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Development of passive and active noise control for next generation locomotive cabs

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ABSTRACT

The noise environment in a locomotive cab has been the focus of recent attention by the Federal Railroad Administration (FRA). In October 2006 the FRA established a new rule to amend its existing occupational noise standards for railroad employees whose predominant noise exposure occurs in locomotive cabs. The noise exposure rule is expressed in terms of the A-weighted noise level and is consistent with OSHA limits set for general workplace noise exposure. Recent studies have shown that low-frequency sound can be an important contributor to noise induced hearing loss as well as fatigue. Therefore the focus of the FRA rule on the A-weighted noise level may not be enough to guarantee a fatigue-free cab environment where low-frequency sound sources are dominant. This paper describes the research project sponsored by the FRA to demonstrate the feasibility of a combination of passive and active noise controls in the cab of next generation locomotives. A mock-up of a locomotive cab was used to demonstrate the feasibility of active noise control to reduce the low-frequency noise levels. The active noise control system focused on eliminating key pure tones that are typically found in the noise spectrum from a diesel engine.

1. INTRODUCTION

The Federal Railroad Administration (FRA) is sponsoring a research program conducted by QinetiQ North America (QNA) Technology Solutions Group formerly Foster-Miller Inc. (FMI)

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to develop the “Next Generation Locomotive Cab.” An SD70MAC locomotive cab shell was obtained by QNA and fully outfitted to demonstrate various safety, ergonomic, and employee health-related upgrades, including vibration and noise control. Harris Miller Miller & Hanson Inc. (HMMH) is working with FMI on various alternative design approaches to reduce in-cab noise. Both passive and active noise control treatments are used to achieve permissible limits for preventing crew hearing loss and fatigue.

2. BACKGROUND

A. FRA Noise Regulations

The noise environment in a locomotive cab has been the focus of recent attention by the Federal Railroad Administration (FRA). In October 2006 FRA promulgated a new rule[1] to amend its existing occupational noise standards issued in 1980 for railroad employees whose predominant noise exposure occurs in the locomotive cab. The rule limits cab employee noise exposure to levels that average less than or equal to 85 dBA consistent with OSHA limits set for general workplace noise exposure. However, FRA points out the cab environment is a mobile workplace and as such is quite different from the typical environment of American workers protected by OSHA. Consequently, FRA places additional requirements on the railroads, including performance standards and other requirements for the design and maintenance of locomotives in the future.

B. Existing Conditions in Cabs of Diesel Locomotives

Noise surveys in locomotive cabs were performed by FRA inspectors and others as background information leading to the rule. Although noise levels in the cab change from moment to moment during typical locomotive operations, levels were found to average 88 dBA under throttle 8 operations, a condition which occurs over 50% of the time for a typical road locomotive. This level is high enough to provide an increased risk for Noise Induced Hearing Loss (NIHL) for railroad employees. There are many noise sources in a locomotive that affect the noise levels in the cab. The major steady source is the diesel engine. Noise from the engine varies according to load and speed, but the main component of the sound spectrum is the fundamental engine rotation speed and its harmonics. This sound spectrum peaks in the range of 50 Hz to 250 Hz, and it sounds like a constant low-frequency rumble. Another important source is the horn, which although intermittently used, is extremely loud in the cab directly below its mounting. Horns are higher in frequency, between 250 Hz and 600 Hz[2], in the range where humans are sensitive to sound. A third key source is the pressure release noise from the air brakes, a source that used to be located in the cab itself, but which has been relocated below the floor in newer locomotives. Even though the release valve is below the floor, the high frequency hissing noise (4000 Hz to 8000 Hz) from the brake system can be a noisy event. In addition, there are secondary sources that add to the noise environment in the cab, including engine cooling fans, alerter sounds, radio communications, and warning bells. Noise levels in a cab from some of these sources are often unmitigated with open windows – a common condition for locomotives without functioning air conditioning in the summer.

There is another potential risk other than NIHL of the railroad employees. When all sources are combined, the noise level masks what could possibly be critical information for safe train operations. When the crew has to shout to each other to be understood, there is a potential for interference with reliable communications.

