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Attenuation of shock transmission through a launch vehicle payload adaptor

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Abstract

Shock transmission through aerospace structures is an important problem which has received a great deal of attention. Transient events generated throughout the flight envelope, such as lift-off and stage separation, can cause damage to delicate payload components. Attenuation of the transmitted shock is a very significant goal. This paper deals with the application of a light weight, optimally damped distributed vibration absorber for the control of shock transmission through a conical payload adaptor. This structure was modelled by finite elements and a matrix of mobilities was measured at a large number of points. The data was used to tune the frequencies of the absorbers, the damping, and their locations. A series of incremental impact tests where a minimum number of DVA's were first installed and subsequently increased in stages were performed. The shock spectra at the top of the cone were computed from the transient time histories. The results indicated a wide band reduction in the transmitted shock. It confirmed that the light weight distributed vibration absorbers could be applied for significant shock attenuation.

1. INTRODUCTION

Shock transmission through aerospace structures is a significant design problem. Components mounted on the structures could be subjected to high shock levels which may cause damage. Payloads mounted on adaptors in launch vehicles are also subjected to several high frequency shock, and low frequency transient sources. These include the lift-off ignition transient forces, the payload fairing separation, and the payload separation from the adaptor. The launch vehicle user's guide typically specifies the expected shock levels that the payload must withstand. The specification is generally given in the form of a shock response spectrum. Therefore, it is highly desirable to develop shock attenuation methods. However, weight in aerospace systems is a major controlling factor in the design of any attenuation treatment. One approach to attenuate the transmitted shock is to design and implement a whole spacecraft isolation system [1, 2]. Other approaches include the application of tuned mass dampers, constrained viscoelastic damping, and the reduction of the shock magnitude at the source.

This paper specifically addresses the application of Compact Distributed Vibration Absorbers (CDVA) to attenuate the shock propagation along its transmission path. This particular DVA is a lightweight optimally damped absorber which was developed both as a passive and active absorber [3]. In the first phase of this study, the CDVA was applied to a stiff sandwich composite panel [4]. A picture and a schematic of the CDVA are shown in Figure 1.

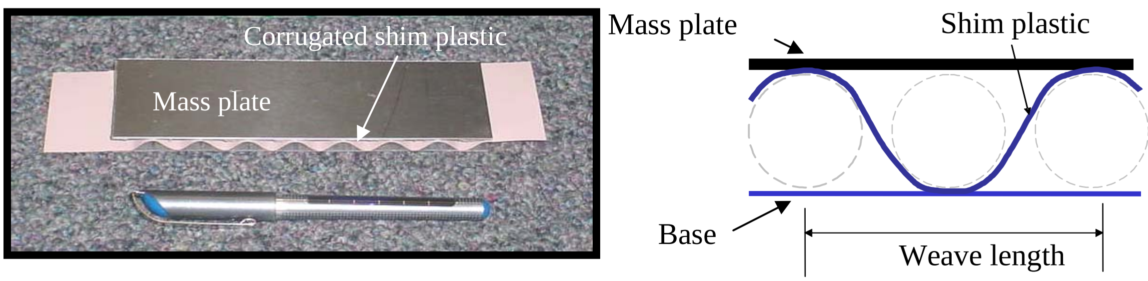

Figure 1: Picture and schematic of a CDVA consisting of a distributed mass layer and a corrugated shim plastic as a spring layer

The previous study [4] confirmed that the CDVA substantially reduces the shock transmitted through the panel due to an impulsive force. The object of this work was to investigate the feasibility of applying CDVAs to a conical large payload adaptor, in order to attenuate the transmitted shock at the top of the adaptor. It is customary in the aerospace industry to characterize the shock in terms of shock response spectra (SRS). The main target of this treatment was the SRS attenuation in the frequency range between 350 and 600 Hz. The optimal design of the treatment requires knowledge of the dominant peaks in the frequency response, the damping of the structure, and a mobility characterization that would determine the location of the devices. As the following discussion indicates, significant difficulties were encountered relative to the previous application on a curved panel.

