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Improved Performance of a Baffle-less Automotive Muffler using Piezoelectric Materials

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ABSTRACT

Piezoelectric materials have been used in the past to reduce noise and vibration in several different applications, but the use of these materials to enhance noise reduction for automotive exhaust systems is a new application of this technology. The work detailed herein shows how an inductive shunt circuit may be used to improve the noise reduction performance of a baffle-less automotive muffler system. The absence of interior baffles in the muffler minimizes backpressure and improves fuel efficiency of the upstream engine system. We designed and built a prototype system utilizing an IM7/bismaleimide composite for the muffler body, stainless steel end caps and PZT 5A piezo-ceramic for the passive/adaptive element. By matching the acoustic resonance of the cavity inside the muffler with that of the structure surrounding it, a fully coupled system was achieved. The mechanical impedance of the muffler shell was then matched to the electrical impedance of a piezoelectric strain device which served as energy converter (mechanical to electrical). The electrical energy could then be dissipated through an inductive shunt tuned for the appropriate structural resonance of the shell. An optimization of the parameters was performed so that the radiated noise at an acoustic resonance could be reduced. Vibration and acoustic tests were performed to confirm the analytical predictions, and reduction of both vibration and noise was achieved with this design at the target frequency. A narrowband acoustic reduction of 5 dB was achieved in the laboratory. While our muffler system is effective in a narrow range around the target frequency, broadband acoustic control can be achieved through the use of multiple tuned segments.

INTRODUCTION

High efficiency, tactical wheeled vehicles are critical to current and future Army operations. The Army maintains hundreds-of-thousands of light, medium and heavy trucks at a cost well in excess of $1B annually. Much of that cost is related to fuel, either in the direct cost of fuel consumption as well as the logistical costs associated with transporting fuel to vehicles on the battlefield. It has been long asserted that increased vehicle fuel efficiency (and thus decreased fuel usage requirement rates) is a top priority of the Army.

A typical muffler is filled with baffles and insulating material for reduced acoustic emission. Figure 1 show the coated particulate filter which acts as a baffle. Additional baffles are typically present in a muffler. The baffles cause an obstruction to the air flow (typically referred to as back pressure). Large values of back pressure because a higher load to the engine which will run less efficiently, hence the fuel consumption improvement can be achieved by the removal of baffles in a muffler.

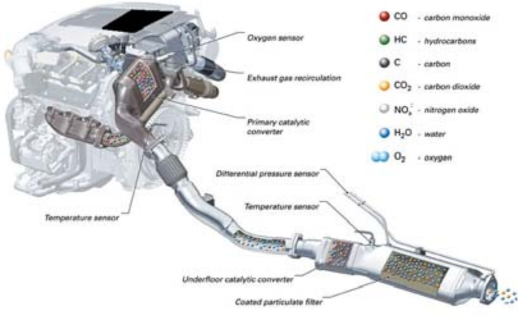

Figure 1 Current state of the art automotive exhaust system for a diesel vehicle [1]

A fair amount of work is currently underway in the development of methods that reduce the sound of an exhaust system. Such systems include sound resonators [2] and perforated silencers [3]. The approach taken here is quite different than these found in literature. The goal of this effort is to demonstrate that smart materials can be used to reduce the noise of an exhaust system, in such a way that no baffles are any longer required in a muffler. Typical noise levels at the exhaust tailpipe may be as high as 105 dB in the low rpm range. This noise is dominant inside the vehicle as well [4].

The Smart Exhaust System (SES), shown conceptually in Figure 2, addresses this need – by enhancing engine fuel efficiency while improving the acoustic signature of the vehicle. The SES concept is to absorb the acoustic energy in the exhaust system by first exciting a structural resonance in the muffler structure (causing a vibration in the structure), then using a shunt circuit in which the mechanical energy generated by the piezoelectric material is dissipated into heat through a resistive element. Such a system is referred as a passive shunt circuit. It is passive because no energy is added to the system (by an amplifier or power supply) and it is shunted because it is tuned for a specific frequency range in which the electrical and the mechanical resonances match. The piezoelectric material is used to convert the mechanical energy present in the system into the electrical energy that can then be dissipated through an electrical circuit. The energy transferred is typically in the order of milliWatts, which could lead to considerable noise reduction if the acoustic response is tonal in nature (structural-acoustic coupling is strong).

