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CONTROLLING SHOCK PROPAGATION IN STRUTS USING CYLINDRICAL DISTRIBUTED VIBRATION ABSORBERS

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Abstract
In aerospace systems there are many potential sources of shock such as rocket ignition, fairing separation, explosions, decompression and turbulence. These shocks propagate through the support structures and can damage delicate instrumentation or payloads. This paper looks specifically at controlling shock propagation through support struts. Struts act as bottlenecks in the transmission path between source and receiver and are therefore good places to place vibration control treatments. This paper presents the results of an experimental investigation into the use of Cylindrical Distributed Vibration Absorbers (or CylinDVAs) for controlling shock propagation through cylindrical struts. CylindDVAs are an extension of an existing technology (DVAs) previously demonstrated to be good at controlling vibration and shocks in large plate type structures. The CylinDVAs consist of a soft distributed cylindrical compliant layer made of foam covered with a cylindrical mass layer. The device can be tuned by varying the mass layer, the foam type and foam thickness. One benefit of the CylinDVA is that it orients its reaction force (circumferentially) to the orientation of the vibration propagating down the strut and can therefore control both orthogonal bending waves in the strut simultaneously. For this work the CylinDVAs were demonstrated on a strut separating a source and receiver structure made of steel and Aluminum ‘I’ beams. The acceleration on the receiver structure was measured when the source structure was impacted by a hammer with and without the presence of the CylinDVA treatment. The vibration levels and shock spectrum were calculated using this measured data and large reductions were demonstrated.

INTRODUCTION

In aerospace systems there are many potential sources of shock such as rocket ignition, fairing separation, explosions, decompression and turbulence. These shocks propagate through the support structures and can damage delicate instrumentation or payloads. This paper looks specifically at controlling shock propagation through support struts. Struts also act as bottlenecks in the transmission path between source and receiver and are therefore good places to place vibration control treatments. This paper presents the results of an experimental investigation into the use of Cylindrical Distributed Vibration Absorbers (or CylinDVAs) for controlling shock propagation through cylindrical struts. CylinDVAs represent an extention of previous work on planar Distributed Vibration Absorbers (DVAs) (see for example [1] and [2]). DVAs have already been shown to be effective in controlling vibration levels [3][4] and shock levels [5] on large planar structures and earlier versions of the CylinDVA were developed to control power flow in fluid filled pipes [6].

Boeing provided a sample tubular strut (see Figure 1) around which a test rig was developed.

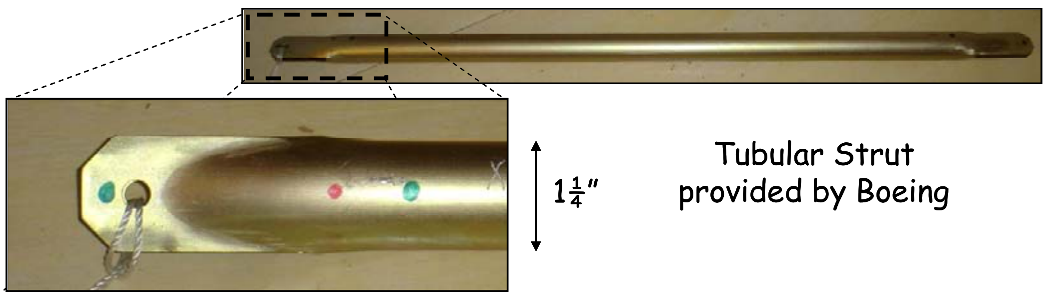

Figure 1: 1¼" tubular strut provided by Boeing for testing

TREATMENT DEVELOPMENT AND TESTING

Design of a cylindrical distributed vibration absorber

Figure 2 shows a schematic of a Cylindrical Distributed Vibration Absorber or CylinDVA. The idea is to use a soft compliant layer such as foam as a spring layer and an outer cylindrical casing made of either plastic or steel to act as a mass layer.

