Williamsburg, Virginia
ACTIVE 04
2004 September 20-22

Global Control in a Mock Tractor Cabin Using Energy Density

Benjamin M. Faber, Scott D. Sommerfeldt
Department of Physics and Astronomy
N283 ESC, Brigham Young University
Provo, UT 84602
benfaber@byu.edu

ABSTRACT

Low frequency tonal noise, associated with engine firing frequency, often makes a significant contribution to sound levels that exist inside tractor cabins. Because these tones are low frequency in nature, they present a considerable challenge to passive noise control techniques, but are good candidates for active noise control applications. The presence of such noise can also threaten machinery operators' auditory health in addition to posing a challenge to machinery manufacturers in their efforts to produce machines that meet standards for operator exposure to noise.

Active minimization of acoustic energy density has been applied to a mock tractor cabin, targeting engine firing frequency in simulated static and dynamic machine conditions. Previous work has demonstrated that active control of energy density generally provides good global control of enclosed sound fields. Multiple microphones were distributed throughout the cab to verify the global nature of the control. Generated sinusoids as well as actual recorded tractor noise were used to simulate the uncontrolled acoustic field. Both static and dynamic results will be presented, showing the local attenuation at the error sensor and the global attenuation throughout the cab.

1. INTRODUCTION

Significant motivations exist for noise reduction in heavy equipment cabins. The noisy environments often encountered in heavy equipment cabins pose a risk to the health and safety of machinery operators, due in part to the amount of time operators spend in such environments.[1,2] Auditory fatigue and discomfort could potentially be reduced and mental concentration and job efficiency increased through the reduction of operator noise exposure. The need for equipment manufacturers to meet existing and future standards for operator exposure to noise presents another reason for the employment of relevant technology in the reduction of noise inside equipment cabs.

Prior investigation of noise in tractor cabins showed that discrete tones that are harmonically related to the rotation speed of the tractor's engine generally dominate the noise spectrum.[1-4] The tonal components of the engine noise make good candidates for active noise control (ANC), because of their relatively low frequencies. The low frequencies also make engine noise difficult to control through passive techniques, which could potentially add to the appeal of ANC from the perspective of equipment manufacturers.

ANC efforts in the past demonstrated the successful attenuation of engine tonal noise inside tractor cabins, but significant weaknesses of the control systems rendered them impractical for commercial installation. Noise reduction tended to be limited to a relatively small spatial region near the operator's head and error sensors were sometimes placed in locations that would be inconvenient for the operator. The inability of such control systems to adequately track rapid changes in tractor engine speed during normal work cycles was an additional drawback.[1-3] The approach taken by these systems was to minimize squared acoustic pressure (SP) at one or more error sensor locations.

The minimization of acoustic energy density (ED) by ANC systems can have certain advantages over the minimization of SP.[5-8] Acoustic ED depends on acoustic particle velocity in addition to acoustic pressure, which allows more information to be utilized by an ANC system that uses ED as a squared error signal. The additional dependence on particle velocity results in a more global control of an enclosed sound field than is often achieved through the minimization of SP alone. Additionally, an ED error sensor has a much lower probability of being placed in a nodal region than an SP sensor for the natural modes of the same enclosure.[8]

The potential advantages of an ED-based control system make it an attractive option for the reduction of low-frequency engine tones in closed tractor cabs. This paper discusses an ED-based ANC system, constructed at Brigham Young University, and the performance of the system in a simulated tractor cabin using synthesized tonal noise as well as recorded noise from an actual tractor.

2. THE CONTROL SYSTEM

A. An Energy-based Error Sensor

Since acoustic ED is a sum of kinetic energy density, which is proportional to the square of particle velocity, and potential energy density, which is proportional to the square of acoustic pressure, its instantaneous value may be obtained by measuring particle velocity and pressure at a point. The dependence of the total instantaneous acoustic ED on particle velocity and pressure is given by:

$$e_i = \frac{1}{2}\rho_0\left[u^2 + \left(\frac{p}{\rho_0 c}\right)^2\right], \tag{2.1}$$

where u^2, p, ρ_0, and c represent the magnitude squared of the acoustic particle velocity vector, the acoustic pressure, the ambient fluid density, and the speed of sound, respectively. By assuming the density of air and the speed of sound in air to be constant and known, the measurement of acoustic ED only requires that the particle velocity and pressure be obtained.

