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A HYBRID ACTIVE-PASSIVE SYSTEM FOR CONTROLLING LOCOMOTIVE EXHAUST NOISE

P. Remington*, S. Knight, D. Hanna**, C. Rowley****

* BBN Technologies, 10 Moulton St., 02138, Cambridge, MA, United States Of America

** BBN Technologies, Union Station, 06320-6147, New London, CT, United States Of America

Tel.: 617-873-3240 / Fax: 617-873-2918 / Email: premington@bbn.com

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ABSTRACT

A hybrid active-passive exhaust noise control system has been designed, installed and tested on a locomotive. The active system utilizes eight actuators and eight residual microphones in an adaptive feedforward configuration to control tonal noise below 200 Hz. The passive system is a compact exhaust silencer designed to control exhaust noise above that frequency while still fitting within the limited space available beneath the locomotive hood. The system has been installed on an F40PH locomotive on the Chicago Metra and tested under stationary conditions. The system performed well providing 4 to 9 dBA of noise reduction depending on operating condition and measurement location while maintaining the temperature of critical components within allowable limits.

1 - INTRODUCTION

In the United States railroads are powered primarily by diesel electric locomotives. These locomotives generate considerable noise and are responsible for increasing the environmental impact due to noise from railroad operations. The diesel engine exhaust on these machines is the most important noise source and must be treated (along with other sources such as the cooling fans) in order to obtain significant reductions in overall noise. Current silencers utilized in locomotives provide very little exhaust noise attenuation. There is a need for higher performance silencers but they must create very little backpressure and must fit within the limited space in the engine compartment. The approach exploited here is to use an active system to control low frequency noise and a passive silencer to control high frequency noise. This is an ideal melding of the two technologies. At low frequency passive systems must be large and heavy to provide high noise reduction with minimum backpressure whereas active systems can be more compact. On the other hand at high frequency passive silencers can provide good noise reduction in a fairly compact package. For large diesel engines there is an added advantage of this approach. In large diesel engines, such as found in locomotives, the exhaust noise signature at low frequency is dominated by tones at multiples of the rotation rate of the engine. Since active control technology is well developed for controlling tonal noise, its application to the control of low frequency exhaust noise in these engines is ideal. While this approach is specifically directed to controlling locomotive exhaust noise, it is also applicable to the control of exhaust noise from any large diesel engine application with severe weight, space and back pressure constraints.

While the technology for feedforward active control of tonal noise is well established and the design of passive silencers for controlling exhaust noise is certainly not new, the synergistic combination of both active and passive systems to accomplish broad band control of exhaust noise is unique, especially as applied to locomotives. Furthermore while the basic technologies are well established, the details of their application presented numerous technical challenges. The sound pressure levels of tones below 100 Hz in the exhaust exceed 140 dB placing considerable demands on the displacement of the control speakers. Temperatures in the engine compartment easily exceed 260 °F requiring special cooling of the control speakers and monitoring of their temperatures. The system had to fit within very limited space within

the engine compartment with minimal changes to the locomotive structure, thereby limiting the size and acoustic performance of the control speakers and passive silencer.
In Sec. 2 below we describe the system components and their installation in an F40PH passenger locomotive. Section 3 enumerates the testing that was carried out to evaluate the acoustic performance and presents the results

2 - THE ACTIVE/PASSIVE SYSTEM

The active-passive system components are illustrated schematically in Fig. 1. The system utilizes a multiple input multiple output (MIMO) feedforward active control system to drive twenty 12-in. high fidelity speakers in ten enclosures (two speakers in each enclosure) surrounding the exhaust outlet. The control speakers are installed in a cool box, which provides physical and thermal protection. A digital controller tailors the sound generated by the control speakers to reduce the low frequency (<200 Hz) tonal noise from the exhaust as measured by eight control microphones. The control microphones are mounted on the roof of the locomotive on each side of the exhaust outlet near the edge of the locomotive hood. An optical tachometer monitors engine speed. The system controller utilizes the-tachometer as a reference sensor and the eight control microphones as residual sensors. These nine inputs are used by the controller in the MIMO Filtered-X LMS algorithm to adjust the control filters, such that when they are driven by the tachometer signal the exhaust noise at the control microphones will be optimally reduced. The outputs of the eight control filters are connected to 10 pulse width modulated (PWM) amplifiers used to drive the control speakers. Each amplifier drives two speakers in each of ten band pass enclosures designed to enhance the sound power output in the 40 to 250 Hz band. Note that two sets of enclosures are driven in pairs by two controller channels, and the remaining six enclosures are driven by the remaining six controller channels. Since the plant transfer functions (relating control speaker input voltage to control microphone output voltage) must be known in order to employ the Filtered-X algorithm, there is also a system for continuous covert measurement of those transfer functions.