If the mass layer acts as a rigid body, then the device has six rigid body modes. i.e. axial, two radial, two rocking and one torsional. It is expected that it is the two radial modes of the

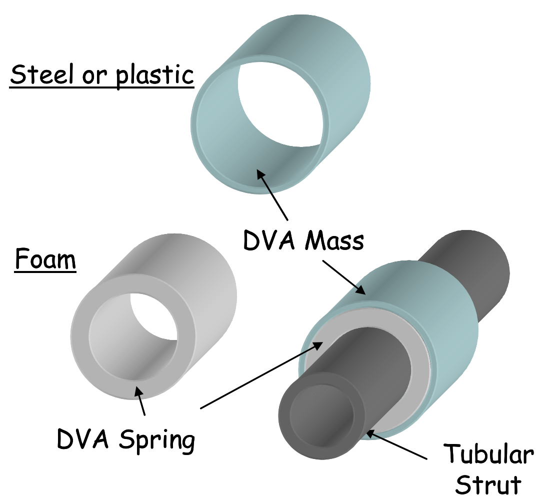

Figure 2: Schematic of a CylinDVA designed for controlling the vibration propagation along a tubular strut

DVA that contribute most significantly to its performance. The two radial modes predominantly control bending waves in the strut (i.e. *n*=1 modes where *n* is the circumferential mode order) and their combined behavior automatically orients the vibration of the CylinDVA to the direction of the bending in the strut. If the CylinDVA is long then it will begin to support higher order modes along its length.

The natural frequencies and damping of the CylinDVA (associated with the six modes) can be changed in a number of ways:

- Increasing the mass of the outer casing decreases the natural frequency
- Increasing the thickness of the foam layer decreases the natural frequency
- Higher foam stiffness increases the natural frequency.
- Compressing the foam increases the natural frequency
- Higher foam damping increases the damping ratio of the device

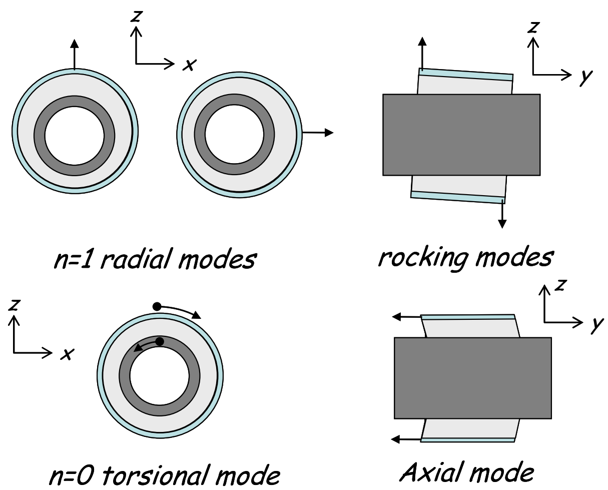

Figure 3: The six rigid body modes of the CylinDVA. The n=1 radial modes are the ones expected to provide most of the control. Note that only one of the two rocking modes

Interaction of waves in struts with cylindrical DVA

Waves traveling down the strut interact with the CylinDVA and can either be reflected, due to a change in impedance, or absorbed. A recent publication [7] showed that the interaction between a DVA and a beam can be viewed in terms of waves traveling in a coupled system, where the wavenumbers are complex functions (i.e. decay as they travel), and that the damping in the DVA can be optimized to control specific bandwidths. A strut is simply a beam with two orthogonal modes of bending and the design of the CylinDVA (also with two radial modes) should interact with the strut in an analogous way to the DVA and a beam. Therefore, most of this theory [7] can be directly applied to this work.

Shock Spectrum

The shock spectrum $S_x(\omega)$ of an acceleration signal $\ddot{x}(t)$ is defined as the maximum absolute acceleration ($\max|\ddot{y}(t)|$) experienced by a single degree of freedom system when (i) it's base acceleration is given by $\ddot{x}(t)$, (ii) its damping ratio is assumed to be ζ=0.05 and (iii) the natural frequency of the SDOF is given by $\omega_n=\omega$. $\ddot{x}(t)$ can be either a directly measured signal or created by filtering an impulsive input, such as a half sine or Hanning pulse, with a known transfer function. The shock spectrum tends to have relatively smooth variation with frequency even if the acceleration signal has large variations in the frequency domain.

EXPERIMENTAL RESULTS

Experimental rig for determining the behavior of cylindrical DVAs

In order to test the natural frequency and damping ratio of the CylinDVAs a test rig was designed and built that consisted of a short, heavy steel pipe of 1¼" diameter. The CylinDVA could then be attached to the pipe and instrumented with an accelerometer. Figure 5 shows a picture of this rig with two closely spaced accelerometers, one on the pipe and one on the CylinDVA. The pipe was hit with a hammer (shown in figure) and the transfer function between the two accelerometers measured. The accelerometer on the pipe (accel #1) was considered the input and the accelerometer on the CylinDVA (accel #2) was the output. A range of foam types and thicknesses were tested during this project along with a number of mass layers. The mass layers were typically either a pipe cut in half and then clamped around the foam or sheet aluminum wrapped around the foam and clamped.

