

Improved Control Source Concept for Active Cancellation of Exhaust Noise

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ABSTRACT

This work is based on a current project related to auxiliary power unit (APU) exhaust silencing technology development, specifically an active exhaust noise cancellation technology. The overriding technical challenge is identified as development of a frequency and amplitude controllable noise source that can survive in a hot and corrosive exhaust environment.

Installation of an APU enables vehicle platforms to turn off the main engine and still utilize auxiliary equipment that requires electrical power. An APU with a small engine potentially consumes much less fuel than a main engine at low power levels. However, past APU integrations have resulted in unacceptable noise levels, often times louder than the main engine at the equivalent operating point.

Exhaust tones created by combustion pose a unique challenge to external acoustic reduction because they generally occur at low frequency, often less than 100 Hz. Low frequency noise propagates efficiently due to its long wavelength, and requires significant space when treated with a conventional passive silencer or tuner. The performance of a passive silencer is highly dependent on volume and/or length, and effective silencing requires expensive packaging and weight burdens.

The APU application is a very good fit for an active noise control solution due to its predominantly steady state operational characteristics. Typical automotive applications deal with rapid changes in engine speed, which introduce tracking and response time challenges for active control. APU's typically operate at relatively constant speed, eliminating the speed tracking challenge.

A review of literature [1,2,3,4,5] indicates expanding success in integrating active noise cancellation in less severe environments such as headphones, electronics cooling systems, industrial stacks, and aerospace applications, yet limited success has been realized in developing a robust and durable system for use as an engine exhaust silencer. Several promising concepts have been proposed and patented in exhaust applications, but without commercial success primarily due to the lack of a suitable control source. Commercially available sensor technology is more mature and offers durable performance in the exhaust environment.

The active exhaust silencing concept presented in this paper offers the potential for a high payoff solution to the challenges and compromises associated with combustion noise and passive silencing devices. Analysis also indicates that it is very effective in a small, lightweight package. The proposed control source includes an electrodynamic shaker that forces a flexible bellow mimicking a piston in a cylinder. The bellow acts as a barrier, effectively separating the control source from exposure to exhaust gas. The concept eliminates any need to seal a moving joint while providing tunable broadband performance.

The system offers flexibility to perform under changing conditions and can be adapted to other engine applications without major modification to system architecture. The space claim of the selected concept is also smaller than an effective passive silencer targeting the same frequencies. Analysis indicates cancellation performance of roughly 30 dB of broadband attenuation, with 40-60 dB of attenuation in frequencies below 300 Hz.

CITATION: Mattson, S., Kowalski, D., Helminen, R. and Kangas, G., "Improved Control Source Concept for Active Cancellation of Exhaust Noise," *SAE Int. J. Passeng. Cars - Mech. Syst.* 6(2):2013, doi:10.4271/2013-01-1952.

INTRODUCTION

The main technical challenge associated with the active cancellation system has been identified as integration and selection of components to enable durable performance in the exhaust environment. Specifically, elevated temperatures, corrosive gas, pressure, and flow rates all contribute to create a difficult environment for actuators and sensors to survive and function. The main innovation resulting from this effort is an actuator concept that eliminates the need for direct exposure of the actuator to the exhaust gas. The actuator concept provides excellent low frequency response.

Additional benefits resulting from this research include modeling and simulation techniques that are capable of accurately modeling the physics of the problem. A complete modeling methodology to facilitate design of the physical active exhaust cancellation system is presented in detail.

TECHNICAL DISCUSSION

A comprehensive process has been developed to facilitate design and optimization of an active noise control system for engine exhaust applications. The process allows for appropriate selection of components, specifically the control source and flexible bellows. A flow chart providing a visual description of the process is included below. Each of the blocks in the flow chart is described in detail in the following subsections.

The goal of sizing the control source and bellows is to choose components that will provide noise generation sufficient for cancellation while maintaining a reasonable size and weight. The current design uses a 25 lbf shaker as the control source and a 3 inch nominal flexible bellows with a 70 lbf/inch spring rate, which is sufficient for producing effective cancellation values.