A two-microphone measurement technique allows one directional component of the particle velocity vector to be obtained in the direction defined by the location of the microphones. By embedding three orthogonally arranged pairs of microphones in a solid sphere, a three-dimensional particle velocity vector can be obtained for the point corresponding to the center of the sphere. The two-microphone technique assumes that some distance, d, separates the microphones and that no obstruction exists between them. However, the bias errors in the measurement due to the presence of a sphere turn out to be beneficial.[9] A spherical sensor with diameter d will behave similarly to a sensor with no obstruction between the microphones, but a microphone separation distance of 1.5d. This allows a spherical sensor to be constructed two-thirds the size of a sensor with no sphere without any loss in accuracy. The performance of a wooden spherical ED sensor with a two-inch diameter and three pairs of inexpensive electret microphones was described by Parkins, et al.[7] The wooden sensor was shown to exhibit total energy density errors within ±1.75 dB in the frequency range 110 < f < 400 Hz. Microphone configurations other than the three orthogonal pairs are possible for energy density sensors and some alternatives have been explored at Brigham Young University.[10]

B. The Algorithm

The well-known filtered-x LMS adaptive filtering algorithm provides a basis for the algorithm employed in the ED-based ANC system. However, the filtered-x algorithm had to be modified in order to minimize acoustic ED and the resultant algorithm is that described by Sommerfeldt, et al.[6] Four control path transfer functions are required in order to produce four of the so-called filtered-x signals. These four transfer functions are obtained via an offline system identification algorithm for the pressure path as well as each of the paths corresponding to the three components of the particle velocity vector. The reference input signal, x(n), is filtered by each of the four control path transfer functions to produce the filtered-x signals, $r_p(n)$, $r_{vx}(n)$, $r_{vy}(n)$, and $r_{vz}(n)$. The update equation for the vector of control filter coefficients, w, at time n, is given as:

$$\mathbf{w}_{\mathbf{n}+1} = \mathbf{w}_{\mathbf{n}} - \mu\left(\frac{p(n)}{\rho_0 c^2} r_p(n) - \sum_{m=1}^{3}\frac{u_m(n)}{\Delta x}\mathbf{r}_{\mathbf{vm}}(n)\right), \tag{2.2}$$

where $u_m(n)$ is the m^{th} component of the instantaneous particle velocity at time n, and $r_p(n)$ and $r_{vm}(n)$ are vectors containing the current (time n) and past values of the four filtered-x signals.

C. Control System Electronics

A 32-bit Texas Instruments DSP processor, capable of performing 120 million floating point instructions per second, provided more than enough processing power for the ED-based, feedforward adaptive algorithm. Analog-to-digital and digital-to-analog conversions were accomplished with the use of 12-bit converters. Because the control system only targeted low-frequency noise, all analog input and output signals were low-pass filtered using fourth order Butterworth filters with a cutoff frequency of 400 Hz. The system was generally operated with a sampling rate of 2 kHz, so the filters were sufficient to avoid any problems with aliasing. The hardware allowed for two control signals to be routed to the loudspeakers used as control actuators. Before passing through a power amplifier and on to the loudspeakers, the control signals passed through a crossover circuit in order to route frequencies less than 90 Hz to a subwoofer and frequencies greater than 90 Hz to one of two smaller satellite speakers. Each of the two control signals was routed to one of the satellite speakers, but the two signals were summed to produce the final control signal sent to the subwoofer.

3. EXPERIMENTAL SETUP

In an effort to simulate the use of an ED-based ANC system in a real tractor cabin, the control system was operated in a mock cabin consisting of a steel frame and 3/8-inch plywood panels on all sides except the front panel, which was made of 1/8-inch Plexiglas®. The frame measured 1.5 meters high and 1 meter wide. The length of the frame was 1.2 meters at the bottom and 1 meter at the top, so that the front panel (resembling a windshield) was sloped. A chair was placed in the back of the cab, centered between the two sides, on which a person could sit to simulate the presence of an equipment operator during measurements or to operate the ANC system from within the cab. Photos of the cab appear in Figure 3.1. Numerically computed mode shapes for the first four modes of the cab, up to 200 Hz, are shown in Figures 3.2 through 3.5.