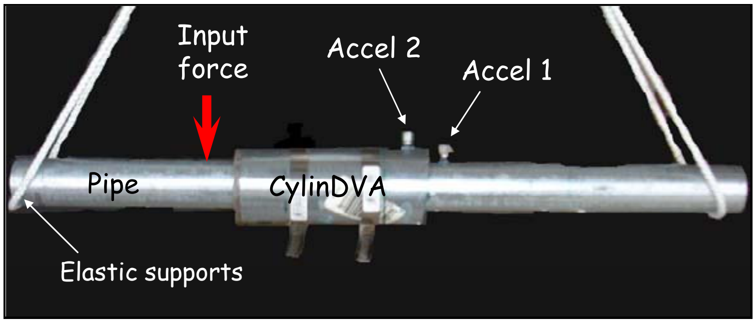

Figure 5: Picture of test rig for determining the natural frequency and damping ratio of a CylinDVA

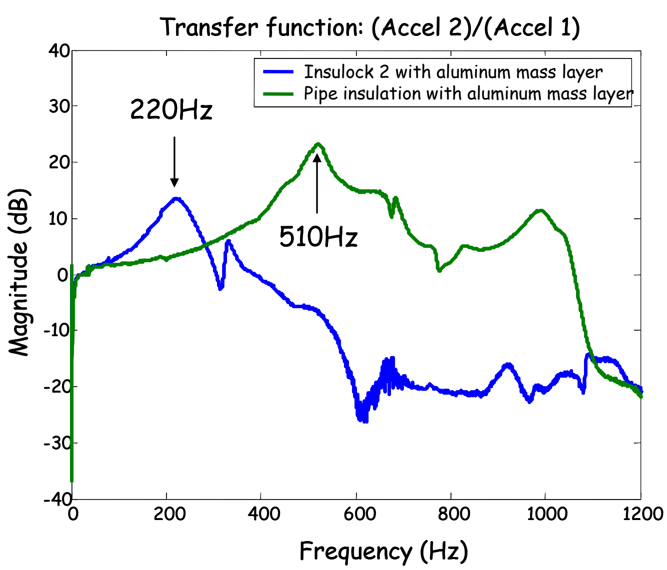

Figure 4: Two examples of the measured transfer functions between the reference accelerometer and the CylinDVA accelerometer for two different CylinDVA configurations

Figure 4 shows results for two different CylinDVA designs. The main *n=1* natural frequency can be clearly seen at 220Hz and 510Hz for the two designs. Modes of the pipe structure and other modes of the CylinDVA are often see in the transfer functions but it is usually fairly easy to determine the dominant *n=1* modes. A single resonance term is fit to the main mode and from this the natural frequency and damping ratio of the CylinDVA are estimated.

Experimental rig for testing shock transmission through strut

In order to test the CylinDVAs a test rig was built which consisted of a source beam and a receiver beam mounted on either side of the strut provided by Boeing. The source beam was designed to be much heavier and stiffer then the receiver beam and both source and receiver were heavy in comparison to the strut itself. The aluminum receiver beam and steel source 'I' beam are shown in the assembled rig Figure 6. Both the source and the receiver beams were designed to have their first resonances above the frequency range of interest (200-600Hz).

In order to determine the behavior of the combined test rig a series of tests were performed in order to identify the main modes occurring within the frequency range of interest. Six main resonances were observed below 600Hz. Table 1 lists the natural frequencies and mode types of these six modes. It was found that the out of plane motion of the strut is important in all but the first mode. This implies that the CylinDVA should be able to couple into all of these modes.

