunted test plate since the circuits do not load the plate or frame. This analysis has been included here in order to provide a subjective feel for the noise level range occurring in the reception chamber during experimentation.

For the unshunted and shunted acoustic data, third-octave sound pressure levels were determined for each center frequency as

$$L_p(\frac{1}{3}Octave) = 10\log\left[\sum_{n=i}^{j}\left(\frac{P_{rms}}{P_{ref}}\right)^2\right](dB) \qquad (5.3)$$

where i and j are the lower and upper third-octave band limits, respectively, and n is the spectral line index. Figure 5.8 presents the third-octave band analysis performed on the shunted and unshunted PZT plate sound pressure levels. Figure 5.9 represents the decrease in SPLs obtained at each third-octave band. The most SPL reductions of 3 to 5 dB occurred in the 125 Hz, 160 Hz, and 250 Hz third-octave bands. This was to be expected since these are the bands where the shunt circuits were designed to operate. The total sound pressure levels for all 8 third-octave bands were determined to be 61.07 dB and 59.13 dB for the unshunted and shunted test plates, respectively. The total broadband noise reduction achieved with the addition of the shunt circuits was 1.94 dB.

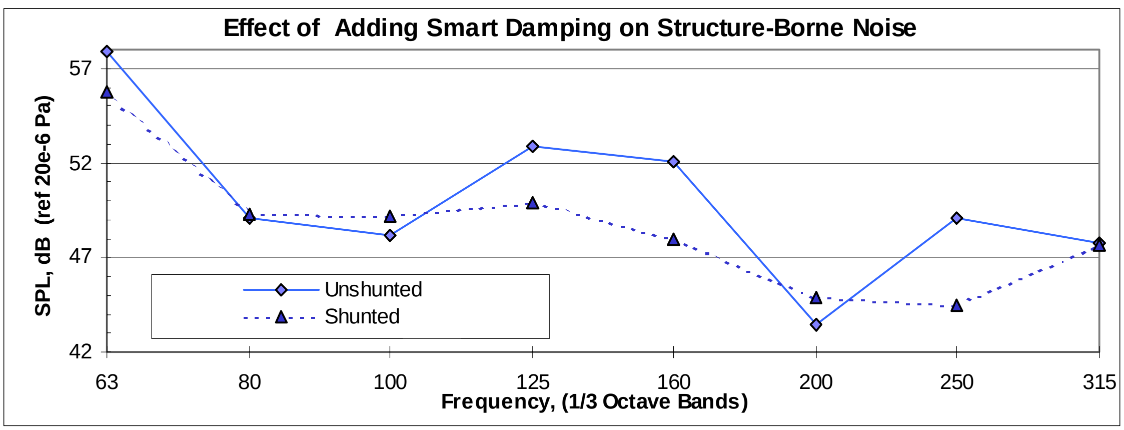


Figure 5.8. Third-Octave Band Analysis of Structure-Borne Noise for an Undamped Plate

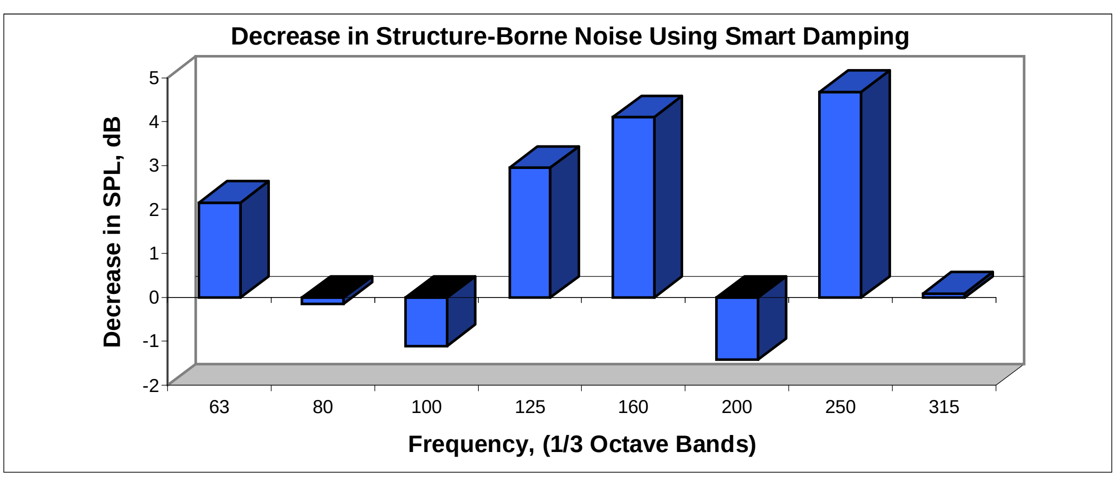


Figure 5.9. Decrease in Structure-Borne Noise for an Undamped Plate (Third-Octave Band)

In order to accurately compare the shunted plate and undamped plate acoustic levels and discount the mass loading effects, the acoustic data must then be presented as acoustic pressure over frame acceleration in Pa/g. Therefore, the new dB scale

$$NSPL = 20\log\left[\frac{Press/Accel_{rms}(Pa/g)}{20e^{-6}{}_{ref}(Pa/g)}\right](dB) \qquad (5.4)$$

was used to perform a third-octave band analysis on the undamped and shunted test data. Figures 5.10 and 5.11 present the third-octave analysis for acoustic levels of the undamped plate and the shunted smart damping plate. It is evident from Figure 5.10 that the addition of smart damping can reduce the NSPL (normalized sound pressure levels) from the test plate by up to 7.9 dB. The smart damping had the most effect in the 160- and 250-Hz third-octave bands. The total NSPLs for all 8 third-octave bands were determined to be 118.04 dB and 114.34 dB for the undamped and shunted test plates, respectively. The total broadband noise reduction achieved with the addition of the smart damping was 3.7 dB.

As with the vibration results presented in the previous section, the increase in NSPLs for the 125-Hz third-octave band is caused by the shift in frequency of peak 2.