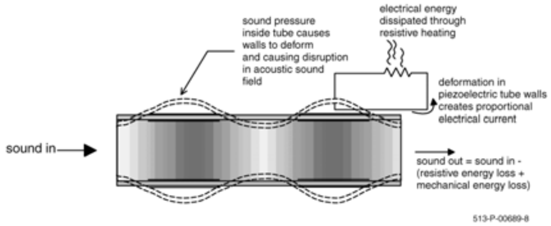

Figure 2: The Foster-Miller Smart Exhaust System (SES) Concept.

CONCEPT DEVELOPMENT

A muffler-like structure was used in this concept. The piezoelectric materials used were discrete piezoceramic plates and no need for poling was required since they were purchased already electroded and poled. The design was experimentally verified through three iterations. The details of this effort are shown in this section.

A finite element model of a muffler-like structure was developed using Abaqus finite element software. This design concept represents a departure from the previous tube-like muffler concepts. The reason for departing from an axisymmetric structure is the ability to couple structural bending modes (radiating modes) of the structure to the acoustic modes of the cavity. Once this coupling is present, then piezoelectric materials can be used as a source of noise reduction. In an axisymmetric structure, the only coupling occurs when the structural breathing mode matches that of the acoustic cavity. For typical structural members, the breathing mode is at much higher frequency than the first bending modes, making the structural acoustic coupling very difficult or impractical (restricted to very thin-walled structures or very compliant structures). The method and the details of the finite element model are provided here.

A finite element model of a muffler-like structure was developed as shown in Figure 3. The geometry and material were selected so that the first structural resonance (out of phase 1-1 mode) could match with the acoustic resonance of the cavity. The target frequency for both was chosen to be at 550Hz or so. The length of the muffler was 12 inches and its height was 4”. The wall thickness and the material properties were modified to obtain a first structural mode at 500Hz. This led to the utilization of 12 plies of carbon fiber woven cloth (IM7/5450 graphite fiber/ BMI epoxy cloth) with a total finished wall thickness of 0.120”.

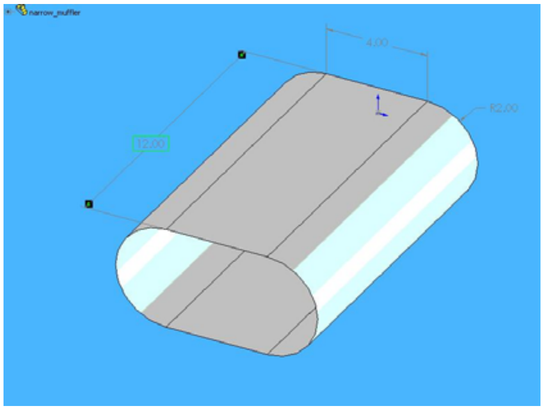

Figure 3. SolidWorks model of a “muffler-like” SES.

NUMERICAL FEASIBILITY

At first, the finite element model, shown in Figure 4, was used to get the first structural resonances. The end caps of the shell had an opening for the attachment of the inlet and exhaust pipes. The end caps were pinned at both ends, a realistic condition for the structure considered. The first three structural modes of vibration are shown in Figures 5-7. The first mode (Figure 5) is referred as to the 1-1 out-of-phase mode since the top and bottom panels of the “muffler” exhibit the 1-1 plate mode behavior, and they move out of phase with each other (one moves up, the other moves down). If excited, this structural mode will generate sound. Similarly, the 2-1 and 3-1 modes generate sound at higher frequencies. The results of the finite element model were then used to determine the location of the piezoelectric material. Notice that the strain profile is shown in the figures above mentioned. Strain is important in determining the proper location of the piezoelectric device since they are strain-based devices.