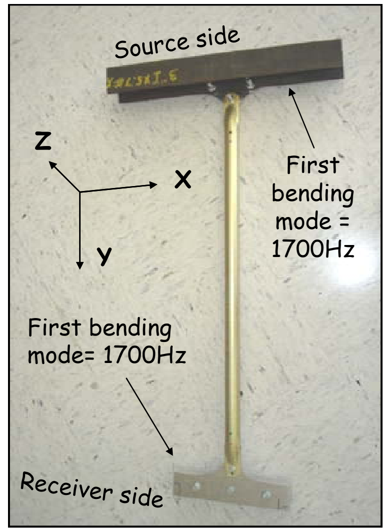

Figure 6: Picture of tubular strut with source and receiver side attachments

Mode #	Fn (Hz)	Description
1	28	Twisting mode
2	101	Receiver acting as a mass bending the strut
3	188	First bending mode of the strut
4	273	Small mixed mode
5	470	Second bending mode of the strut
6	580	Third bending mode of the strut

Table 1: List of first 6 major modes below 600Hz and their description

Application of cylindrical DVA to strut

For every test of the rig a modal hammer was used with 1-3 accelerometers placed on the structure. The sample rate was typically 8192Hz with a 1 second window used. Five averages were taken of each measurement. The accelerance with and without the CylinDVA attached to the strut could then be compared for different source and receiver locations. Figure 7 shows a CylinDVA attached to the strut. Three measurement locations (7-9) are shown.

Figure 7: CylinDVA installed on strut

Cylindrical DVA effect on vibration transmission

Figure 8 shows the accelerance between an input force on the source beam to location 8 on the receiver beam for three cases. The first case (shown in blue) is without any treatment and acts as the baseline case, the second case (shown in green) is for fairly lightly damped foam and the last case (shown in red) is for a highly damped foam (*insulock material*). Very large reductions of up to 20dB are achieved and are particularly impressive for the heavily damped Insulock foam. The attenuation is also significant over a wide range of frequencies.

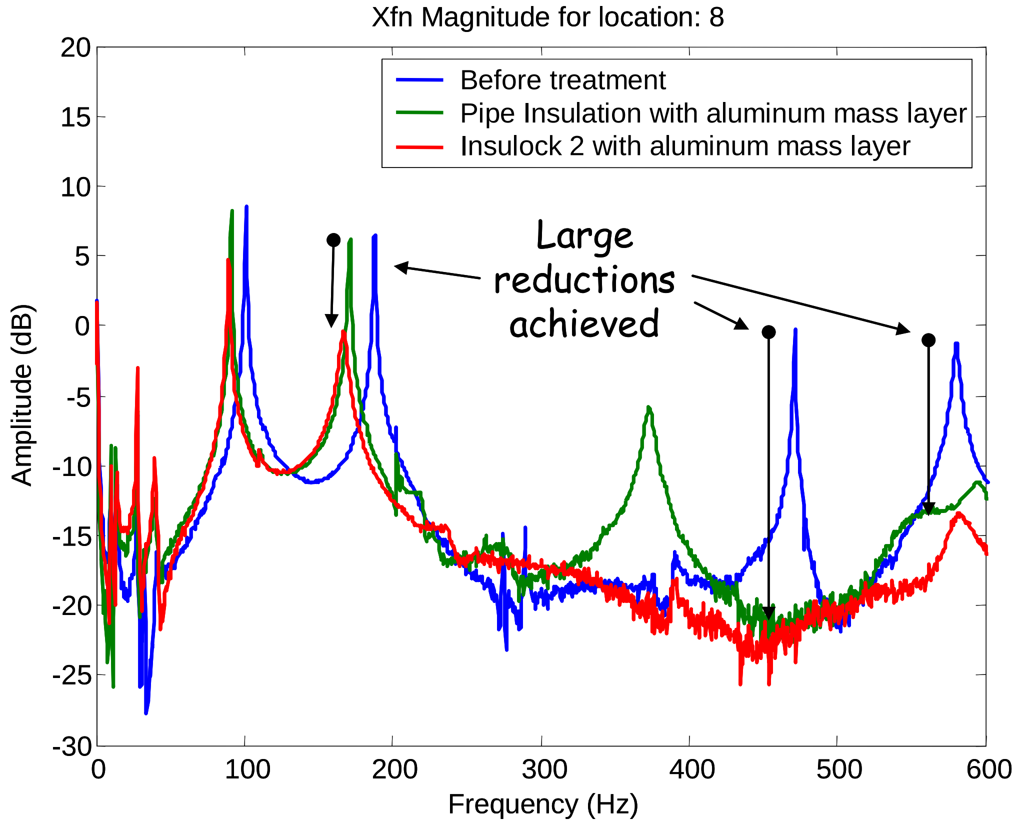

Figure 8: Resulting accelerance measured from an input force on the source to position 8 in the receiver. Very large reductions in vibration were achieved over a wide bandwidth with the highly damped CylinDVA

Cylindrical DVA effect on shock

Once an accelerance is measured it can be inverse Fourier transformed into the time domain to determine the impulse response between the input force and the output acceleration. This impulse response can then be convolved with a short pulse to determine the acceleration at the receiver due to "realistic" force input. The resulting acceleration can then be run through a shock spectrum code to determine the shock spectrum of the acceleration over a range of frequencies. Figure 9 shows a typical shock spectrum calculated from measured accelerance data with and without a heavily damped CylinDVA attached to the strut. A 1.5ms half sine pulse was used as an input. Significant reductions from 200-2000Hz were achieved in this case with peak reductions of up to 7dB.