Uncontrolled noise was produced in the cab using a Mackie HR824 loudspeaker (the source speaker) with reasonably flat frequency response down to 37 Hz. The source speaker was placed underneath the chair inside the mock cab. The two satellite control speakers were positioned, near the top corners of the mock cab in order to be near the operator's head as well as to be in a position to couple well with the acoustic modes of the cab. The subwoofer was placed in the front left corner of the cab on the floor. The control speaker locations can be seen in the photos in Figure 3.1. The error sensor was located directly above the operator's head. The benefit of this error sensor placement is that enables the center of the so-called "zone of silence" to be as close as possible to the operators ears, while keeping the sensor out of the operator's way. Since the operator of a tractor will generally be centered between the two side walls of the cab, this placement would be more problematic for a simple pressure sensor. The potential presence of axial modes possessing nodal regions centered between the two side walls suggests that a pressure sensor be placed to one side of the operator's head (see Figure 3.4). An ED sensor, however, will only encounter an ED node where two or more pressure nodes overlap, which could not happen at the chosen error sensor location in the 0 to 200 Hz range of the mock cabin.

For measurements in which the uncontrolled noise was a synthesized sinusoid, the same signal was sent to the source speaker as well as to the reference input of the control system electronics. The tractor noise recordings, however, had two channels—one for the noise inside the cab, and the other for a tachometer signal from the tractor's engine. When the recorded tractor noise was used as the uncontrolled noise in the mock cab, the tractor noise signal was routed to the source speaker under the seat and the recorded tachometer signal was routed to the reference input of the control system electronics.

Fifteen microphones measured the sound pressure inside the mock cab in order to determine the global nature of the noise control. Twelve of these microphones were arranged in two parallel horizontal planes, above and below the height of the operator's ears. Two other microphones were strapped to a set of headphones to measure the sound pressure levels near the operator's ears. These headphones were sometimes worn by a person sitting inside the cab and sometimes suspended from the ceiling of the cab for measurements without a person in the cab. One additional microphone was used to measure the sound pressure at the error sensor location. Figure 3.6 shows the placement of the microphones.

4. MEASUREMENTS

Both static (fixed frequency) and dynamic (swept frequency) sinusoids served as uncontrolled noise signals inside the mock cab to help quantify the performance of the ED-based ANC system. Static sinusoids were synthesized with several different frequencies ranging between 40 and 200 Hz, to test the control system at or near modes of the cab as well as away from modes. The chosen frequencies, for which results are discussed in the next section, are 50, 80, 113, 125, 154, 171, and 195 Hz. A dynamic excitation signal was created to explore the tracking abilities of the ANC system. This dynamic signal was composed of four different sections. The frequency of the sinusoid was swept at a linear rate between 40 Hz and 200 Hz at two different rates. The slower sweeps had a duration of four seconds while the faster sweeps had a duration of one second. For portions of the test signal, the end frequencies were held for the same duration as the corresponding sweeps. A spectrogram of the dynamic noise signal can be seen in Figure 4.1.

In order to more closely simulate the use of the ANC system in an actual tractor cab, static and dynamic engine noise was recorded inside a tractor cab along with a tachometer signal to be used for the reference input to the adaptive control algorithm. Static engine noise was recorded at engine speeds of approximately 820, 1800, 2000, and 2340 rpm, which produced dominant engine tones at 41, 91, 99, and 117 Hz. The dominant tones correspond to the engine firing frequency, which is three times the engine rotation frequency for a typical six-cylinder diesel engine. Additional recordings were made of the tractor engine noise as the engine speed was swept up and down between idle and full-throttle. Three different sweep rates were recorded, with the faster two corresponding to roughly the same sweep rates as the synthesized swept sine signal.