2. ADAPTOR CHARACTERIZATION

Finite Element Model

The modal analysis of the FEM indicated a very high modal density in the frequency range of interest. The complexity of a modal characterization can be better appreciated by considering the mode count in 1/6th octave bands, which is shown in Figure 2. A typical modes shape is shown in Figure 3.

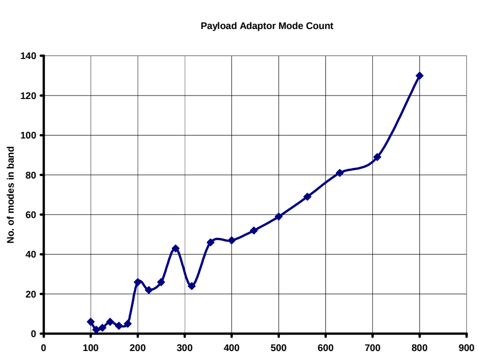

Figure 2: Mode count in 1/6th octave bands

Figure 3: Mode shape (28,3) at 577.34 Hz

It can be seen that there are 60 modes in the 1/6th octave band at the center frequency of 500 Hz, which has a bandwidth of 57 Hz. It was apparent that targeting specific modes is not realistic.

Mobility Test

A dynamic test was performed to measure the mobilities on the adaptor cone using hammer excitation. Figure 4 shows the force and accelerometer locations which were limited to half the cone due to the structure symmetry.