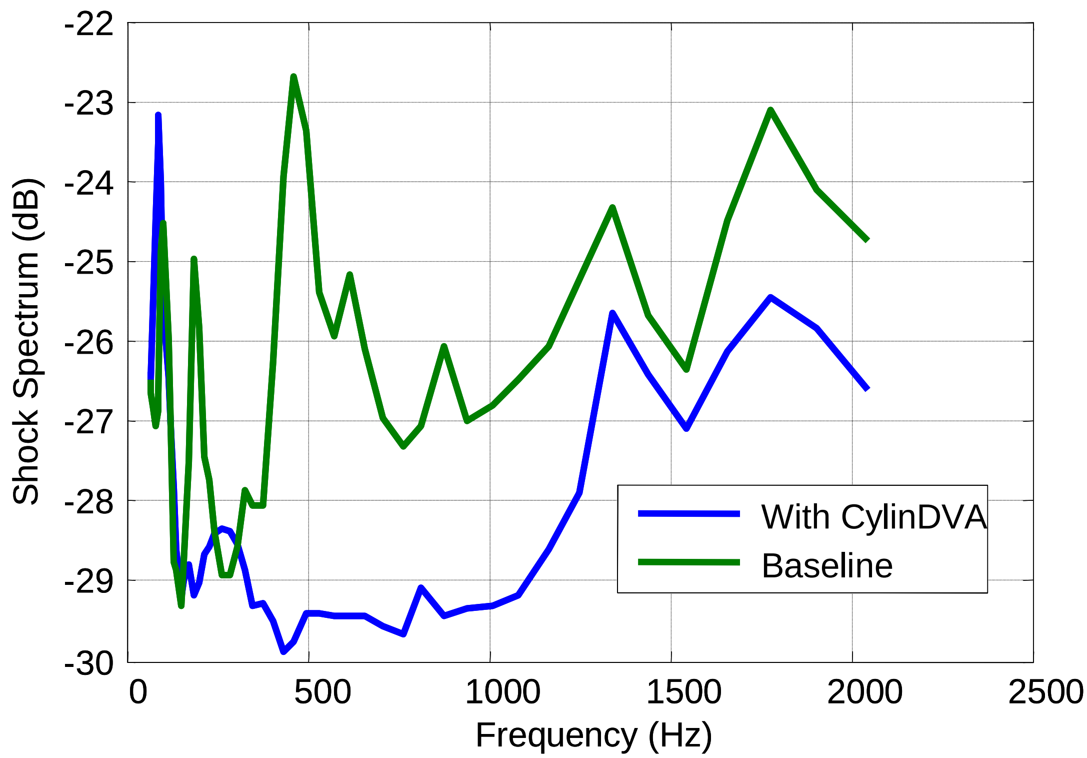

Figure 9: Shock spectrum with and without the application of a single CylinDVA using heavily damped Insulock damping material

SUMMARY AND CONCLUSIONS

The theory of Cylindrical Distributed Vibration Absorber (CylinDVAs) was adapted from previous work and successfully applied to a tubular strut. A test rig for measuring the natural frequency and damping ratio of CylinDVAs was built and successfully tested and a large number of CylinDVA designs built and measured. Damping ratios were typically in the ζ=0.04-ζ=0.12 range and natural frequencies could be varied from 100Hz to 500Hz by changing the foam and mass properties and dimensions. In fact adaptive tuning of the CylindDVA using the clamping mechanism was also demonstrated i.e. as the clamp was tightened the resonance frequency was observed to increase. This could be used as a technique for fine-tuning the treatment.

A test rig using a payload adapter strut (supplied by Boeing) and a “source” and “receiver” was designed, built and characterized experimentally. A modal analysis showed six modes under 600Hz and five of the six modes showed significant radial acceleration of the strut. Treating the strut with CylinDVAs was demonstrated to lead to large reductions in both the vibration response and shock spectrum of the receiver.

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