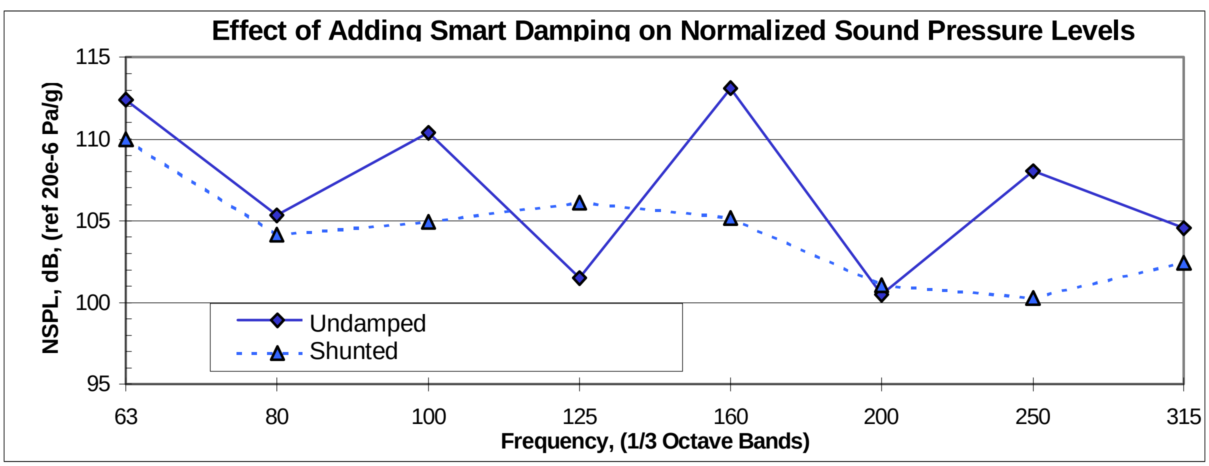


Figure 5.10. Third-Octave Band Analysis for Undamped and Shunted Plates

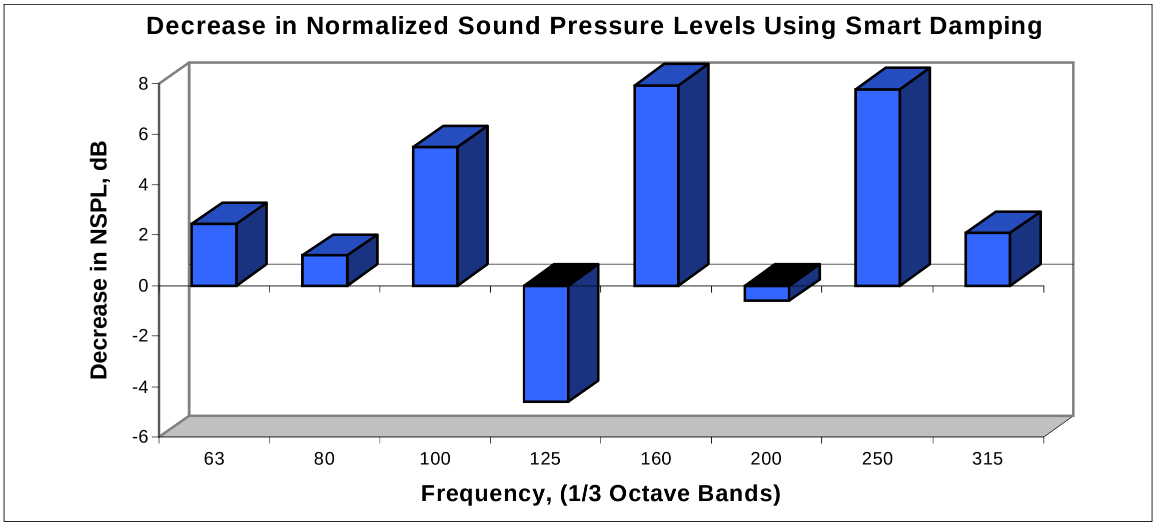


Figure 5.11. Decrease in Acoustic Levels Using Smart Damping

As expected and also shown in Figure 5.12, in each band, the NSPL reductions directly correspond to the vibration reductions which were discussed earlier. Therefore, it can be concluded that smart passive damping of structural vibrations can yield significant reductions in structure-borne noise.

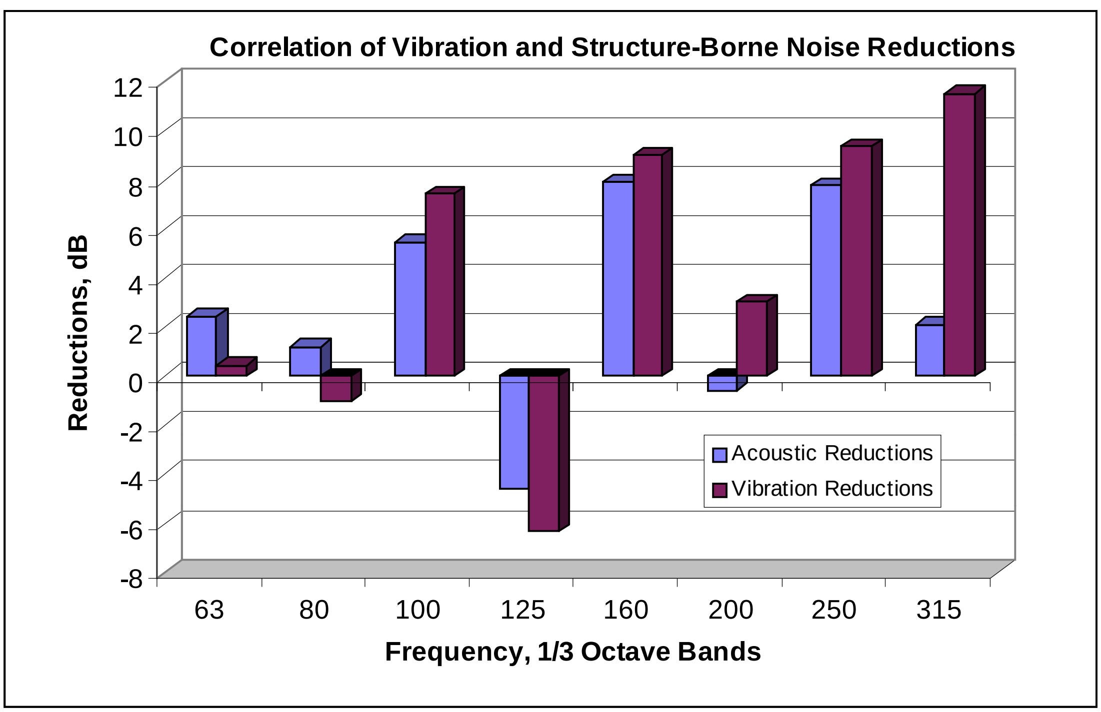


Figure 5.12. Correlation of Plate Vibration Reductions to Structure-Borne Noise Reductions

5.3. Benefits of Smart Damping for Damped Structures

This section investigates the added benefits of applying smart damping when used with conventional passive damping materials. The effect of adding smart damping materials to a plate damped with

- unbacked carpet,
- shoddy and unbacked carpet, and
- shoddy and 0.3 PSF backed carpet

was evaluated. The evaluation was based on comparing the noise and vibration measurements with and without smart damping for each of the above treatments. These treatments, as shown in Figure 5.13, were cut into 400 mm x 500 mm samples that were placed over the test plates. Each material is evaluated by measuring the plate vibrations and emitted noise, similar to the undamped cases.

Shoddy is a foam pad made of interwoven fabric scraps that is placed under the carpeting in vehicles. The backed carpet has a layer of rubber melted onto the carpet to add damping with mass loading. The grade of carpet is measured as pounds per square foot or PSF.