5. RESULTS

A. Synthesized Test Signals

Figure 5.1 shows the noise reduction achieved at the frequencies selected for static ANC performance tests. Three measurements are shown at each frequency: the attenuation achieved at the error sensor location; the average attenuation at the 2 microphones near the operator's ears (the ear mics); and the spatially averaged attenuation (the global reduction), as recorded by the 12 microphones distributed throughout the upper half of the cab. The same 12 microphones were used in static noise tests using synthesized tones as well as recorded tractor noise. At nearly all frequencies, reduction of the noise tone is significant throughout the cab. At 50 Hz, the amount of reduction at the error sensor is close to the dynamic range of the 12-bit analog-to-digital converters used in the control system electronics. Reduction throughout the rest of the cab is, on average, greater than 40 dB, which is to be expected due to the large wavelength of the low-frequency tone. The ED-based ANC system also performs well at high frequencies with a global reduction exceeding 10 dB at 195 Hz. The performance of the ANC system was diminished at 154 Hz, however, at which a single axial mode existed in the mock cab. The presence of an axial pressure mode should not have caused a problem for the energy density sensor, however. Since the cab sat in a rigid-walled hallway, which also had an axial mode near 154 Hz, it is possible that the environment in which the cab was located contributed to the degraded performance of the ANC system at that frequency.

Dynamic performace was recorded in terms of the amount of reduction in the equivalent sound level, L_{eq}, over the length of the test signal of interest. L_{eq} was measured with a flat frequency weighting. For dynamic measurements (with the synthesized test signal as well as recorded tractor noise), microphone signals were streamed to a computer hard disk for post processing. This allowed for accurate comparisons to be made in L_{eq} over the duration of the test signal. However, at the time the dynamic measurements were made, only 4 of the 12 microphones distributed in the cab could be used for direct-to-disk recording. The 4 microphones chosen were the 4 closest to the front of the cab in the upper 6-microphone plane. The results obtained by the ANC system, using the previously described swept sine signal, are shown in Figure 5.2. In the figure, "Global Reduction" refers to the spatially averaged reduction measured by 4 microphones rather than 12. The system tracked the changing noise signal well enough to achieve approximately 3 dB of global reduction in the L_{eq} over the duration of the entire swept sine test signal as well as during each of its individual sections. The noise reduction at the error sensor often exceeded 4 dB and the average reduction seen by the ear mics even approached 5 dB. At all measurement locations, the system performance was nearly as good for the faster sweeps as it was for the slower sweeps. It should be noted that similar reductions in sound level were observed between the two ear mics in nearly all measurements.

B. Recorded Tractor Engine Noise

Attenuation of the tone corresponding to the tractor engine firing frequency for four different engine speeds appears in Figure 5.3. Again, the best global reduction was seen at the lowest frequency. In this case, that frequency was 41 Hz, at which the global reduction exceeded 20 dB and was even slightly better than the reduction at the error sensor or ear mics. For all tested engine speeds, the noise reduction at the ear mics was nearly equal to the noise reduction at the error sensor, which suggests that a good location was chosen for the placement of the ED-based error sensor. Even at the highest frequency of 117 Hz, over 10 dB of global reduction was achieved. The uncontrolled engine tone was much lower in amplitude at 99 Hz, which may explain the apparent reduction in ANC system performance at that frequency.

As mentioned previously, three different engine speed sweep rates were recorded for use in dynamic testing of the ANC system with recorded tractor noise. The fastest sweep was obtained by ramping up (and down) the engine speed of the tractor as fast as it would go. Figure 5.4 shows the measured results for each of the three sweep rates. As the sweep rate increased, the amount of reduction in L_{eq} over the duration of the measurement decreased. At the slowest sweep rate, global reduction exceeded 6 dB. However, even at the fastest sweep rate, the system still achieved over 1 dB of reduction at all measurement locations (at all microphones, not just on average). These results suggest that the ED-based ANC system may reduce overall sound levels experienced in a tractor, even when the tractor is being operated through fast-paced work cycles in which engine speeds can vary rapidly.

Figure 5.5 shows time-averaged spectra of the noise at the left ear microphone with and without ANC running. This example is for a slow engine speed sweep and shows that the ANC system was able to attenuate the engine tone throughout its entire frequency range (40 to 120 Hz).