C. Limitations of the Noise Exposure Rule

The noise exposure rule is expressed in terms of A-weighted sound level (dBA). Sound levels measured with the A-filter are meant to represent the way in which the human hearing system works, but repressing low frequency (below 250 Hz) and high frequency (above 4000 Hz) sounds. Recent studies have shown that low-frequency sounds can be an important contribution to NIHL as well as operator fatigue[1]. Therefore, the FRA rule focus on dBA may not be enough to guarantee a fatigue-free cab environment where low-frequency sound sources are dominant. Consequently, if a quieter cab environment is going to be a part of the next generation locomotive, something must be done to control the sound environment in the cab from the full range of noise sources.

3. FUNDAMENTALS OF CAB NOISE

The noise environment of a locomotive cab is the result of the contributions from many sources. Sound is transmitted to an operator's ears via an air-borne path and vibration is transmitted through the structure. A sealed window and door will break the sound path from airborne noise generated outside the cab, resulting in significant noise reduction. A complicating factor is that sound waves are also generated by structure-borne vibrations of the walls, ceiling and floors inside the cab. Each of these surfaces acts like a loudspeaker and re-radiates sound at the frequencies carried in the frame, as well as resonant panel frequencies of their own.

The dominant source of structure-borne vibrations is the diesel engine. Vibrations generated by the engine at its rotational speeds are transmitted throughout the locomotive chassis. If the cab is mounted directly on the same chassis structure as the engine, the vibrations will be transmitted directly to the panels and will re-radiate as sound waves to the interior of the cab. Moreover, the interior of a typical cab is generally made of hard reflective surfaces that create a reverberant space so the sound waves are undiminished as they bounce off the interior surfaces. The shape of the cab also has an effect in worsening the situation. Resonant modes—areas of anti-nodes and nodes ("noise hot spots" and "cold spots") form in the space so that noise levels may be extremely high in one place and lower in another.

Consequently, the challenge in providing noise control for the locomotive cab involves breaking the structure-borne paths as well as all the air-borne paths between sources and the receiver. Additionally the low frequency nature of the sound and large wavelengths are challenging to deal with.

4. SOUND LEVELS INSIDE A LOCOMOTIVE CAB

HMMH measured the noise inside the cab of an Alaska Railroad SD70MAC locomotive during a gravel train trip from Palmer, AK, to south of Anchorage, AK, in late September 2006. This model features the "Whisper Cab" treatment. Consequently, this cab represents the best available noise control technology on the market today.

Figures 1 and 2 below show the results of measuring the noise levels inside the cab for a short segment at throttle setting 8 and a stationary segment at idle. In all cases the in-cab noise levels are well below the limits in the FRA rule, expressed in dBA. However, the low frequency components, below 200 Hz, dominate the overall noise level. It is interesting that even at idle, the low frequency peaks at 20 Hz and 50 Hz are comparable to those measured at throttle 8. This means that even at idle the engineer continues to be exposed to the low frequency noise that may be a key factor in causing fatigue. This frequency spectrum provides compelling evidence to support the need for control of low-frequency noise in Next-Generation Locomotive Cabs.