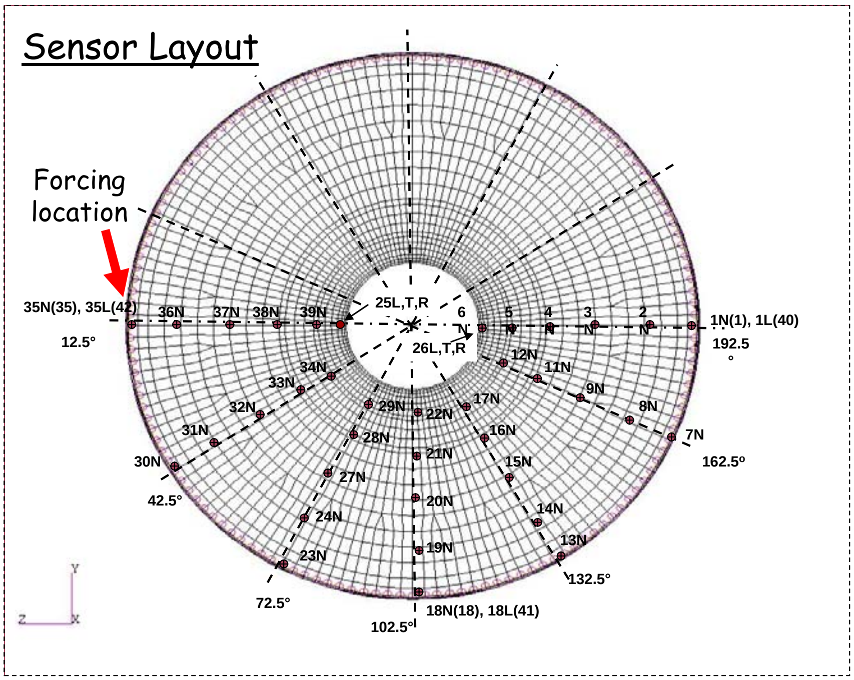

Figure 4: Sensor layout for Mobility test

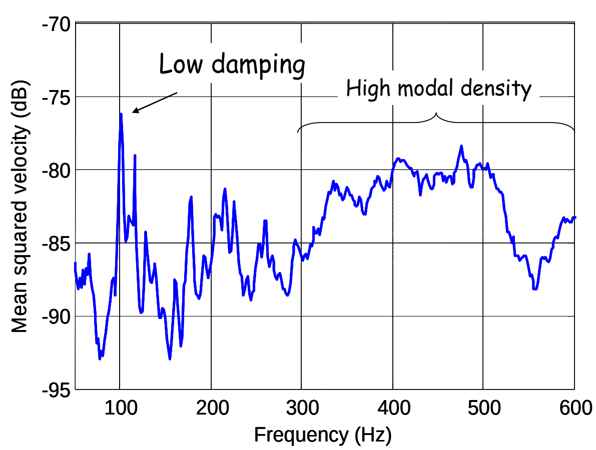

Figure 5: Mean square velocity on cone

Figure 5 shows the mean square velocity of all positions on the cone. The high modal density in the frequency range of interest can be seen. Implementation of the mobility coupling that was presented in [4] was not feasible for this case. The information gained from the frequency response functions led to the choice of three groups of CDVA, each tuned to the nominal frequencies of 220, 400, and 510 Hz. One of the features of the CDVA is the inherent damping due to the corrugated shim plastic. This damping is beneficial in the broadening of the absorber resonance peak, thus de-emphasizing the need for tuning to well determined resonances. Moreover, with the manual construction of the CDVA, there are inherent variations in both the device natural frequencies and damping for the same nominal design frequency, although the variations in damping are less significant than those of frequency. In view of the complex dynamic characteristics of the adaptor and the high modal density, these random variations in the CDVA may in fact be beneficial.

Treatment Verification

Each CDVA was attached to a rigid plate on the shaker head, and the transmissibility between the acceleration of the CDVA plate and the rigid plate was measured. This yields the resonance frequency and damping of the absorber. As expected, variations were observed for both the natural frequencies and the damping ratios due to manufacturing variances. Table 1 shows the variations of some samples in terms of their individual values, averages, and standard deviation.

3. TREATMENT APPLICATION

The CDVA for a particular frequency were applied to locations where higher amplitudes were observed in the measured frequency response functions. In order to achieve a meaningful attenuation (a minimum of 3 dB) of the transmitted shock to the top of the adaptor, a large number of CDVA was needed based on previous studies [3-5].

Table 1: CDVA Verification of variations

Type:	**A**		**C**		**B**	
Shim Color:	Tan		Tan		Clear	
Weight, g:	95		55		95	
Sample #	fn (Hz)	Damping Ratio	fn (H	Damping Ratio	fn (Hz)	Damping Ratio
1	184	0.1960	373	0.1809	513	0.0743
2	189	0.1208	414	0.0882	494	0.0613
3	217	0.1449	431	0.1483	480	0.0608
4	218	0.0800	427	0.0751	543	0.0994
5	211	0.1045	380	0.0805	504	0.0604
6			409	0.1082		
Average	**204**	**0.1292**	**406**	**0.1135**	**507**	**0.0712**
Std Dev	**16**	**0.0442**	**24**	**0.0424**	**24**	**0.0168**

In order to observe the performance of smaller numbers of CDVA, the treatment was applied in stages. In the first stage, a total of 96 type C were applied. Their total weight was 5.3 kg. The layout for stage I is shown in Figure 6. Note that the coverage is over the whole cone. In stage II, 36 type B were added for a total weight of 8.7 kg. Stage III added 60 type A for a total weight of 14.4 kg. The final treatment consisted of: 120 type A, 60 type B, and 180 type C for a total weight of 27 kg. A picture of the CDVA applied to the adaptor is presented in Figure 7.

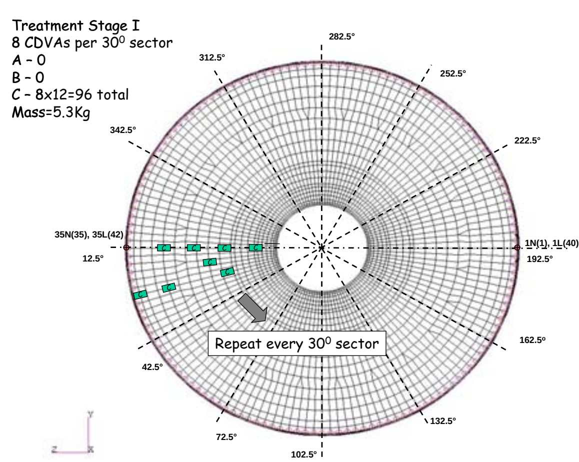

Figure 6: CDVA layout for stage I

Following the stage IV final treatment test, another configuration was tested, by removing a whole sector of CDVAs. In Figure 6, it can be seen that the cone is divided into 30 degrees sectors. Stage V consisted of removing all the CDVAs applied to 4 sectors as shown in Figure 8. Stage VI consisted of removing CDVAs from four more sectors, and stage VII had only two sectors populated with CDVAs and ten bare sectors.