6. CONCLUSIONS

Significant levels of noise reduction were achieved in the mock cabin, using the ED-based ANC system. Good global control was demonstrated in the cab with synthesized static and dynamic test signals as well as noise recorded from an actual tractor cab. The global nature of the control was apparent in all tests except for one static test in which an acoustic mode of the environment in which the cab was located may have adversely affected ANC system performance. These results suggest that at certain frequencies, the energy-based control system may indeed have some advantage over a similar pressure-based control system for this type of application. The advantages may be seen in that the ED-based system provides uniform control of the enclosed sound field over a relatively large frequency range (one for which acoustic modes of the enclosure are encountered) and the system is relatively insensitive to error sensor placement. Additionally, the system's ability to track recorded engine noise well enough to provide global noise reduction at the highest engine speed changes likely to be encountered suggests that such a system could potentially improve operating conditions and satisfy noise exposure standards in a real world environment.

7. REFERENCES

1. Y. Peng, A. Sasao, and S. Shibusawa, "Active noise control in proximity of a tractor operator's head," Trans. ASAE, 44, 447-455 (2001).
2. E. Carletti, D. Stanzial, and I. Vecchi, "Application of the active noise cancellation technique to earth-moving machines," Proc. Noise-93, St. Petersburg, Russia, May 31 – June 3, 1993, pp. 141-146.
3. E. Carletti and I. Vecchi, "Reduction of noise inside cabs of earth-moving machines by active noise cancellation technique," Proc. Inter-Noise 94, Yokohama, Japan, Aug. 29-31, 1994, pp. 1417-1420.
4. E. Carletti, G. Miccoli, and I. Vecchi, "Earth-moving machine cab enclosed sound field active control simulation," Proc. Inter-Noise 96, Liverpool, U.K., July 30 - Aug. 2, 1996, pp. 1183-1186.
5. J. W. Parkins, S. D. Sommerfeldt, and J. Tichy, "Narrowband and broadband active control in an enclosure using the acoustic energy density," J. Acoust. Soc. Am. 108, 192-203 (2000).
6. S. D. Sommerfeldt and P. J. Nashif, "An adaptive filtered-x algorithm for energy based active control," J. Acoust. Soc. Am. 96, 300-306 (1994).
7. J. W. Parkins, S. D. Sommerfeldt, and J. Tichy, "Error analysis of a practical energy density sensor," J. Acoust. Soc. Am. 108, 211-222 (2000).
8. J. W. Parkins, J. Tichy, and S. D. Sommerfeldt, "A comparison of two active control methods through an investigation of node structures," Proc. Active 99, Ft. Lauderdale, FL, Dec. 2-4, 1999, pp. 729-740.
9. G. W. Elko, ''An acoustic vector-field probe with calculable obstacle bias,'' Proc. Noise-Con 91, July, 1991, pp. 525–532.
10. L. L. Locey and S. D. Sommerfeldt, "Analysis and comparison of three energy density probe designs," J. Acoust. Soc. Am. 114, 2443 (2003).

Figure 3.1 Mock cabin photos. Front and side views on the left and right, respectively.

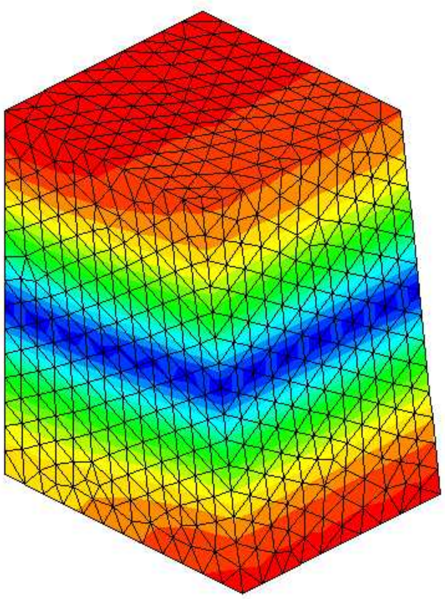

Figure 3.2. First cab mode at 113.2 Hz.