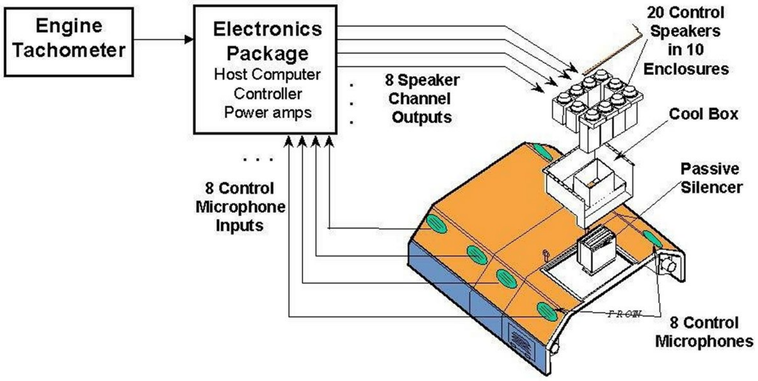

Figure 1: Components of the active-passive system.

The active system is designed to provide low frequency tonal reduction of exhaust noise in the environment surrounding the locomotive. Reducing the noise at the control microphones on the hood of the locomotive does not necessarily guarantee that the noise will be reduced everywhere (globally) around the locomotive. However when the speaker enclosure outlets are placed as close as possible to the exhaust outlet, compatible with the locomotive geometry, analytical estimates indicate that good far field cancellation will occur everywhere around the locomotive near ground level up to approximately 300 Hz.
The passive silencer design is shown in Fig. 2. Its geometry is sufficiently complex that its design was carried out with the aid of finite element analysis. In size it is a little larger than a 2-ft. cube. The design consists of a two large baffled cavities in the side walls and a small baffled cavity in the center body, all covered with a flow resistive screen (five layers of 11 % open area screen cloth with a total flow resistance of 600 MKS Rayls at 650°F). In addition there is a labyrinth in the center body near the exit of the silencer tuned to 250 Hz with a 4 % open area perforated metal screen over the entrance. All of these silencer components have been designed to provide an insertion loss that together with the active system will yield the desired exhaust noise reduction.
The test locomotive is shown untreated in Fig. 3a and with the active system installed in Fig. 3b. Figure 3b shows a view of the locomotive from the roof looking forward. It shows the 10 control speaker outlets surrounding the exhaust outlet, covered by their circular weather protective covers. The eight control

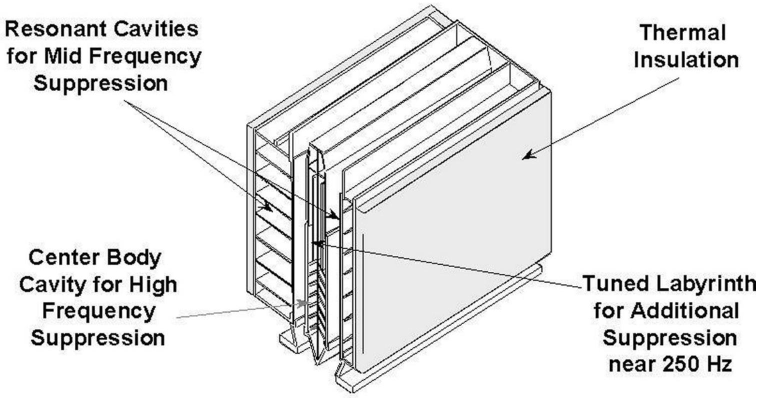

Figure 2: The passive silencer.

microphones are also shown in their protective enclosures near the edge of the roof of the locomotive. The exhaust outlet can be seen in the center of the cluster of speaker outlets. Below the outlet and not visible in the figure is the new passive silencer.

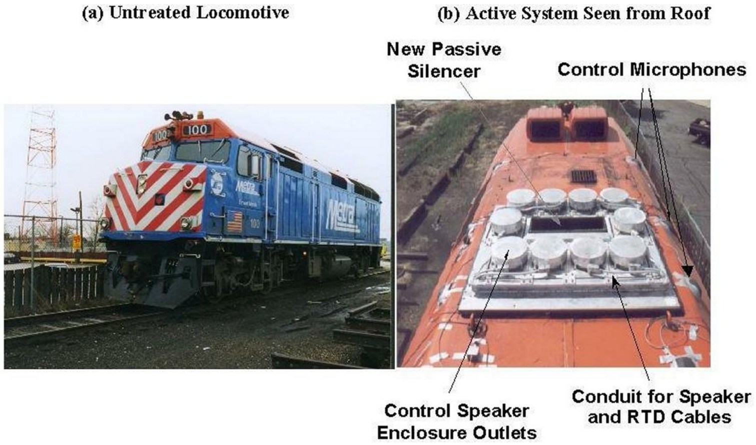

Figure 3: The test locomotive.