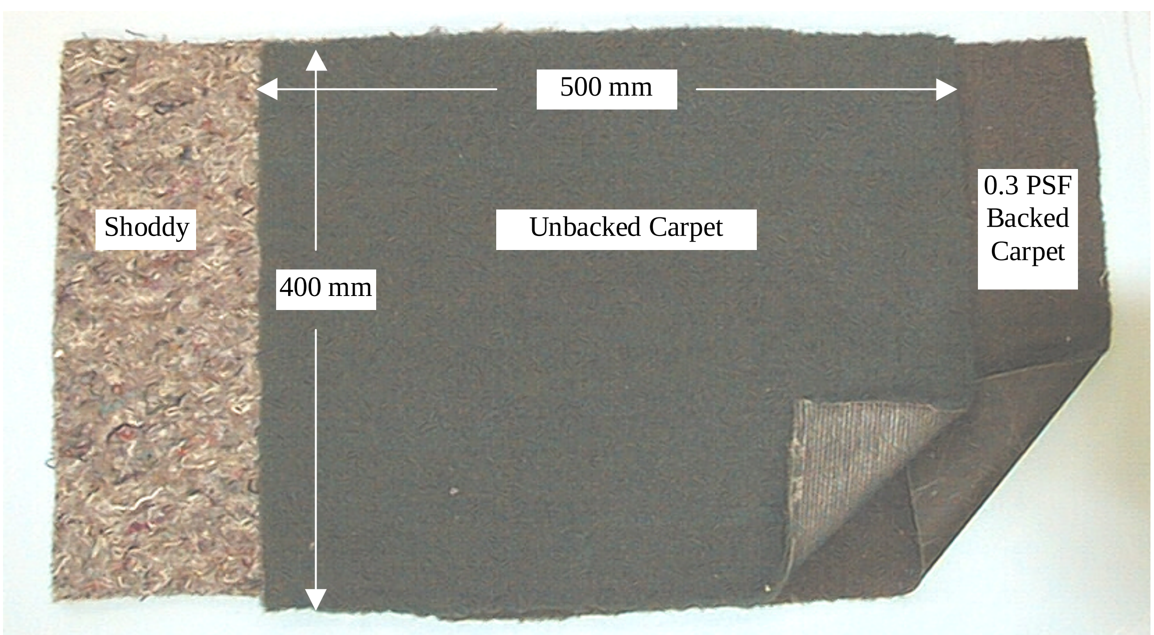


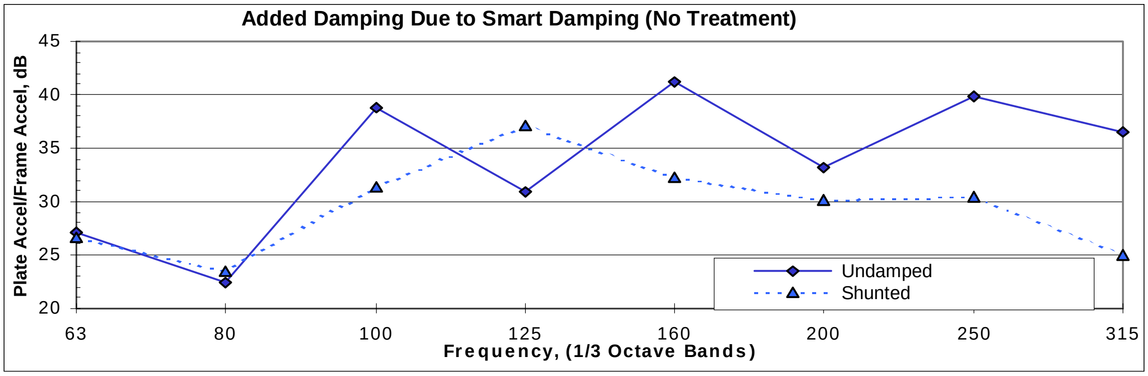
Figure 5.13. Passive Treatments Used with Smart Damping Materials

As was expected, the damping treatments altered the frequency response of the plate which required the shunts to be retuned for each damping case. Once the shunt circuits were optimized, the three different treatments were tested for both the shunted plate and the undamped plate. The augmenting vibration benefits of PZTs are presented first followed by the acoustic benefits.

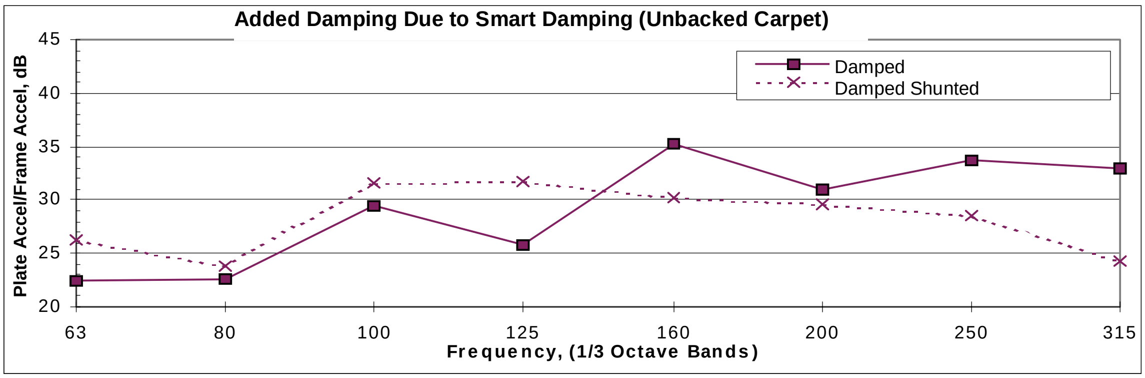
5.3.1 Vibration Benefits of Adding Smart Damping to Damped Structures

The third-octave analysis of the vibration responses of the undamped and smart damping plates with the different damping treatments is presented in Figure 5.14. Figure 5.15 shows the vibration reductions achieved for each third-octave band using smart damping. The test results for the smart damping plate and the undamped plate without treatment have been included in these figures to illustrate the baseline test results obtained in the previous section.

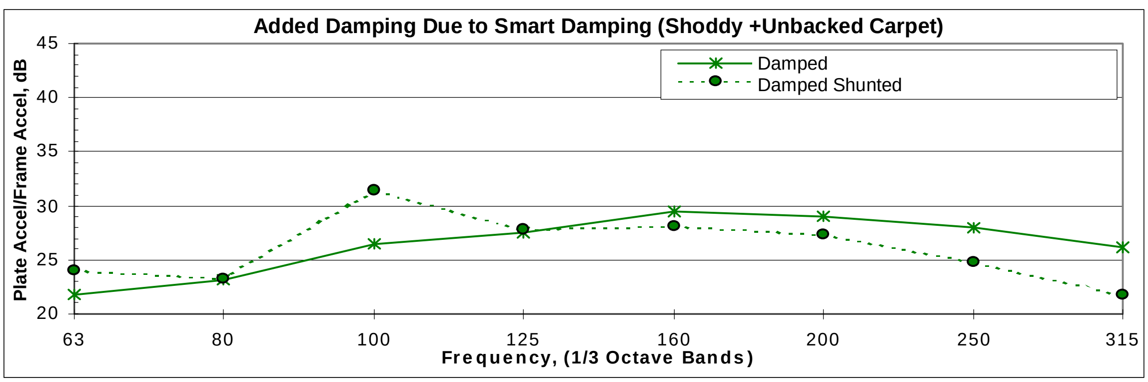
It is evident in Figures 5.14 and 5.15 that the smart damping has the most effect on accelerations above 125 Hz. It is also noted that the PZTs add less additional damping as the amount of treatment increases and the vibrations decrease. For the unbacked carpet case, there is no decrease in vibrations at 125 Hz due to the same reasons mentioned in the baseline test results. In the 100-Hz third-octave band, it appears that the addition of the treatments has little effect on the smart damping plate vibrations as compared to the undamped plate. When the treatments are tested with the smart damping plate, they are laid over the PZTs, the copper tabbing, and the wiring. This yields a poor contact between the treatment and the plate, and therefore reduces the vibration damping benefits of the treatments.