Impact Test

Performance of the CDVA was evaluated with a frequency response function test similar to the mobility test mentioned earlier. The excitation force was an impact hammer applied to the ring at the bottom of the adaptor in three perpendicular directions. The force and sensor locations are similar to Figure 4. All the data was acquired simultaneously through a multi channel digital system. Since it was desired to compute the shock spectra up to 2 kHz, all the data were sampled at 20 kHz. For each test ten impacts were applied. The shock response spectra (SRS) are computed from the acceleration time histories. However, the accelerations are dependent on the exciting force, and in order to compare the results of different tests, one needs a common reference.

In most dynamic testing, the frequency response function (FRF) plays that role. Unfortunately, the objective of this study was to evaluate the treatment effect on the SRS. This issue will be discussed shortly. During the test every effort was made to maintain the force peak value at a constant level. The first data analysis performed was to look at the mean squared accelerations over the entire cone. Figure 9 shows a plot in 1/3 octave bands. It is apparent that the CDVA result in significant

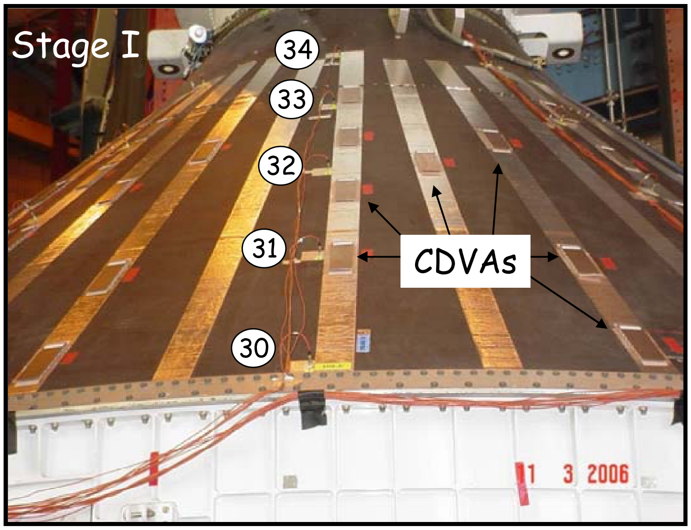

Figure 7: Photo of CDVA on the adaptor-the numbered items shown are accelerometer locations