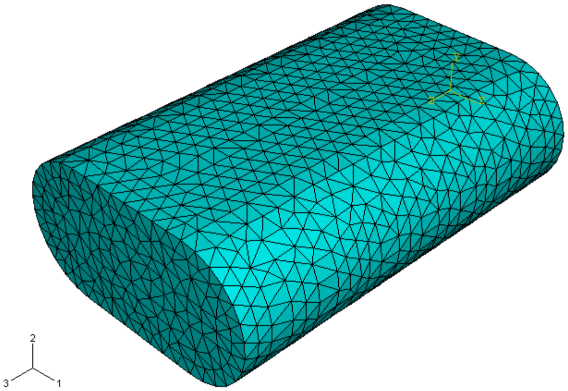

Figure 4. Finite element model of a "muffler-like" SES.

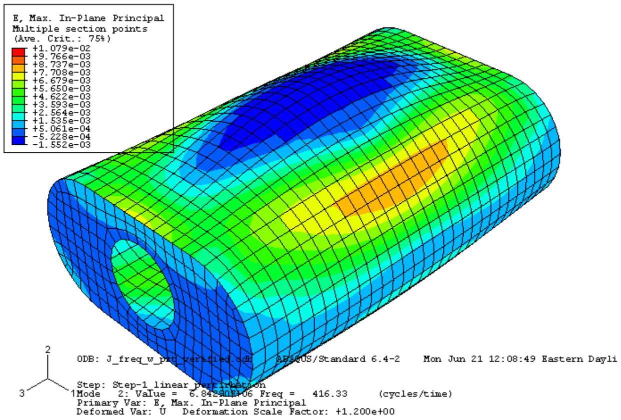

Figure 5. Elastic strain of first noise generating mode (1:1).

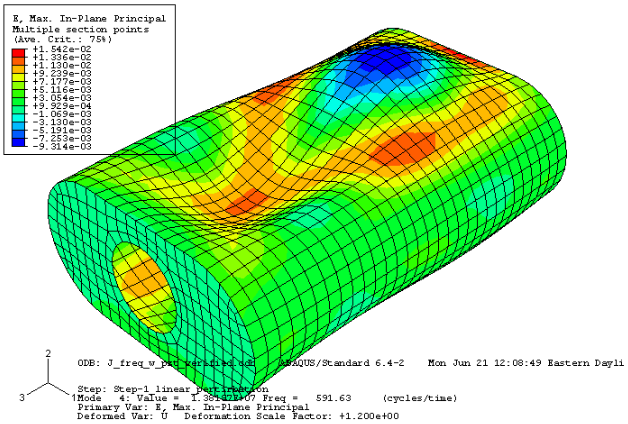

Figure 6. Elastic strain of second noise generating mode (2:1).

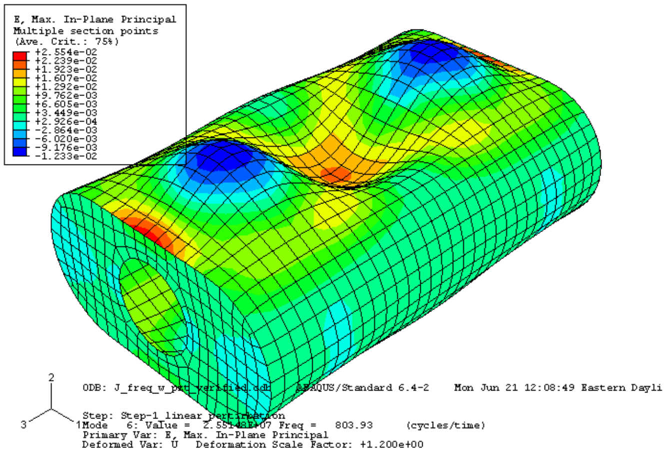

Figure 7. Elastic strain of third noise generating mode (3:1).