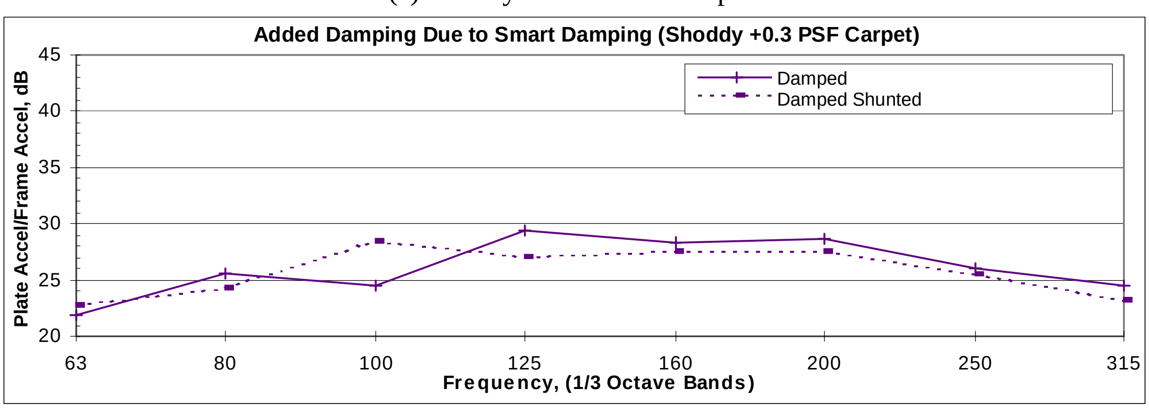
(a) No Treatment



(b) Unbacked Carpet

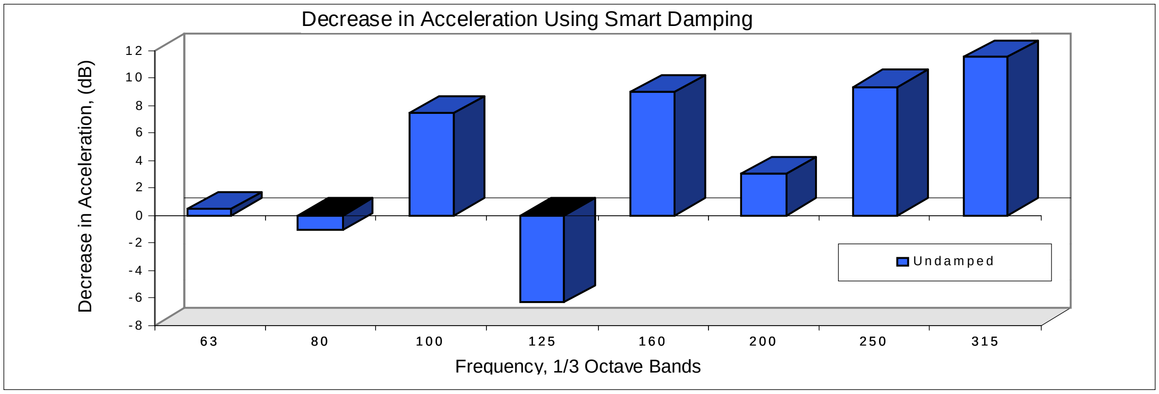


(c) Shoddy + Unbacked Carpet

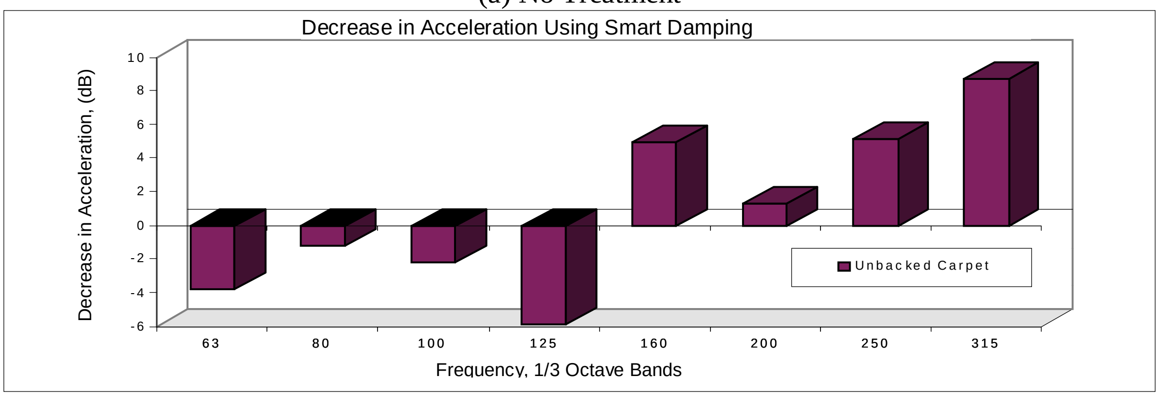


(d) Shoddy + 0.3 PSF Carpet

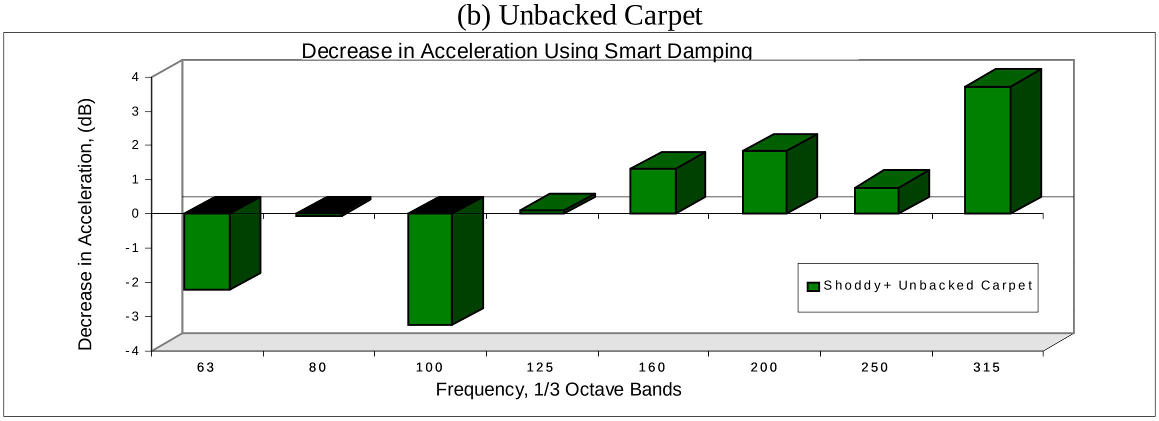
Figure 5.14. Vibration Benefits of Smart Damping Materials for a Damped Plate