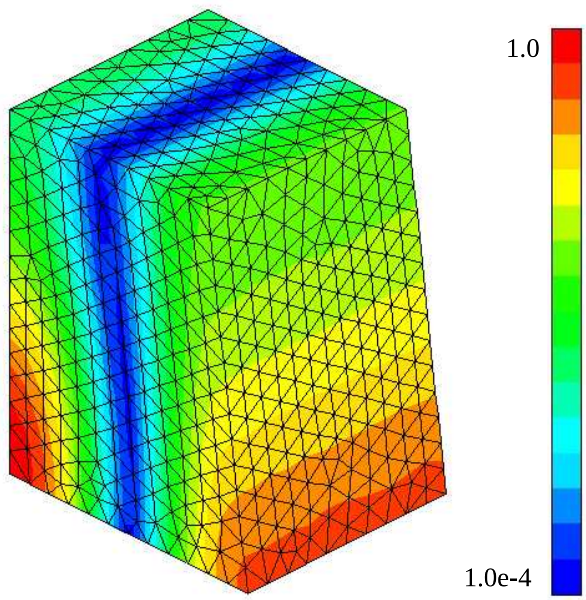

Figure 3.3. Second cab mode at 154.0 Hz.

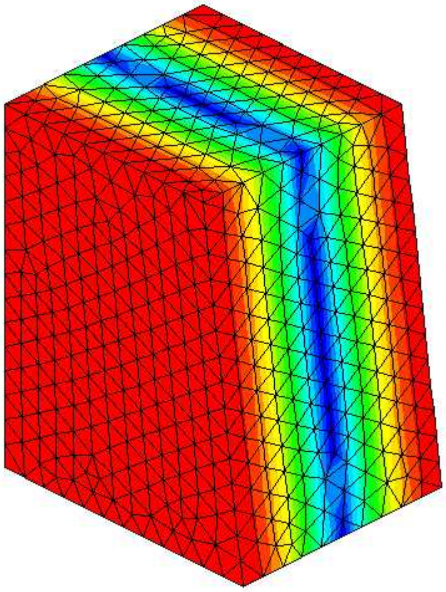

Figure 3.4. Third cab mode at 170.8 Hz.

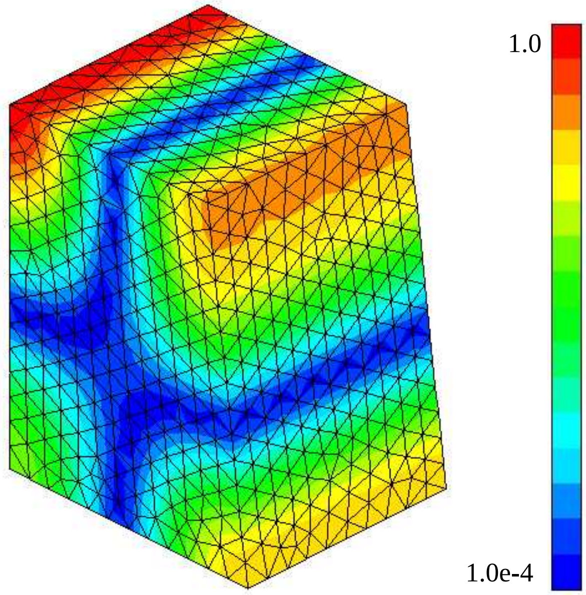

Figure 3.5. Fourth cab mode at 194.8 Hz.