The cavity inside the muffler shell was modeled. Air was assumed to be the acoustic fluid inside the muffler. Figure 8 shows the acoustic model developed using Abacus finite element code. Figures 9 and 10 show the first two acoustic cavity modes. Without the addition of end pipes the first acoustic cavity mode (Figure 9) and the first structural mode (Figure 5) matched in frequency and shape, leading to a strong coupling effect. This coupling was used by the piezoelectric material and the passive attenuation system. Inlet and exhaust pipes have a large impact on the acoustic cavity resonance of the system.

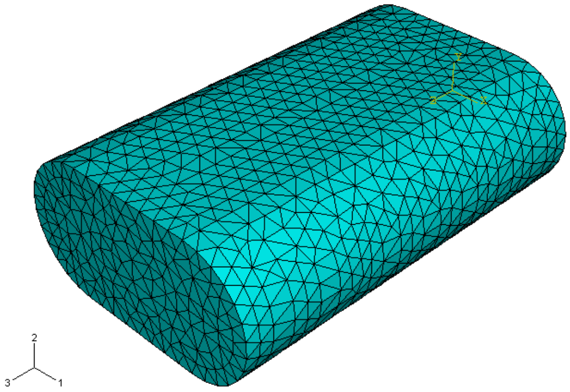

Figure 8. Acoustic finite element model of a "muffler-like" SES.

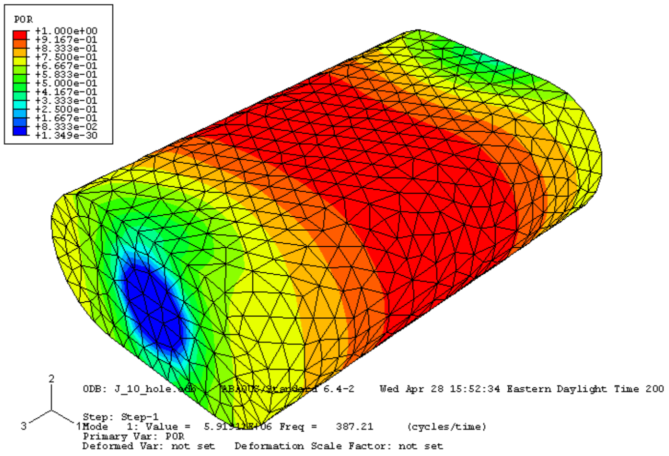

Figure 9. First acoustic cavity mode (no pipe ends).

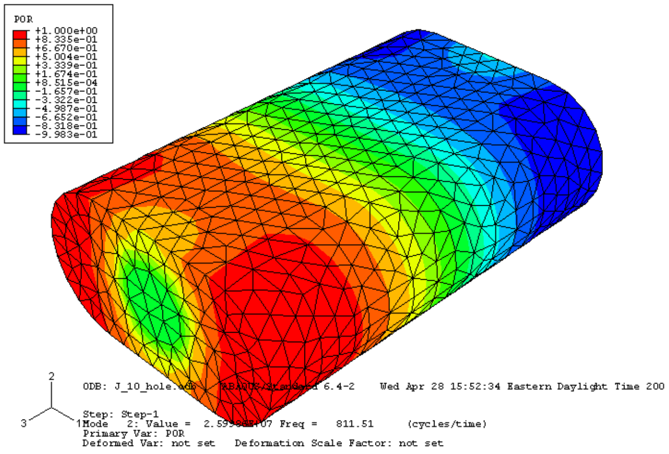

Figure 10. Second acoustic cavity mode (no pipe ends).

Two 6" long pipes were added to the system so that they could be used for in vehicle testing. This caused a shift in the acoustic frequency of the system. A more detailed finite element acoustic model was developed to include the effects of the inlet and exhaust pipes. Figure 11 shows the first four acoustic modes of the muffler when both ends are open (atmospheric pressure at both ends). Notice that the first cavity mode shifted from 370 Hz to 108 Hz and the second shifted from 811 Hz to 560 Hz. The second structural mode of the shell was close in frequency to the second acoustic mode; this mode had the highest structural-acoustic coupling potential. Figure 12 shows the effects of shortening the end pipes, meanwhile Figure 13 shows the effects of adding a 48" long pipe to the inlet of the muffler. This was done to mimic a typical exhaust system. In order for the solution to be robust it has to be independent of the inlet and exhaust pipe length. It was clear that the second acoustic mode (also referred as 1st cavity mode in Figure 9, above), had the least influence on the changes in length of inlet and exhaust pipe.