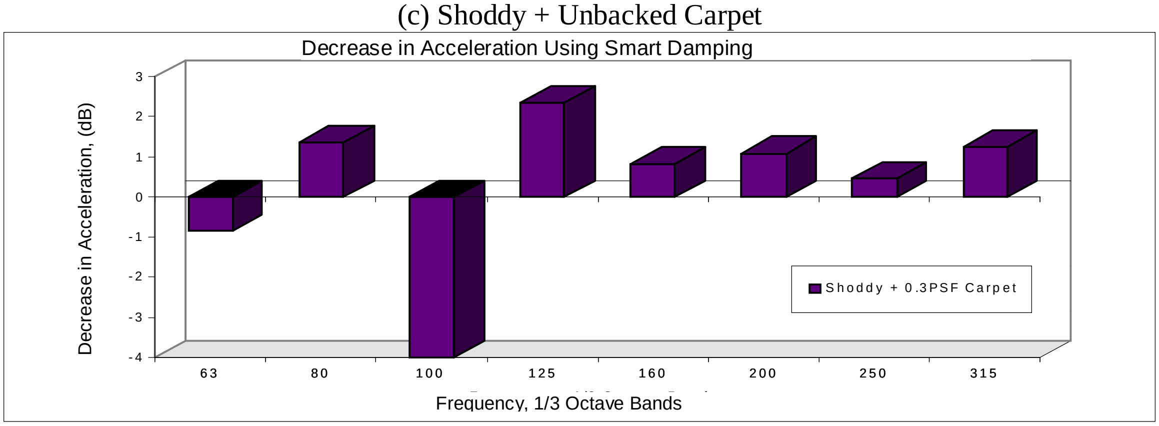
(a) No Treatment



(b) Unbacked Carpet



(c) Shoddy + Unbacked Carpet



(d) Shoddy + 0.3 PSF Carpet

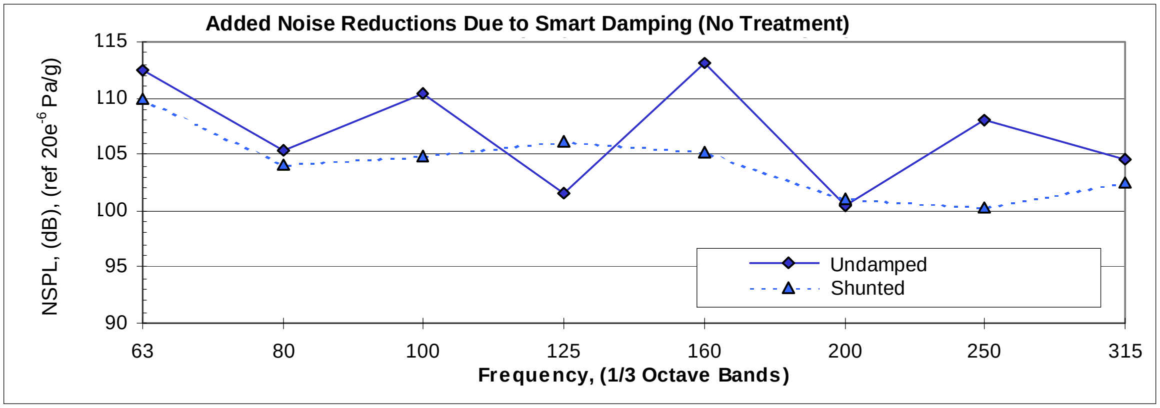
Figure 5.15. Vibration Decrease due to Smart Damping Materials Applied to a Damped Plate

5.3.2 Acoustic Benefits of Adding Smart Damping to Damped Structures

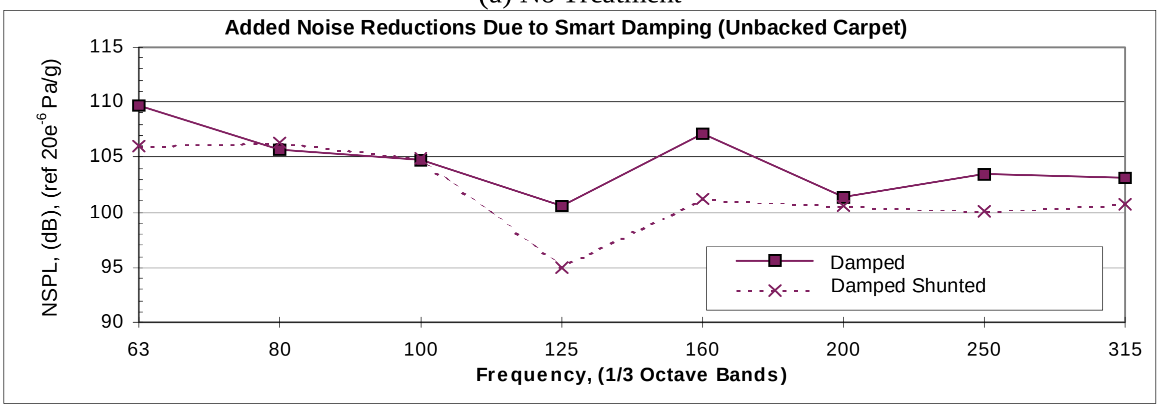
A third-octave analysis, using the decibel scale in Equation (5.2), was performed on the sound pressure measurements of the undamped and smart damping plates with the different damping treatments. These results are presented in Figure 5.16. Figure 5.17 shows the NSPL reductions achieved for each third-octave band using smart damping. The test results for the smart damping plate and the undamped plate without treatment have been included in these figures to illustrate the baseline test results obtained in the previous section.

These results show that smart damping has the most added damping effect for the 160- and 250-Hz third-octave bands. As with the vibration analysis, it is also evident that the PZTs add less noise reduction as the amount of treatment increases. It is noted that the addition of shoddy or 0.3 PSF backed carpet has no added effect on the NSPLs for the shunted plate. This is either because of the poor contact with the plate caused by the PZTs or the added stiffness of the PZTs. Further, as addressed in Section 2.1, the negative value at 125 Hz is caused by the shifting of the resonant frequency of peak 1 from the 100-Hz frequency band to the 125-Hz frequency band.

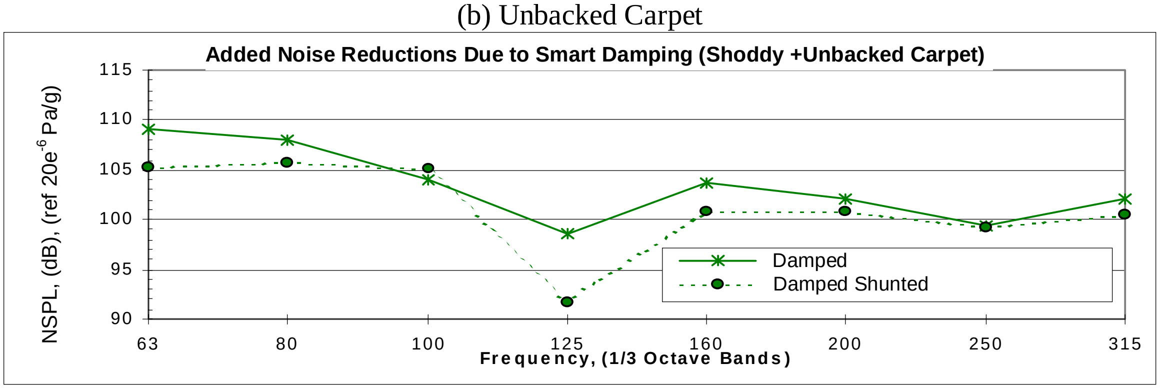
Overall, the damped shunted plate contributes a notable amount of structure-borne noise reduction. For the unbacked carpet case, the smart damping decreases the NSPLs by an average of 2.6 dB. For the plate treated with shoddy and unbacked carpet, the average added reduction is 2.2 dB, and for the shoddy- and-0.3-PSF-damped plate, the average added reduction is 0.9 dB.