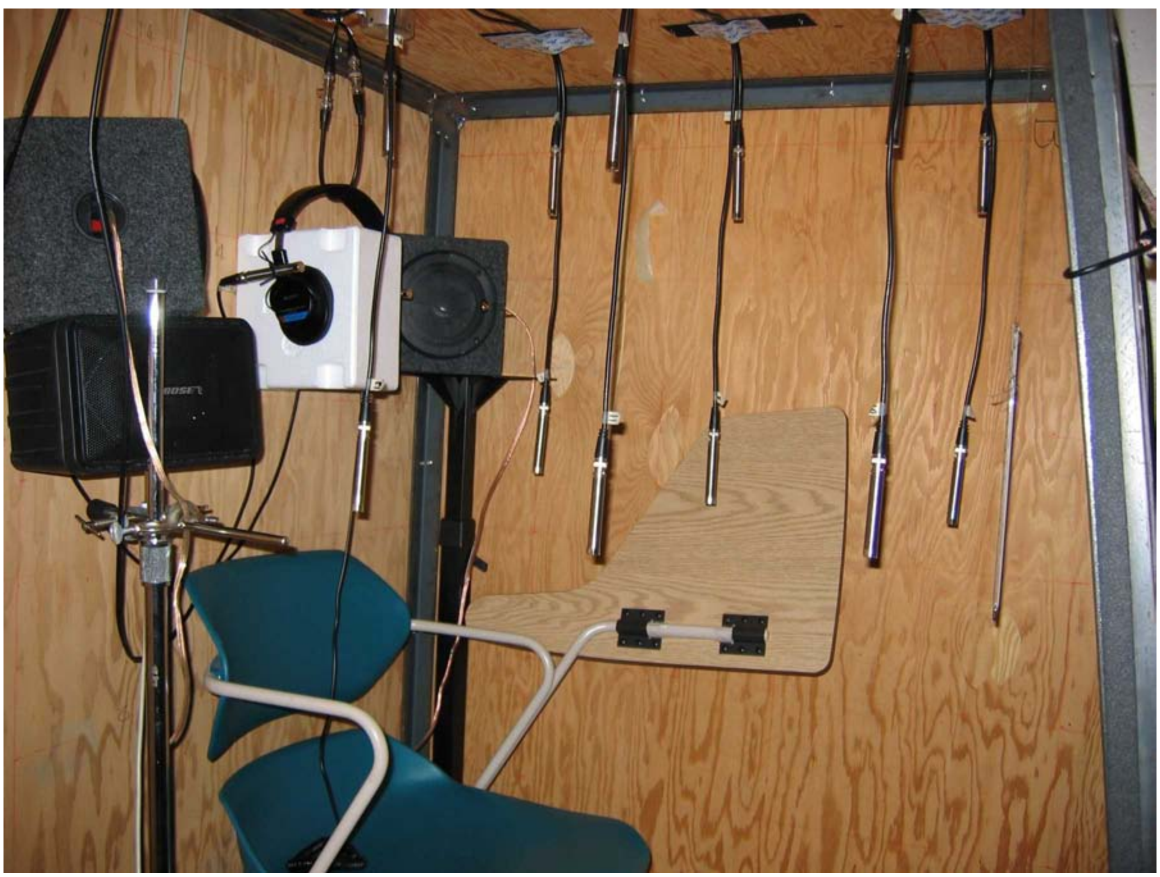

Figure 3.6 Microphones used to measure the performance of the ANC system.

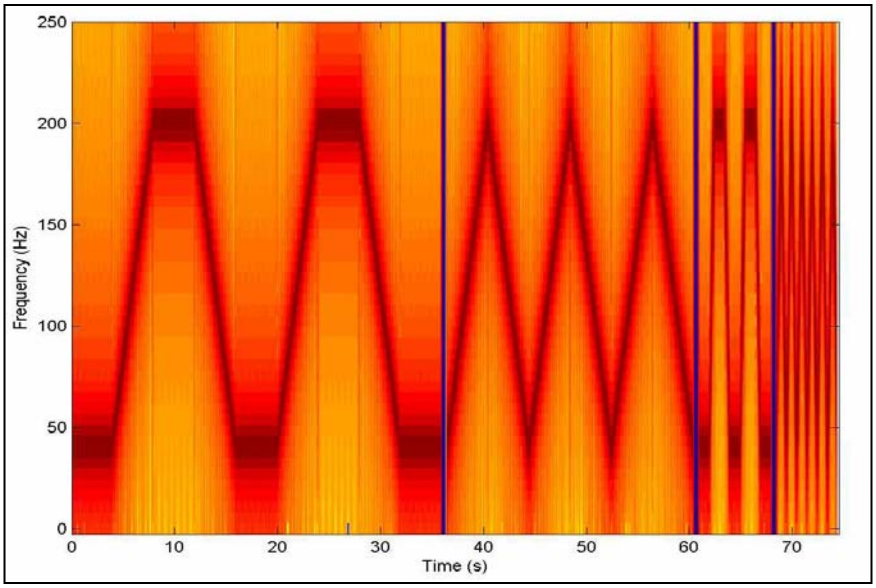

Figure 4.1. Swept sine excitation signal for studying dynamic ANC performance.