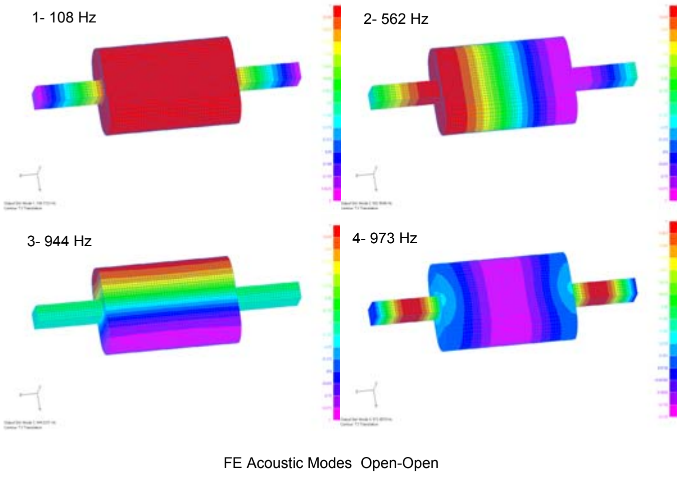

Figure 11. Acoustic model of the muffler with the inlet and exhaust pipes.

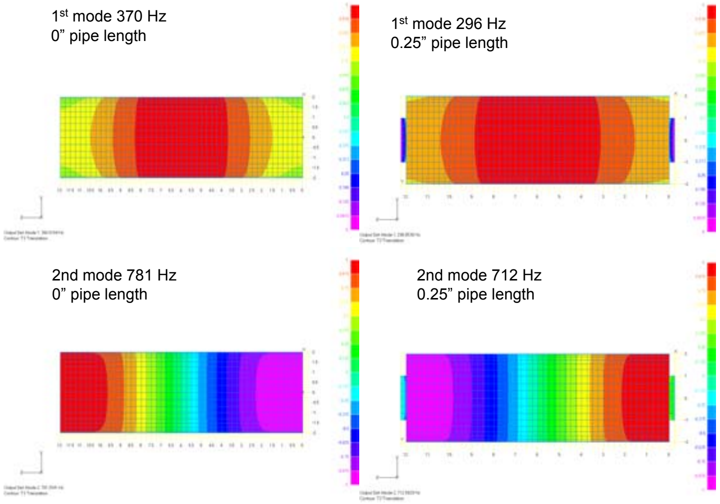

Figure 12. Acoustic model of different length inlet and exhaust pipes.

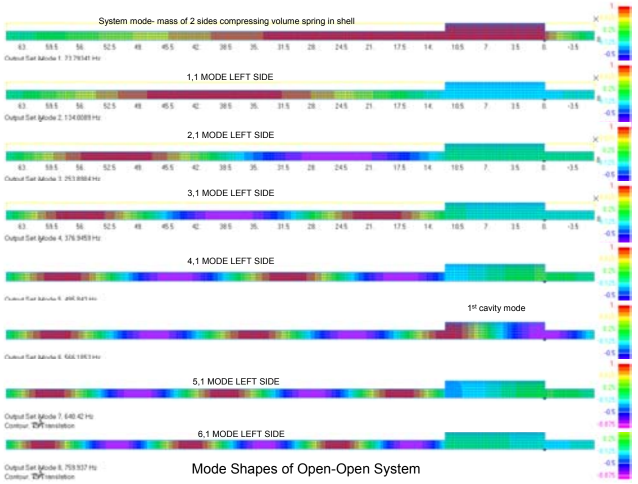

Figure 13. Acoustic model of different length inlet pipe.

With that in mind, it was decided to target the 2-1 mode, so the optimum location of the piezoelectric patches was at the off center positions.