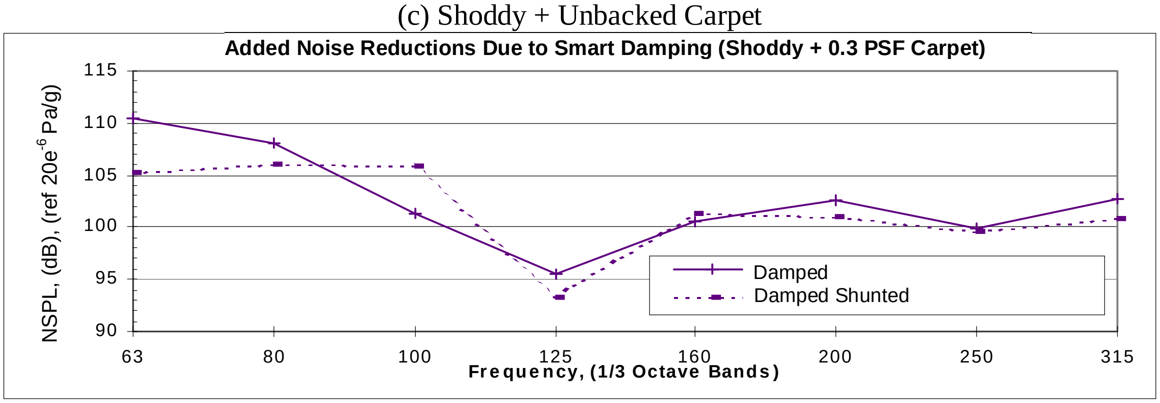
(a) No Treatment



(b) Unbacked Carpet

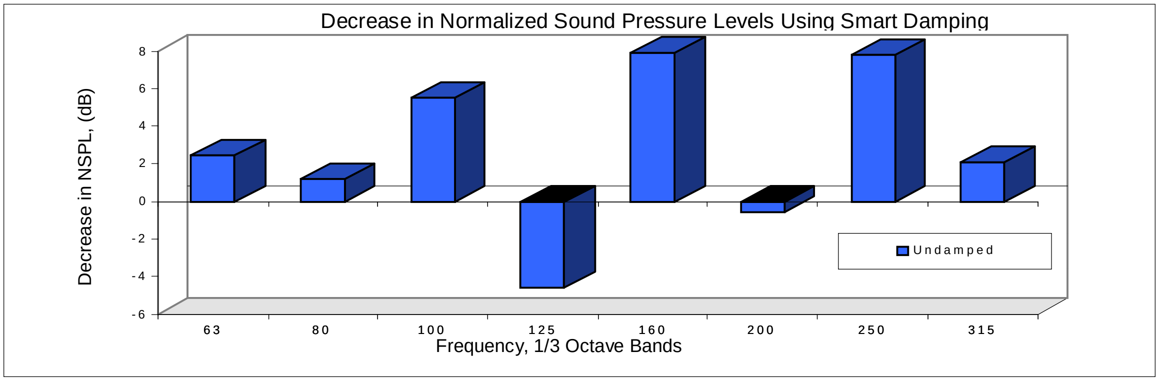


(c) Shoddy + Unbacked Carpet

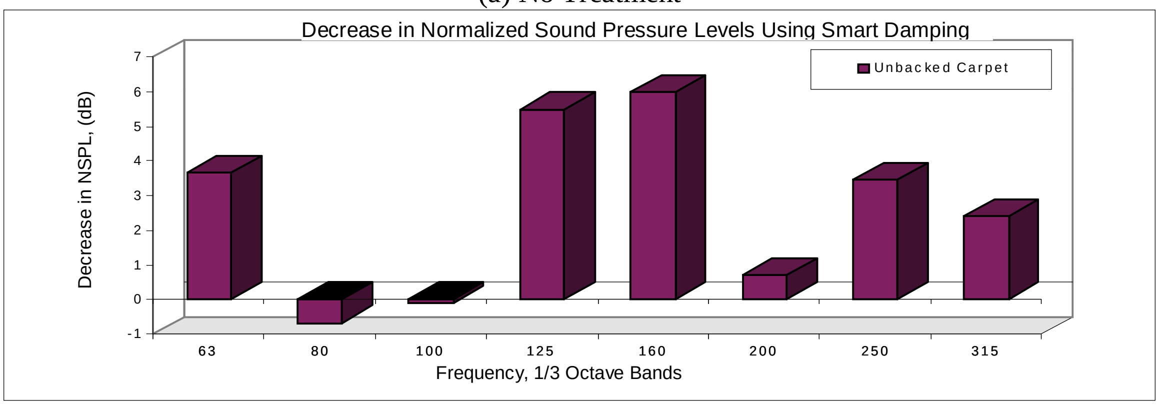


(d) Shoddy + 0.3 PSF Carpet

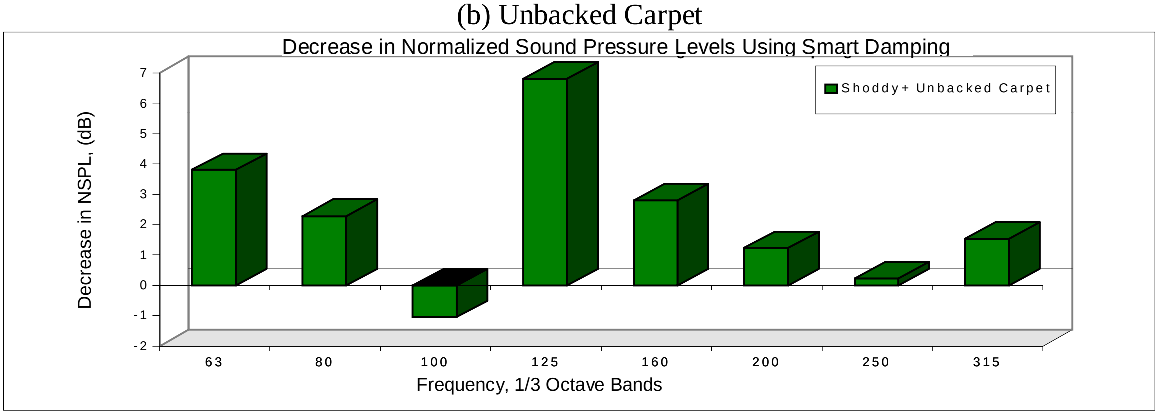
Figure 5.16. Acoustic Benefits of Smart Damping Materials for a Damped Plate



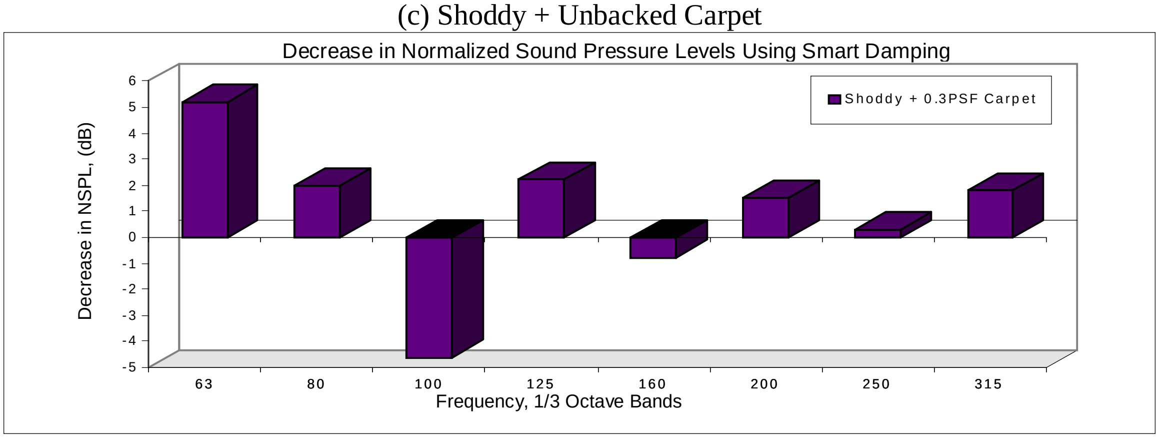
(a) No Treatment



(b) Unbacked Carpet



(c) Shoddy + Unbacked Carpet



(d) Shoddy + 0.3 PSF Carpet

Figure 5.17. Decrease in NSPL due to Smart Damping Materials Applied to a Damped Plate

5.4 Weight Saving Benefits of Smart Damping Materials

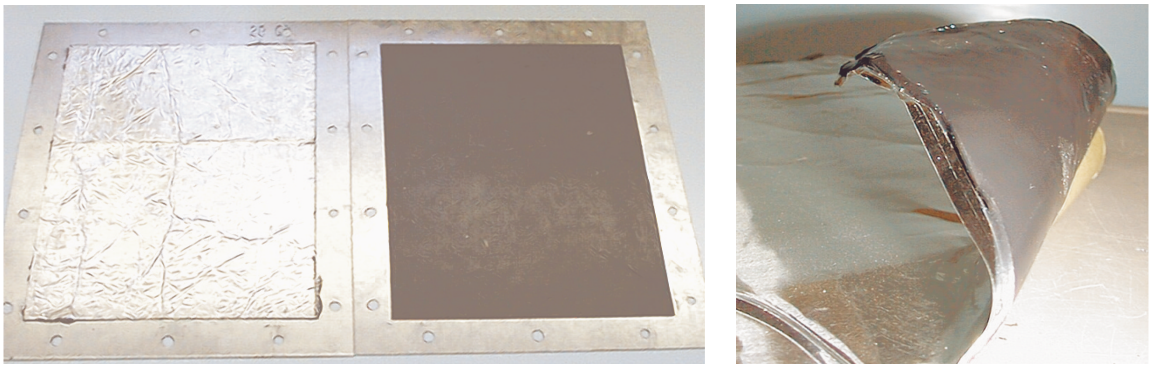
One of the design elements that is often considered in the automotive industry is the weight savings for different vibration and acoustic solutions. For this reason, this section examines the performance of various treatments normalized to the amount of weight they add. To this end, a series of tests were run using eight different combinations of treatments as shown in Table 5.3.