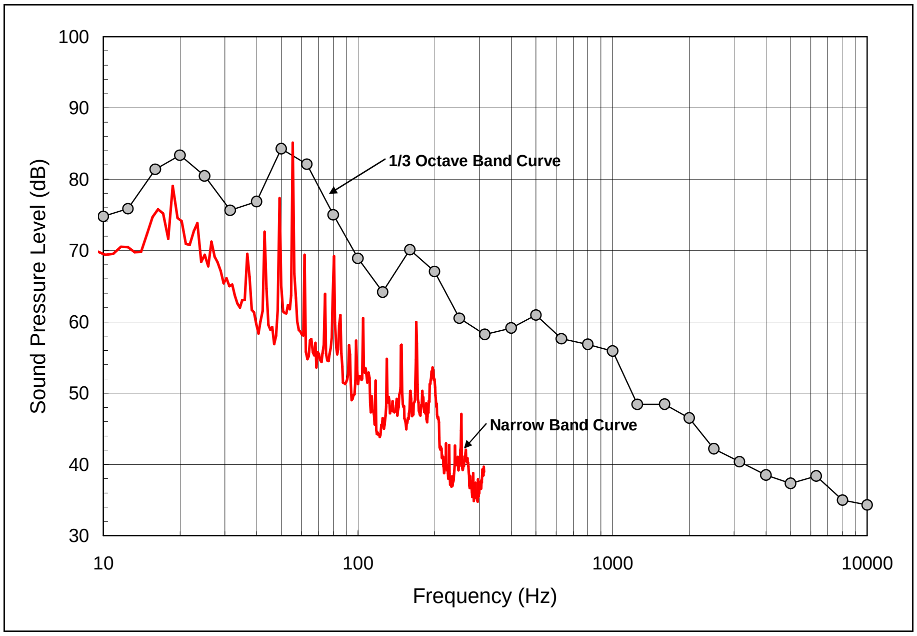

Figure 1: In-Cab Noise at Throttle 8Averaged Over 40 Second Duration at 9 mph

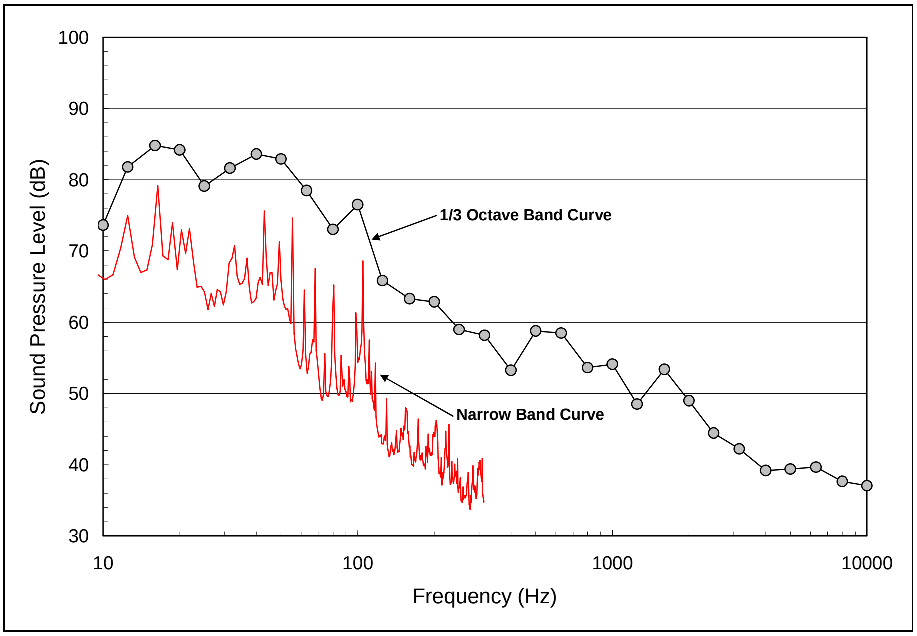

Figure 2: In-Cab Noise Level at Idle

5. APPLICABLE NOISE CONTROL TECHNOLOGIES

A. Passive Technology

Noise control in an enclosed environment like a locomotive cab can be implemented through the use of passive methods. Damping material is attached to the interior panels to reduce structure-borne vibrations, and a covering of acoustically absorptive material is applied to exposed parts of the walls and ceiling to cut down on the reverberant noise. Passive treatments are effective over a broad range of frequencies and can be quite effective, especially in the range of 200 Hz to 10,000

Hz where the human hearing system is most sensitive. The negative side of passive treatments is that they add weight that increases axle load without being productive for the railroads.

Damping tiles are available in sheets with pressure sensitive adhesive for attachment to bare metal panels. Damping of panel vibrations takes more mass to reduce amplitudes of the low-frequency vibrations than to reduce the high-frequencies. Panels of a locomotive cab vibrating at 50 to 200 Hz would require thick, heavy coatings of damping material, thereby adding to the weight problem.

The usual sound absorption methods for walls and ceilings are effective at higher frequencies where the wavelengths are on the order of one foot or less. An ideal application of passive sound absorption requires open cell foam of about one-quarter wavelength to be effective. Obviously it is impossible to apply acoustical material more than 1-foot thick to the inside of a locomotive cab, but the principle is valid – the thicker, the better. And, of course, the penalty is more weight.

B. Active Technology

A recent innovation in noise control technology is “Active Noise Cancellation” (ANC). The physical principle behind this technology is not new – the concept has been around since the 1930’s, but it has only been recently that computer-aided control systems have been developed to handle the signal conditioning requirements. The concept is quite simple – sample the sound signal, create a signal of opposite phase, and add the new signal to the sound to result in a cancellation.

Most cases are complex. The sound signal is often not periodic. The sound field is distributed. The incoming sound cannot be sampled adequately. The cancellation may not be perfect, but reduction still can be attained through application of the technology.