DETAILED DESIGN

At first the strain present in the shell structure during the first mode of vibration is recorded as shown in Figure 14. Since piezoelectric materials are strain-based devices, they are most effective in areas of large strain. Although the 1-1 mode would normally be closer to the fundamental engine frequency, in this case a better structural acoustic coupling could be obtained in the second (2-1) out of phase plate mode. In the mode of interest the areas of high strain are located in the center section of the panel. Figure 14 shows the location of the piezoelectric device.

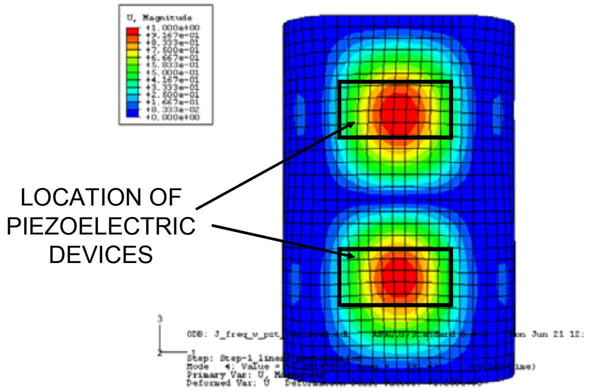

Figure 14. Structural model of the SES showing the location of piezoelectric patches over areas of high strain energy.

The strain energy present in the piezoelectric material is the usable energy that can be converted into electrical energy and hence be dissipated into heat using a resistive or inductive electrical device (i.e., inductor). The thickness of the piezoelectric material has been optimized so that the stiffness of the piezoelectric material matches that of the underlying structure. In this example, the thickness of the piezoelectric material is determined to be 0.010”. Coverage of 13.5 in^2 will result in 20% of the total strain energy present in the system at the first radiating mode. This coverage will be used for the calculations described here. Two devices are used having the following dimension: 3” x 2.25” x 0.01” and will be located in the center section of the shell as shown in Figure 14. If the material is PZT-5A, then the capacitance of both devices is 246 nanofarads (nF).

A Matlab-based predictive tool was used to determine the proper values of the electrical components used for this system. The input to the Matlab model were the strain energy capture (20%), the capacitance of the material (246nF), the frequency of interest (500Hz), and the frequency band at which performance should be optimized for (+/- 5% off center frequency). The optimization routine provided the following values for inductance and resistance: 0.46 Henry and 226 Ohms respectively.

Using the LRC circuit values presented above, the Matlab model provided the predicted vibration reduction due to the shunt circuit. Figure 15 shows the vibration levels of the system unshunted, and shunted. The center frequency vibration reduction was calculated to be 53% of the original, providing an added damping to the system of 4.6%. This vibration reduction will lead to a noise reduction at this acoustic frequency.

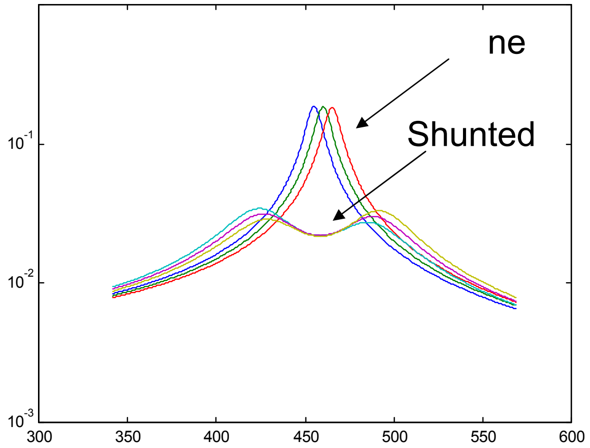

Figure 15. Matlab prediction of the shunted RL-circuit.

A muffler-like structure was fabricated. The overall dimensions were 12” in length with an 8” x 4” cross section as described in Task 4. The material used was IM7/BMI high temperature cloth. The lay-up was such that the structural resonance will match the acoustic cavity resonance. The end caps were made of steel and two 6 inch long pipes were welded in place. Figure 16 shows the first SES prototype as-built.

Figure 16. First SES prototype.