The initial input to the process is a sound pressure spectrum measured in the exhaust pipe at operating condition. This data is used to estimate the level of sound power created by the engine, assuming a fully reflective boundary condition at the engine manifold. In reality, an engine specific complex acoustic impedance is present at the manifold interface that would allow improved active cancellation performance.

Control Source Placement

Significant time and effort was dedicated to developing an algorithm to optimize the control source location. Optimization of control source placement is important because it allows for more effective cancellation using smaller components and less power, resulting in an overall efficiency improvement for the active cancellation system. Initially a simple approach was used to place the control source at the position where the maximum overall sound pressure level (SPL) occurred in the pipe. However, this proved to be a less than optimal approach because it does not effectively account for important acoustic modes of the exhaust system. An improved algorithm for control source placement is currently under development.

Component Selection

A bellows and control source are initially chosen, and acoustic/structural analysis is run to determine the input levels necessary for active cancellation. Cancellation performance is predicted with the selected components and then re-evaluated with truncated force inputs to represent the limitations of the control source, as certain frequencies may require forces greater than what is capable from the control source for complete cancellation.

Once the analysis sequence is run, the displacements and forces are assessed, and the control source and bellows are re-sized as needed. The biggest challenge in sizing the system is deciding how much force from the control source is necessary to provide "sufficient" cancellation. Due to the harmonic nature of the engine source, the sound pressure contains large tonal peaks at several frequencies and it may not be possible to fully cancel each with reasonably sized components.

Durability/Environment Assessment

The bellows stress results are compared to the fatigue endurance limit. Stresses in excess of the endurance limit require modification to the bellows to reduce stress which can include material changes, modified or additional convolutions, or a larger diameter bellow resulting in lower deflection to create similar volume velocity.

CFD/thermal analysis is run to determine the contact surface temperature between the control source and bellows, the bellows wall temperature, and the back pressure of the system. A specific challenge in active exhaust systems is getting the control source to survive in a hot environment. Fluid/thermal modeling is useful in understanding the heat rejection requirements for controlling the temperature of the shaker.

CONTROL SOURCE DESIGN CONSIDERATIONS

Coupled Vibroacoustic Model

A coupled structural and acoustic analysis is used to simulate important acoustic and structural properties of the system. [Figure 2](#) shows an example of a coupled model. Some general features of the coupled model are:

- The exhaust pipe is modeled as a rigid body - a reasonable assumption for this analysis since flexible modes of the pipe capable of influencing the acoustic response occur above the analysis frequency range
- Mass and stiffness properties in the bellows and end cap are represented using plate formulated finite elements (FE)
- Force is applied to the end cap to simulate the actuator