A feedforward system is appropriate for a locomotive cab environment where the incoming signal can be measured, conditioned and sent to a secondary source for cancellation. This type of system requires knowledge of the cancellation performance of the signal at the crew positions where cancellation is desired so that adjustments can be made on a continuous basis. An example of the application of ANC technology in a locomotive environment is proposed by the NVH Controls Systems Division of Cooper Tire & Rubber Co. with promising test results[3].

6. APPLICATION OF NOISE CONTROL TO A LOCOMOTIVE CAB

A. Estimated Performance of Noise Control Methods

Taking the measured one-third octave band noise spectrum from Figure 1 as an example, an estimate can be made of the effectiveness of various noise control treatments to a locomotive cab. Figure 1 shows the results of in-cab noise measured over a 40-second period in which the locomotive was at throttle 8 setting and pulling the gravel train at 9 miles per hour. Consequently, the dominant noise was from the engine and associated equipment and little contribution from outside sources such as the wheel-rail interaction.

Although a thorough diagnosis of noise sources was not conducted, an estimation of typical noise reductions over various frequency ranges can be made. The measured locomotive was an EMD SD70MAC equipped with the “Whisper-cab” treatment with rubber isolation pads between the cab body and the frame, special door and window seals, and sound absorption on ceiling and walls. The actual treatments and their effectiveness is proprietary information and have not been made available. However, basic principles of noise control allow estimates to be made of the effectiveness of various treatments. Assumptions are listed in Table 1 with the resulting noise reductions applied to the measured in-cab noise spectrum shown in Figure 3.

Table 1: Estimated Effectiveness of Noise Control Treatments

Noise Control Treatment	Estimated Noise Reduction	Effective 1/3 O.B. Frequency Range
Rubber isolating pads	3 dB	4 Hz – 100 Hz
Active Noise Cancellation	7 dB	31.5 Hz – 200 Hz
Steel panel damping	3 dB	200 Hz – 10, 000 Hz
Acoustical absorption on ceilings and walls	5 dB	500 Hz – 800 Hz
	10 dB	1000 Hz – 2500 Hz
	15 dB	3150 Hz – 10,000 Hz

All of the treatments except the active noise control (ANC) are applied to the “Whisper Cab” and none of them are applied to the “Untreated cab” in our example. Table 2 shows the comparison of the effectiveness of the noise reductions on the overall un-weighted noise level and the A-weighted noise level in each case. The base case is an assumed “untreated cab.” The expected results from the introduction of ANC and passive noise control show that the overall noise levels may decrease only two or three dB. However, there is a dramatic decrease in estimated low-frequency noise from 30 Hz to 200 Hz, the range of frequencies thought to be an important factor in combating fatigue. Any further reductions below 30 Hz would have to be the result of application of vibration isolation.

Table 2: Estimated Results of Noise Control Treatments for Various Cab Configurations

Configuration	Noise Reduction compared to Untreated Cab	
	A-weighted	Un-weighted
Untreated (baseline)	0	0
Cab with ANC	2	2
Cab with Passive NC	7	2
Cab with ANC & Passive NC	9	5