The same procedure described above was used to size and locate the piezoelectric actuators. Figure 17 shows the first prototype with the two piezoelectric patches bonded on the new location. The device could be driven by using two wires soldered directly onto the top and bottom face of the piezoelectric device. An inductor (shown in Figure 18) could then be attached to the wires to close the RLC circuit. The inductors used had three taps corresponding to different levels of inductance and resistance.

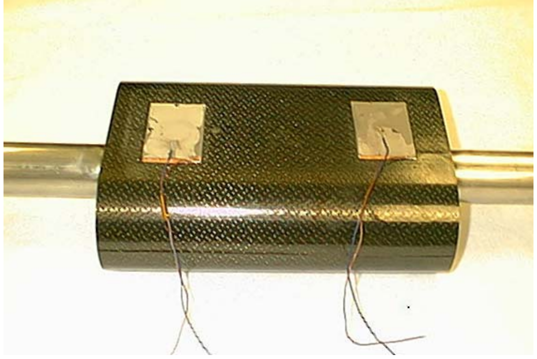

Figure 17. First prototype SES with integrated piezoelectric patches designed to target the 2-1 mode of the structure.

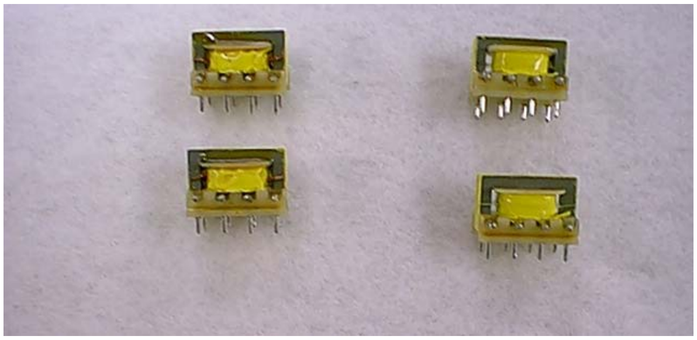

Figure 18. Inductors used for the RLC shunt-circuit.

EXPERIMENTAL VERIFICATION

Both vibration and sound testing was performed at Anteon in their Cambridge Facility. At first a modal analysis of the muffler with and without the piezoelectric materials was performed. An experimental modal analysis was used throughout the program to validate the numerical model. The muffler structure was tested in a free-free boundary condition, and then compared to the finite element model. With the new experimental data, the material properties of the model were changed and updated accordingly. Subsequently, sound testing was performed. The test set up is shown in Figure 19. A speaker in a box was used as excitation source and the sound output was recorded by a microphone at the exhaust end of the muffler shell. The noise input from the speaker was a fixed voltage white noise signal. The microphone was located inside the exhaust pipe, suspended from the structure itself. This was done to make sure that its response was due to the airborne noise input from the speaker only. Accelerometers and an impact hammer were used to measure the structural resonance of the system.

Figure 19. Vibration and acoustic test setup, showing the acoustic source in an acoustically isolated box (at left of picture).

A couple of iterations occurred between so that the coupling between the electrical circuit, the piezoelectric material and the acoustic cavity could be achieved. A second muffler was built and tested. There is a shift in the structural modes of the muffler and that there is a structural mode at 600 Hz that matches the target acoustic frequency.

A new series of inductors was specified with lower DC resistance. Although their size was slightly bigger than the ones used in the first two prototypes, this particular inductor has better electrical properties. Using the same test set up described in the previous sections, considerable vibration reduction could be obtained by the shunt circuit. Two inductors were independently connected to each of the piezoelectric actuators bonded onto the muffler shell. A 14 dB vibration reduction could be obtained at the resonance at 550 Hz, and 11 dB was obtained at the 600 Hz peak. The vibration reduction obtained by the shunt was evident also in the acoustic response of the system. A 5 dB noise reduction was obtained at the 550 Hz and a slight 3 dB reduction was achieved at the higher frequency mode (which moved to 630 Hz).