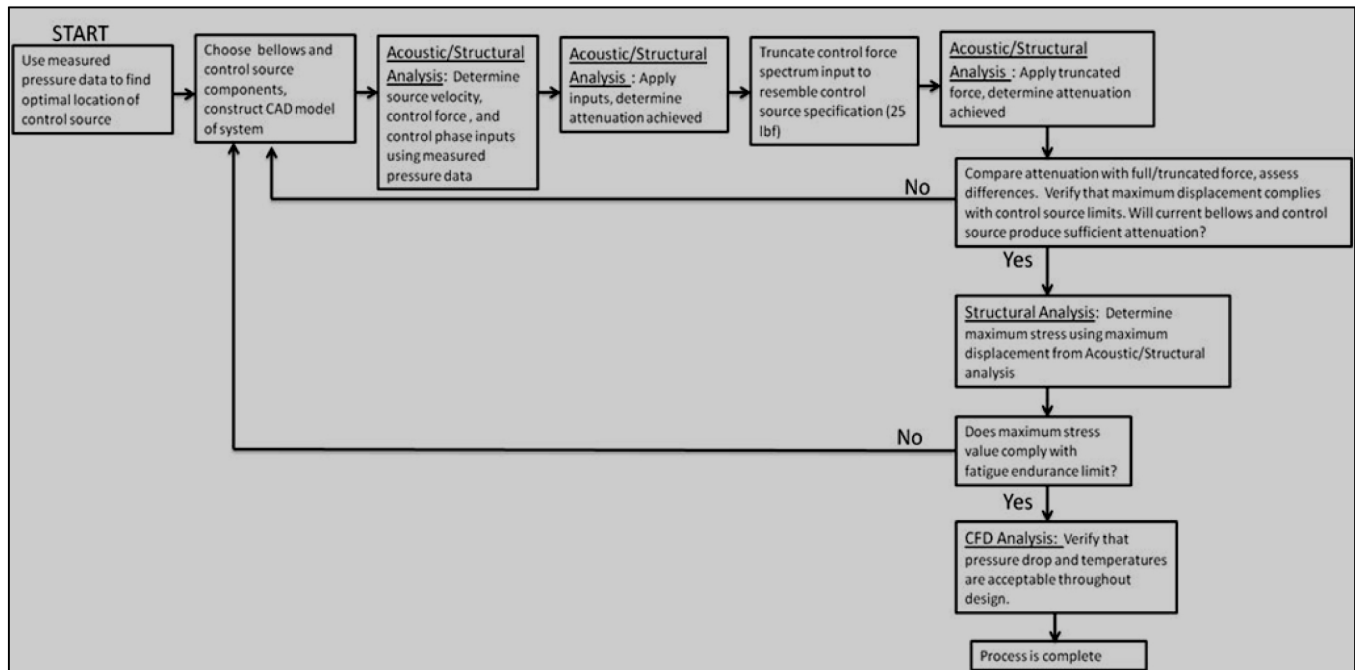


Figure 1. Design flowchart

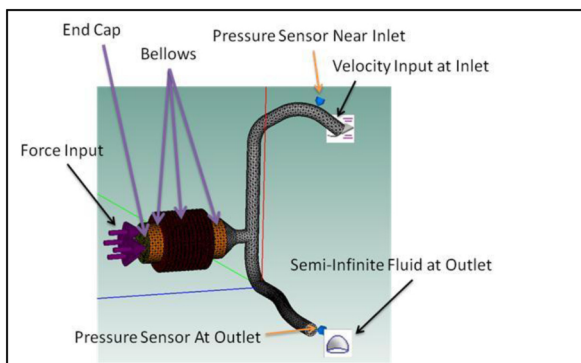


Figure 2. Acoustic/Structural Analysis Description

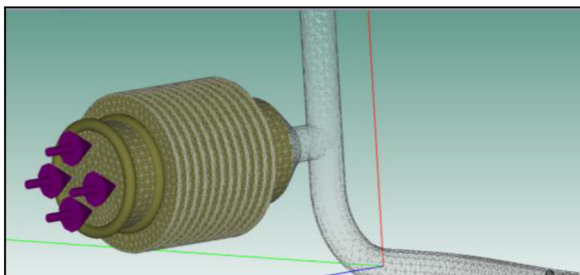


Figure 3. Area junction - structural to acoustic.

The coupling between structural mesh and the acoustic mesh is accomplished using an FE junction formulation. Figure 3 illustrates the area junction that couples the acoustic and structural response in the model. This junction effectively

couples the structural velocity at structural nodes to the acoustic cavity velocity at acoustic nodes.

Source Power Characterization

An acoustic model was created to derive the engine source strength spectra. The model mimics the physical system used to measure the in-pipe noise spectra. The noise due to the engine source is introduced using a velocity constraint at the interface between the exhaust manifold and the exhaust pipe. The velocity constraint is adjusted until the acoustic pressure at the virtual sensor matches the measured sound pressure data. An image of this model is included in Figure 4.

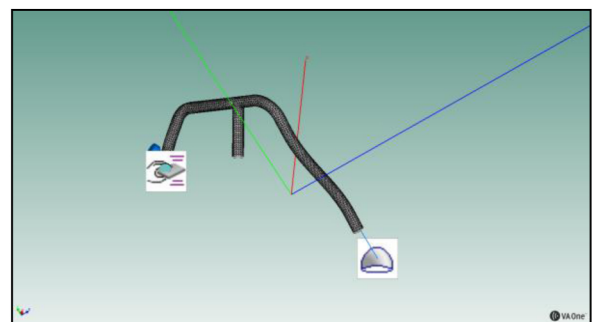


Figure 4. Model used for Engine Source Strength Estimate.

Subsequent analyses are run to verify the sound pressure magnitude and phase required by the control source to provide maximum cancellation at the error sensor. The acoustic pressure measured near the end of the exhaust pipe is