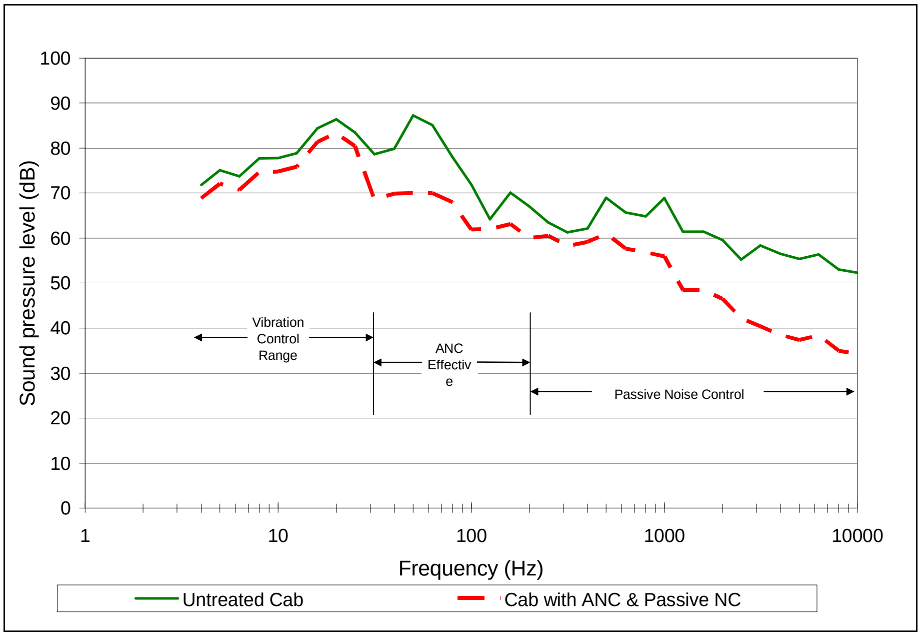

Figure 3: Estimated In-Cab Noise Spectra from Application of Treatments

B. Active and Passive Noise control in Mock-up of Locomotive cab

The QinetiQ North America (QNA) mock-up of a locomotive cab is intended to demonstrate the interior features of a next-generation cab. For this project, QNA outfitted the shell of an SD-70MAC cab with a new interior that simulates the improvements in ergonomics and advanced displays as well as an isolated floor to reduce undesirable vibrations that could be a prototype for the next-generation cab. Along with passive noise control treatments in the interior of the cab, the project includes a demonstration of the potential effects of an ANC system to reduce the low-frequency sounds that lead to crew fatigue.

The sound field inside a real locomotive cab is generated both by outside sources, primarily the diesel engine, as well as by vibrations of interior panels. Lacking an engine for the mock-up cab, however, the sound from a diesel engine is replicated by a loudspeaker and subwoofer system positioned behind the cab.

Inside the cab, noise reduction of higher frequencies is provided by passive treatments. All interior panels are covered with sheets of vibration damping material (Soundown Vibration Damping Sheets, ¼” thick, 1.9 lb/ft^2). Acoustical open cell foam is applied over the damping sheets (Soundown Open Cell Foam, 2” thick, 0.28 lb/ft^2). A thin perforated aluminum panel provides a protective cover for the foam.

The ANC system is made up of four key components: a controller, a reference microphone, an error microphone and a control loudspeaker.

The ANC system used in the mock-up cab is controlled by on an off-the-shelf “EZ-ANC II” unit manufactured by Causal Systems. EZ-ANC II is a professional product for use as a tool in research and development. The system combines hardware with a computer interface for parameter adjustments. Up to 10 reference and error signals and up to 10 control outputs can be handled by this unit. Although it is not a field-hardened unit, the EZ-ANC II is sufficient to demonstrate the potential of ANC in a locomotive cab.

Microphones are used to measure the sound from the diesel engine (reference microphone) and the sound at the location where cancellation is desired (error microphone). The reference microphone on the mock-up is located outside the cab facing the diesel engine simulation loudspeaker. Inside the cab, the error microphone at the seat headrest location measures the amount of cancellation and provides continuous information for the controller to adjust the signal to the control loudspeaker inside the cab.

The control source is a loudspeaker installed in the ceiling above the seat. The loudspeaker is a Thor 10” in-wall subwoofer driven by an XJ600R matched pro-amplifier, both manufactured by Earthquake Sound Corporation. The loudspeaker is housed in an extremely shallow case that allows for in-ceiling application. As with other elements of the ANC system, the loudspeaker is adequate for demonstration purposes but is not field-hardened. Figure 4 shows the locations of the control loudspeaker and the error microphones in the mock-up cab.

Figure 4: Error Microphones on Seat and Control Loudspeaker in Ceiling

7. RESULTS

A. Passive Noise Control

Noise measurements were made inside the cab before and after installation of the passive treatments. A pink noise spectrum was played through the exterior loudspeaker system mounted outside the cab in both configurations. Performance of the passive noise control treatment is shown in Figure 5. Six to 10 decibels of reduction was measured between 200 and 10,000 Hz. Below about 200 Hz the passive treatment is essentially ineffective.