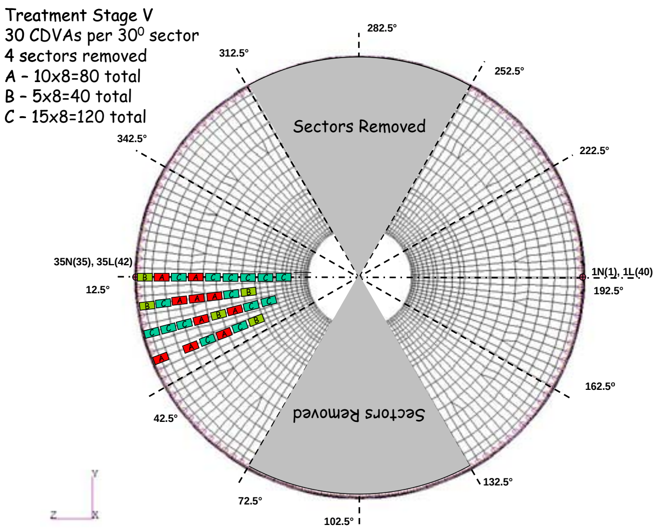

Figure 8: CDVA Layout for stage VI

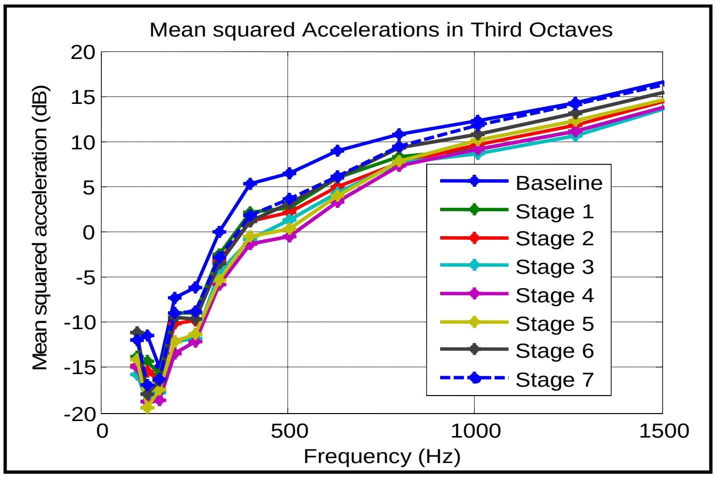

Figure 9: Average 1/3 octave acceleration of the cone

acceleration reduction in a wide frequency band. This can't be attributed to a mass effect as the total mass of the full treatment (27 kg for stage IV) is a very small fraction of the mass of the cone. In particular, the reduction at 1/3 octave band of 500 Hz is 7 dB for the full treatment, and 6 dB with the removal of 4 sectors (stage V).

Data Normalization

The solution adopted for the data normalization is as follows:
1. For each test compute the accelerance FRF using the data average from the ten impacts.
2. Inverse Fourier Transform to obtain the impulse response.
3. Construct a reference force signal.
4. Convolve the impulse response and the reference force to obtain the normalized acceleration time histories.

Once the normalized acceleration time histories are obtained, their SRS can be compared for different configurations. The evaluation of the SRS was significant only at locations at the top of the adaptor, since these are the target of the treatment attenuation. Results for three accelerometers are presented here. One accelerometer is in the longitudinal direction (sensor 48) and two in the radial direction (sensors 50 and 53). Instead of presenting the results of the SRS themselves, we present the differences between the SRS for the base line case; i.e., no treatment applied, and the SRS with different stages of CDVA treatment. Figure 10 presents the attenuation in the SRS for sensor 50 for stages 3 through 7. It will be recalled that stage 4 is the full treatment, and stage 7 is for CDVA on two sectors only covering 60 degrees. The full treatment results in the highest attenuation, followed closely by stage 5 in which CDVA from four sectors were removed. The reduction is between 1 and 2 dB in the frequency range of 200 to 400 Hz, 3 dB at 500 Hz, and 5.4 dB at 650 Hz. High attenuation is also observed at the higher frequencies between 1200 and 1400 Hz. It is not clearly understood why the highest attenuation occurred above the CDVA targeted frequencies. Figure 11 shows the attenuation for sensor 53, which is located

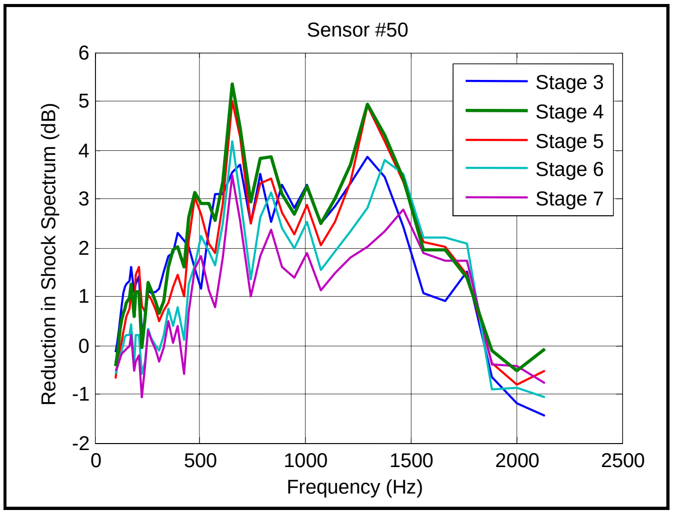

Figure 10: Attenuation of SRS for sensor 50(Radial)