Table 5.3. Different Treatments Tested with Smart Damping

Test #	Viscoelastic Treatments	Foam Pads	Carpeting	Typical Package Type
1	None	No Pad	Unbacked Carpet	Worst
2	None	Shoddy	Unbacked Carpet	Economy
3	None	Shoddy	0.3 PSF Backed Carpet	Mid-size Sedan
4	Asphalt	Shoddy	0.3 PSF Backed Carpet	Family Car
5	Asphalt	2.5 PCF Foam	0.3 PSF Backed Carpet	Sport Utility
6	Asphalt	2.5 PCF Foam	0.3 PSF Backed Carpet	Luxury Sport Utility
7	Constrained Layer (CLD) (Masdamp 755)	2.5 PCF Foam	0.3 PSF Backed Carpet	Luxury Sedan
8	Constrained Layer (CLD) (Masdamp 755)	2.5 PCF Foam	0.7 PSF Backed Carpet	Best

Figure 5.18(a) shows the two types of viscoelastic damping treatments, commonly used in vehicles, that were evaluated for this test. Constrained layer damping, illustrated in Figure 5.18(b), has an aluminum foil backing and a viscoelastic material that is a pressure-sensitive adhesive. The asphalt damping material is the most commonly used treatment in the automotive industry and is either melted onto the surface or attached with contact cement. For this test, the asphalt was attached with contact cement.

Figure 5.19 shows the types of commonly used foam pads and carpeting that were tested to assess the weight-saving benefits of smart damping. These treatments are placed over the different damped plates with the foam padding between the plate and the carpet.



(a) Constrained Layer and Asphalt Damped Plates (b) Constrained Layer Damping

Figure 5.18. Damping Treatments Applied to Test Plates

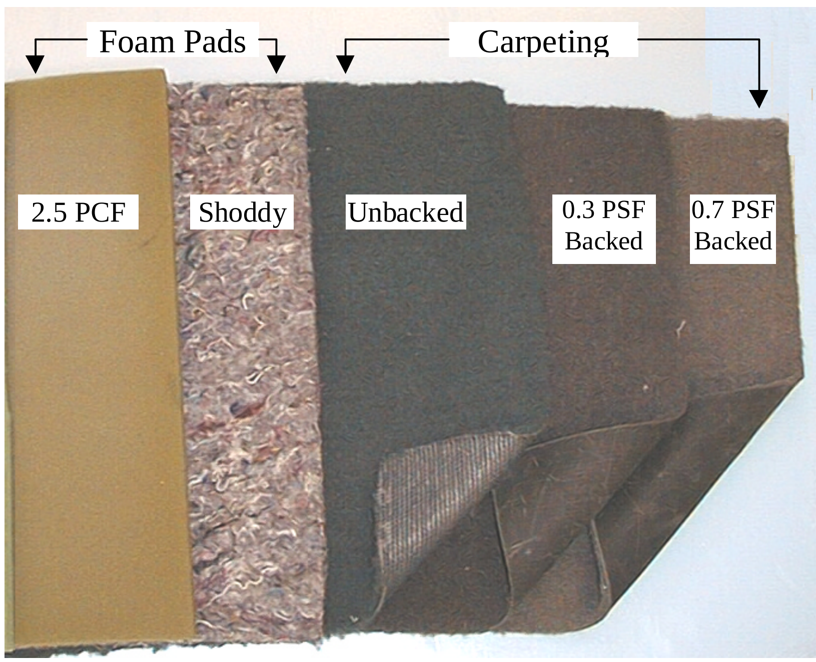


Figure 5.19. Different Foam Pads and Carpeting Damping Treatments

For each case, the vibration and acoustics reductions were normalized to the added weight due to the treatment, i.e.

$$\frac{\Delta(Accelerations,\ (dB))}{(Added\ Weight,\ (lb))} \tag{5.5}$$

and

$$\frac{\Delta(NSPL,\ (dB))}{(Added\ Weight,\ (lb))}. \tag{5.6}$$

The added weights of the different treatments are shown in Table 5.4

Table 5.4. Weights of Different Treatments

Plate Treatment Tested	Weight (lb)	Weight of Added Treatment (lb)	Weight Increase (%)
Undamped Plate	4.72	Baseline	Baseline
Undamped Plate w/ PZTs	4.82	0.11	2.33
Unbacked Carpet	4.94	0.23	4.87
Shoddy and Unbacked Carpet	5.49	0.78	16.5
Shoddy and 0.3 PSF Backed Carpet	6.09	1.37	29.0
Asphalt, Shoddy, and 0.3 PSF Backed Carpet	7.59	2.87	60.8
Asphalt, 2.5 PCF Foam, and 0.3 PSF Backed Carpet	7.50	2.78	58.9
Asphalt, 2.5 PCF Foam, and 0.7 PSF Backed Carpet	8.30	3.58	75.5
CLD, 2.5 PCF Foam, and 0.3 PSF Backed Carpet	7.07	2.36	50.0
CLD, 2.5 PCF Foam, and 0.7 PSF Backed Carpet	7.87	3.15	66.7

The differential vibration and acoustic reductions, and the differential weights are all computed with respect to the undamped plate. As the results of Figures 5.20 and 5.21 show, the PZT treatments offer the most noise and vibration benefits with respect to the weight they add to the structure. This is especially true when the weight benefits of smart damping are compared to the plates damped with a viscoelastic layer. The reduction per weight benefits of the PZTs are more than 10 times those of these treatments. Although these treatments can be very effective, a minimum of 50% weight increase is required to achieve the desired damping levels. These test results show that smart damping could replace the viscoelastic damping without the added weight.