Notice from Figures 20 and 21 that both in the vibration and noise response the coupling of the shunt circuit causes the frequency to shift to the right (making the system slightly stiffer than the baseline). This is another data point confirming the coupling between the shunt circuit, the mechanical structure and the acoustic response of the baffle-less muffler.

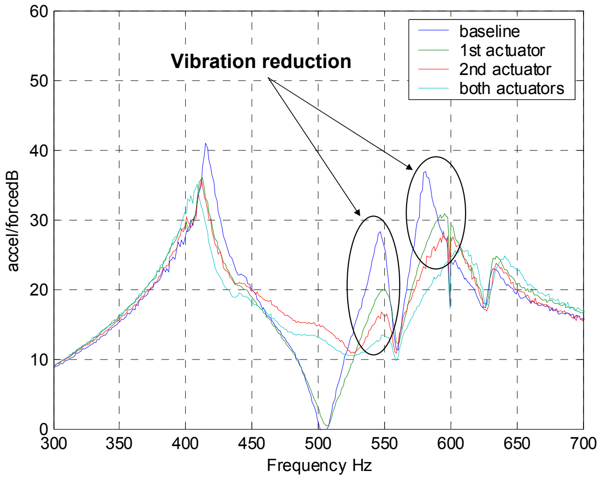

Figure 20. Vibration response of prototype #3 – Baseline, single actuator, multiple actuators.

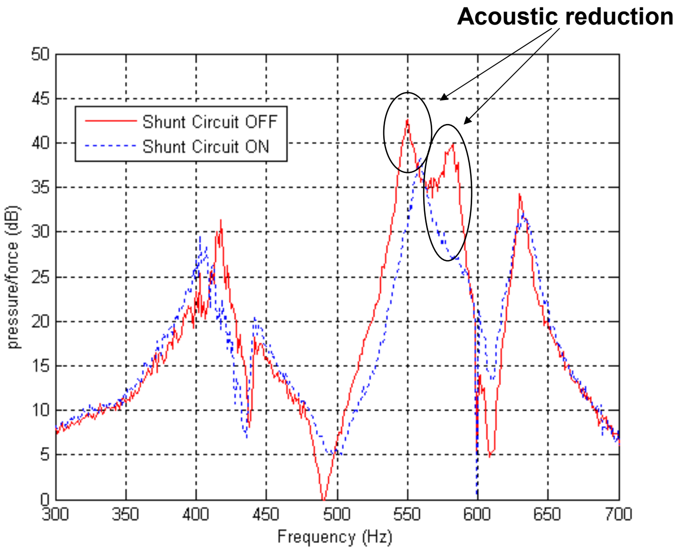

Figure 21. Acoustic response of prototype #3 – Baseline, multiple actuators.

CONCLUSION

Several concepts for coupling the mechanical and acoustic behavior of an exhaust system were designed, analyzed and prototyped. The best result was obtained in a muffler-like structure where the structural acoustic coupling could be achieved in the radiating plate modes of the structure. The RLC shunt circuit was proven to be effective in reducing vibration at a target mode, and if that mode is also coupled to the acoustic response, then the acoustic signature could be modified and noise reduction could be achieved. A 5 dB acoustic noise reduction at the target mode was obtained using this method and a baffle-less muffler structure.

The authors believe that the work presented here is just the first step of a novel approach to reducing noise in an exhaust system. The approach will be the same if it is used in a real exhaust system, but the values of frequency, speed of sound, piezoelectric capacitance, inductor resistance and inductance will change accordingly. The RLC shunt circuit will work as long as the inductance, capacitance and resistance of the system are set to match the specific target frequency of interest. Products have been designed, produced and sold to consumers using this type of approach in the past [5, 6]. Careful consideration will have to be taken by the design engineer so that electrical, acoustic and mechanical properties are matched for the application.

Furthermore, this approach could be expanded to different coupled modes leading the way to a baffle-less muffler design that will lead to minimal back pressure and increased fuel efficiency. Further investigation could address the noise reduction of multiple spaced acoustic modes. The temperature limitation of the piezoelectric material may be overcome by adding thermally insulating material between the muffler structure and the piezoelectric material.

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