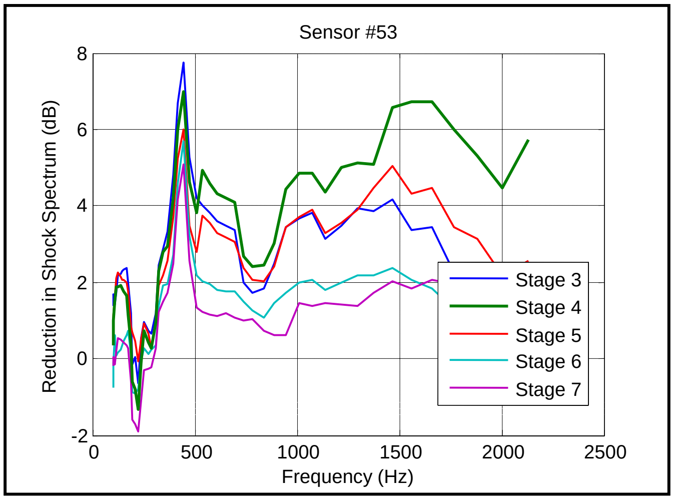

Figure 11: Attenuation of SRS for sensor 53(Radial)

at 180 degrees from sensor 50. At this location the maximum shock reduction of nearly 8 dB occurs at the targeted frequency region between 400 and 500 Hz. The attenuation at the lower frequencies around 200 Hz is about 2 dB. The CDVA treatment is identical for each 30 degrees sector. Therefore, the locations of the CDVA do not explain the differences between sensors 50 and 53. However, since sensor 50 is in line with the force application point while sensor 53 is 180 degrees apart, it can be surmised that it is the positioning relative to the input force location that causes the observed differences. The observed dynamic response without CDVAs at the location of sensor 53 contained high amplitudes at the frequency band between 400 and 500 Hz. Figure 12 presents the shock reduction for sensor 48 in the longitudinal direction. The attenuation in the low frequency region is about 2 dB. However, there is virtually no attenuation at the band around 500 Hz. As in the radial direction case, significant attenuation occurred at the higher frequencies between 1 KHz and 1500 Hz. Sensor 48 was at the same location as sensor 50, and it is possible that another sensor at locations such as sensor 53 may have shown a different reduction. These results indicate that the shock spectrum in the lower frequency range below 1 KHz significantly vary with locations which may be attributed to the variations in the modal response. It points to the need for employing several sensors for the SRS evaluation.

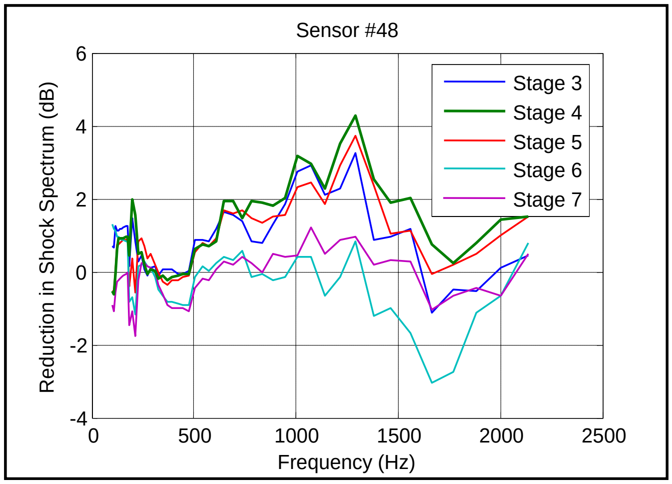

Figure 12: Attenuation of SRS for sensor 48(longitudinal)

4. CONCLUSIONS

Compact Distributed Vibration Absorbers were developed and evaluated for the attenuation of the shock transmitted through a payload adaptor. The CDVA is a light weight device which is advantageous for aerospace structures. The application of the CDVA was tested for transient conditions through a hammer impact test. It was shown that significant shock reduction up to 8 dB was achieved by the application of the CDVA. The study indicated the need to employ multiple sensors for the evaluation of the shock.

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