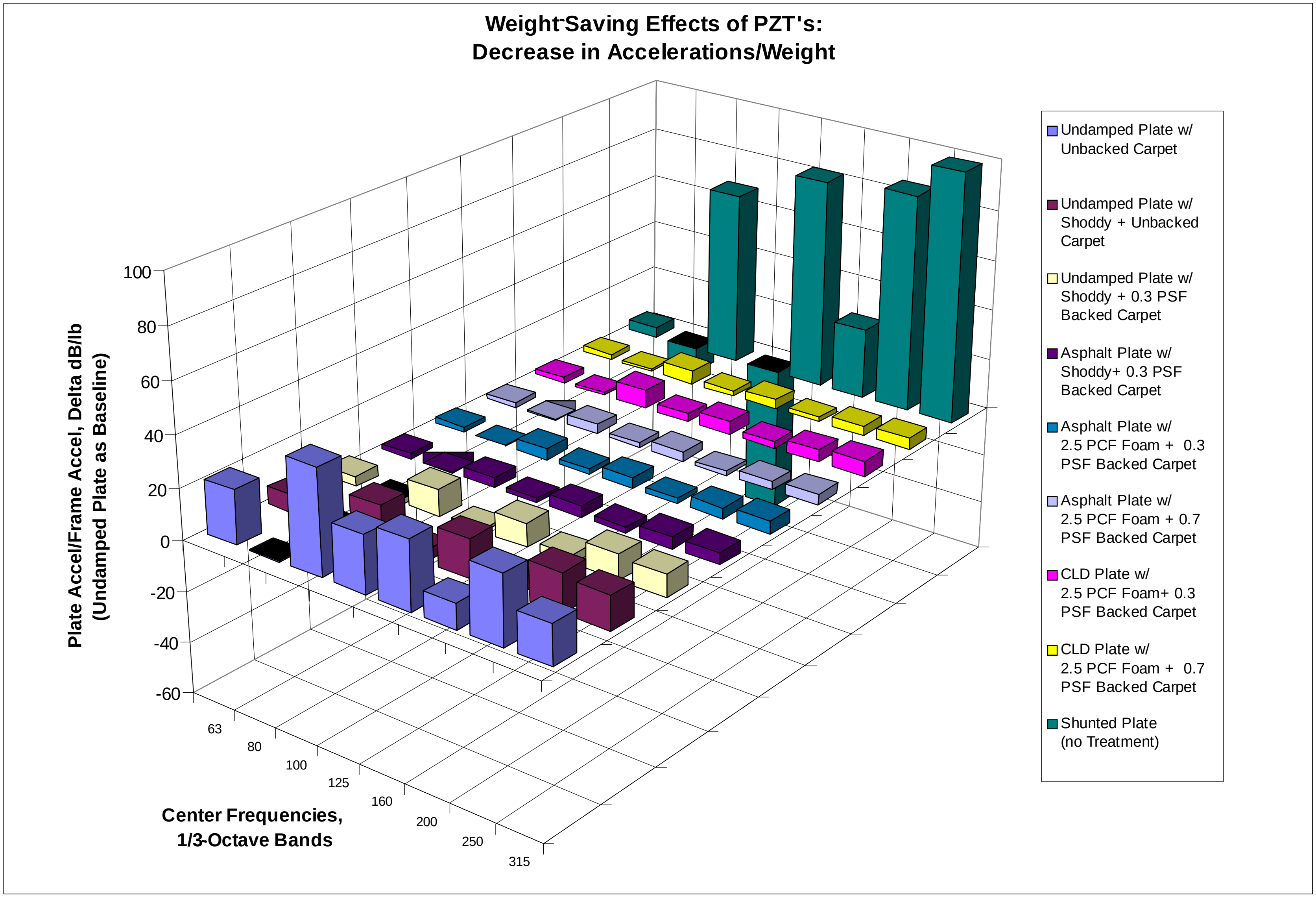
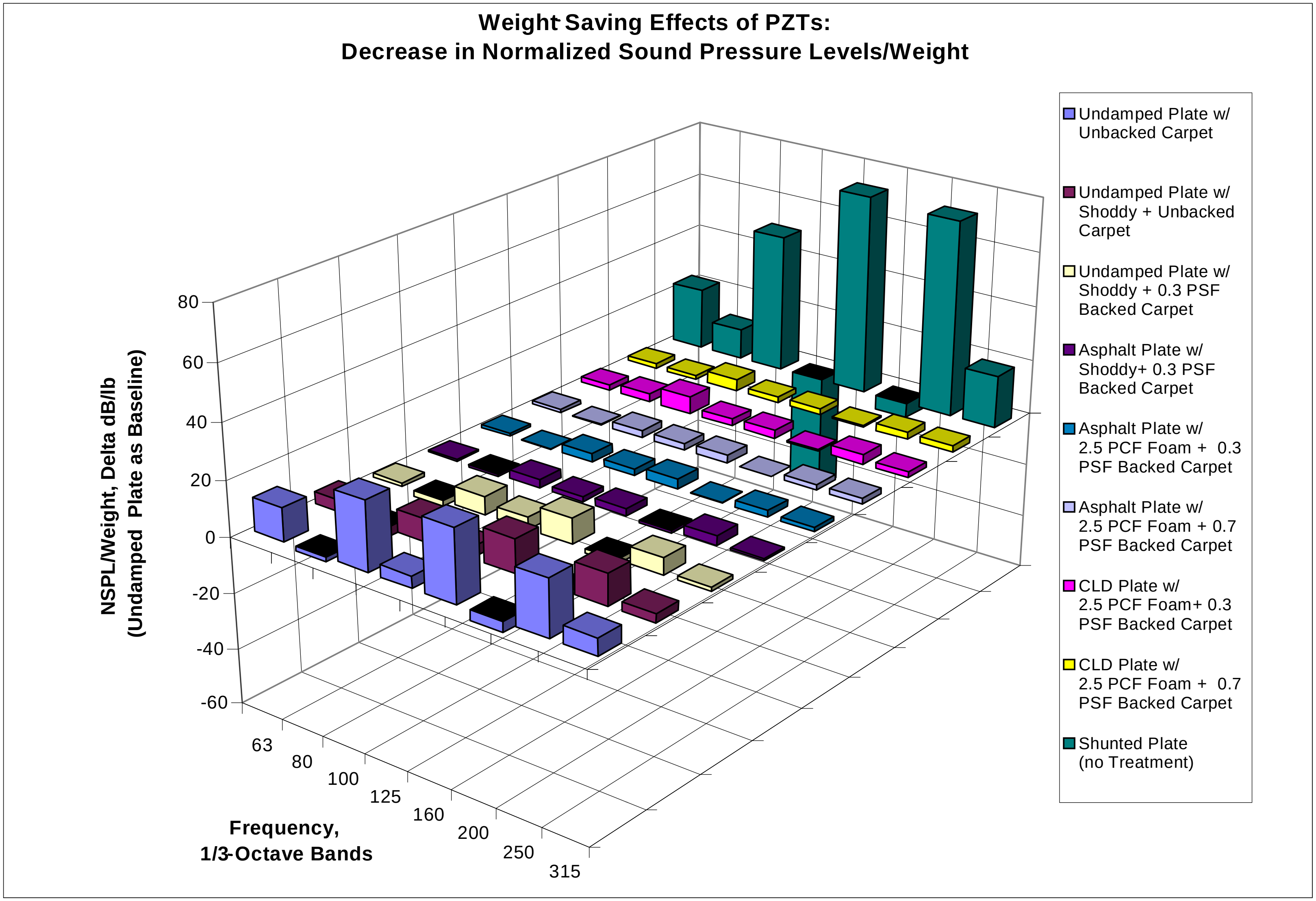


Figure 5.20. Decrease in Accelerations with Respect to Added Weight


Weight Saving Effects of PZTs:
Decrease in Normalized Sound Pressure Levels/Weight
NSPL/Weight, Delta dB/lb
(Undamped Plate as Baseline)
80
60
40
20
0
-20
-40
-60
63
80
100
125
160
200
250
315
Frequency,
1/3-Octave Bands
Undamped Plate w/ Unbacked Carpet
Undamped Plate w/ Shoddy + Unbacked Carpet
Undamped Plate w/ Shoddy + 0.3 PSF Backed Carpet
Asphalt Plate w/ Shoddy+ 0.3 PSF Backed Carpet
Asphalt Plate w/ 2.5 PCF Foam + 0.3 PSF Backed Carpet
Asphalt Plate w/ 2.5 PCF Foam + 0.7 PSF Backed Carpet
CLD Plate w/ 2.5 PCF Foam+ 0.3 PSF Backed Carpet
CLD Plate w/ 2.5 PCF Foam + 0.7 PSF Backed Carpet
Shunted Plate (no Treatment)

5.5 Summary

The benefits of smart damping materials, specifically piezoceramics with shunt circuits, in reducing vibrations and structure-borne noise were addressed. Using the test rig described in Chapter 3, a series of tests were conducted on a test plate with shunted PZTs. A comparison of the results with an undamped plate showed that the smart damping materials can significantly lower both the plate vibration and the structure-borne noise for both narrowband and broadband frequencies. The augmenting benefits of adding smart damping to commonly used damping treatments were presented, as well the weight-saving benefits of PZTs.