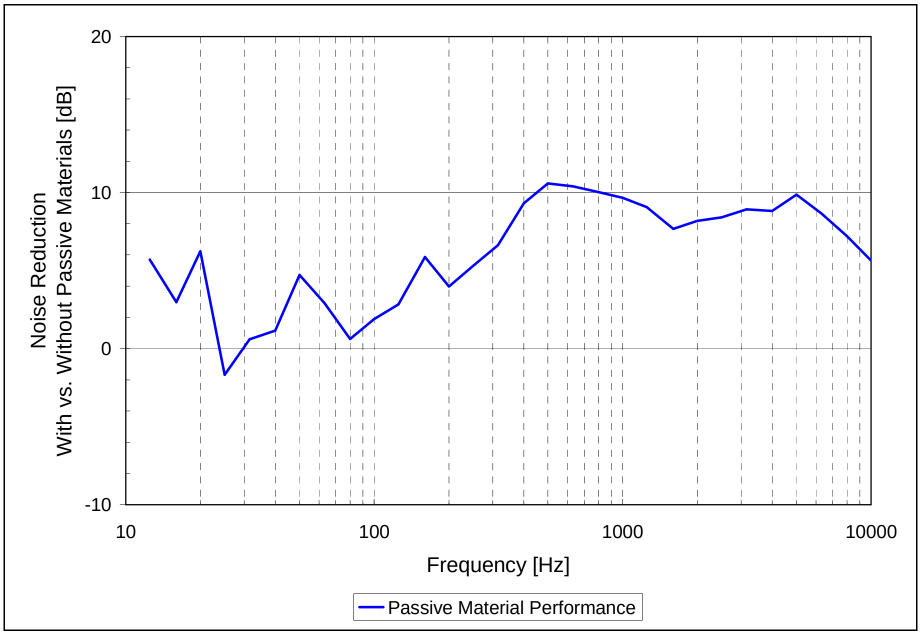

Figure 5: Measured Noise Reduction of Passive Noise Control Treatment in Cab

B. Active Noise Control

Measurements of the ANC system to date have focused on eliminating key pure tones that are typically found in the noise spectrum from a diesel engine. Typical results are shown in Figure 6, where the tones at three frequencies (57 Hz, 67 Hz, and 89 Hz) are each reduced by about 30 dB. The reduction is strongly noticeable in a space of about three feet around the head of a person sitting in the seat. This space is centered on any possible movement made by a person leaning forward and to the side of the seat. Some observers have commented that the reduction does not appear to be dramatic. However, the human hearing system does not respond well to frequencies in this low range. The effect may well be in reduction of fatigue more than in reduction of audibility.

Note that the cancellation of sound at low frequencies is quite effective, but sound at some higher frequencies may have been amplified. Further tuning of the system with more control sources and more error microphones is required to address these effects.

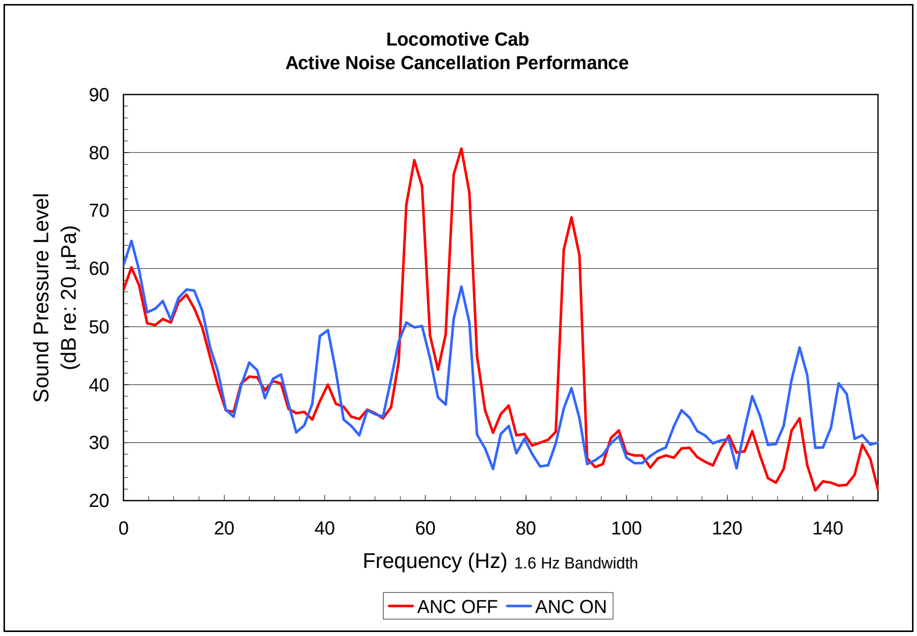

Figure 6: ANC Performance in Cab

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