3 - NOISE REDUCTION PERFORMANCE

A plan view of the microphone arrangement for testing the locomotive is shown in Fig. 4. Four far field microphones were used to determine the noise reduction far from the locomotive and one roof-mounted microphone measured the noise reduction near the control microphones. While it would have been desirable to have additional far filed microphones located on both sides of the locomotive, the limited space in the 51st Yard of the Chicago Metra and the nearness of sources of high background noise prevented our doing so. For example, one side of the locomotive was against the property line in order to allow us enough room to place two microphones 100 ft from the locomotive but away from the large reflecting surfaces of nearby buildings. In addition because the site is in an urban area, the presence of heavy truck traffic, transit lines and construction activities created intolerably high background noise at some locations in the yard further limiting microphone placement.

The locomotive was tested while stationary in both a loaded and unloaded condition. Loading the locomotive was accomplished using its self-load capabilities by dissipating locomotive power from the main alternator through its dynamic brake resistor grids. During self-load to prevent overheating of the resistor grids the dynamic brake fan operates and draws cool air over the grids. Noise from the dynamic brake fan did not contaminate the measurements of the performance of the active system, because the exhaust noise tones could be distinguished from fan noise both near the exhaust outlet and in the far field. The performance of the passive silencer under loaded conditions, however, could not be reliably measured in the far field. Consequently we relied on the measurement of noise near the exhaust outlet before and after installation of the new silencer to determine silencer insertion loss.

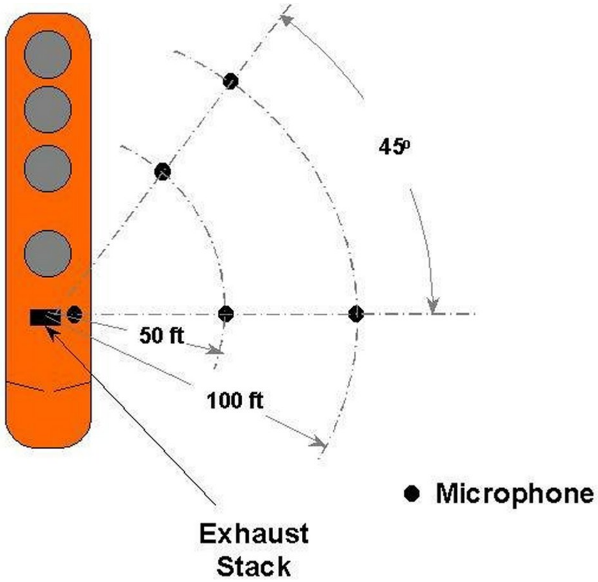

Figure 4: The arrangement of microphones for testing.

The noise at the five locations in Fig. 4 was measured before installation of the system and once again after installation. Figure 5 shows the before and after comparison for the combined active passive system as measured by the roof top microphone. The figure shows overall noise reduction of between 4 and 9 dBA. Especially encouraging is the 9 dBA reduction at high idle and the nearly 7 dBA reduction at throttle 8 loaded, the full power setting of the locomotive. The latter is especially important since it is typically one of the most common operating condition for the locomotive and in addition is the noisiest. Direct measurement of the far field noise reduction of the combined system is difficult because of the high background noise at the test site and the contaminating noise from the dynamic brake fans. We did, however, make an estimate of the noise reduction at the four far field microphones by directly measuring the noise reduction of the active system at those locations and using the noise reduction of the passive silencer as measured by the roof top microphone to compute the far field noise reduction for the combined system. The result for each location showed noise reductions quite similar to those in Fig. 5.

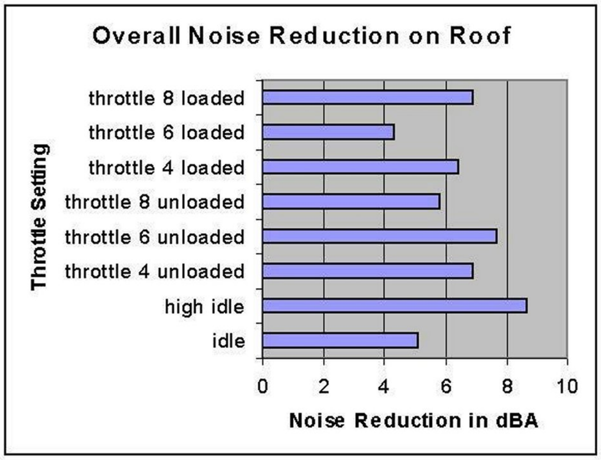

Figure 5: Overall noise reduction of the active-passive system as measured on the roof of the locomotive near the exhaust stack.

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