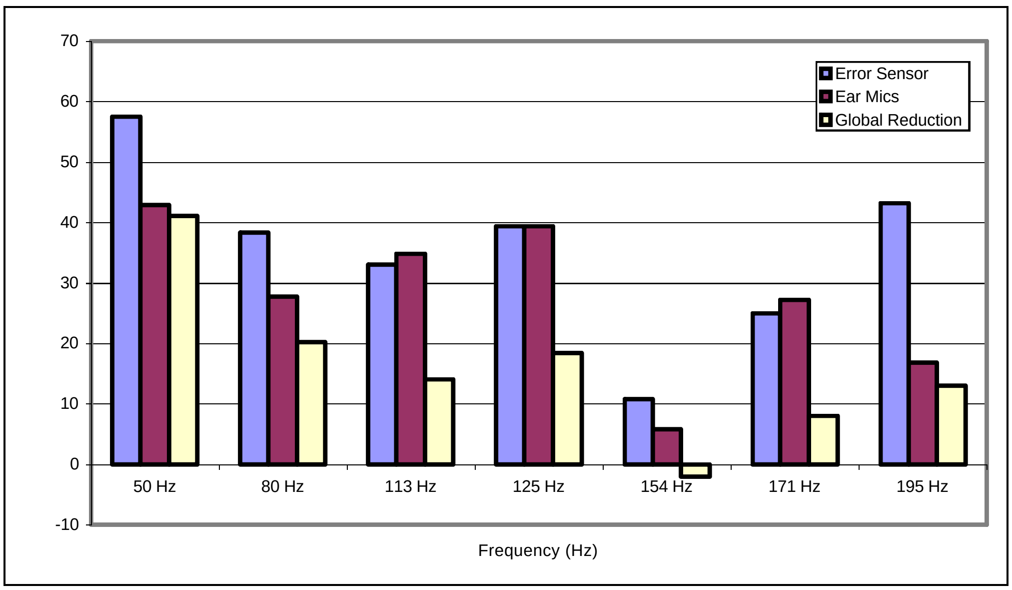

Figure 5.1. Attenuation of static tones, comparing noise reduction achieved at various locations inside the cab.

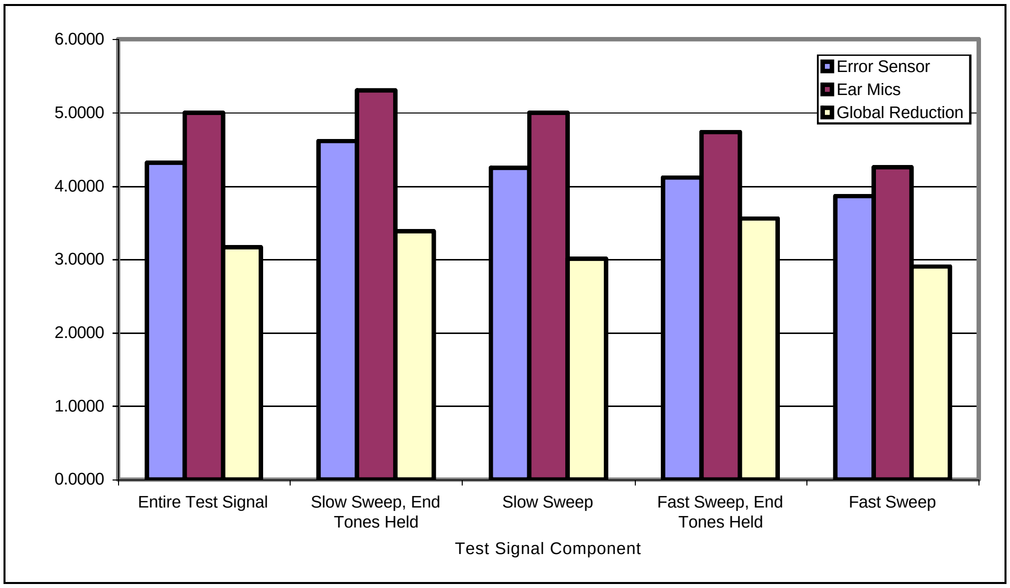

Figure 5.2. Reduction in L_{eq} achieved during different sections of a dynamic test signal at various locations inside the cab.

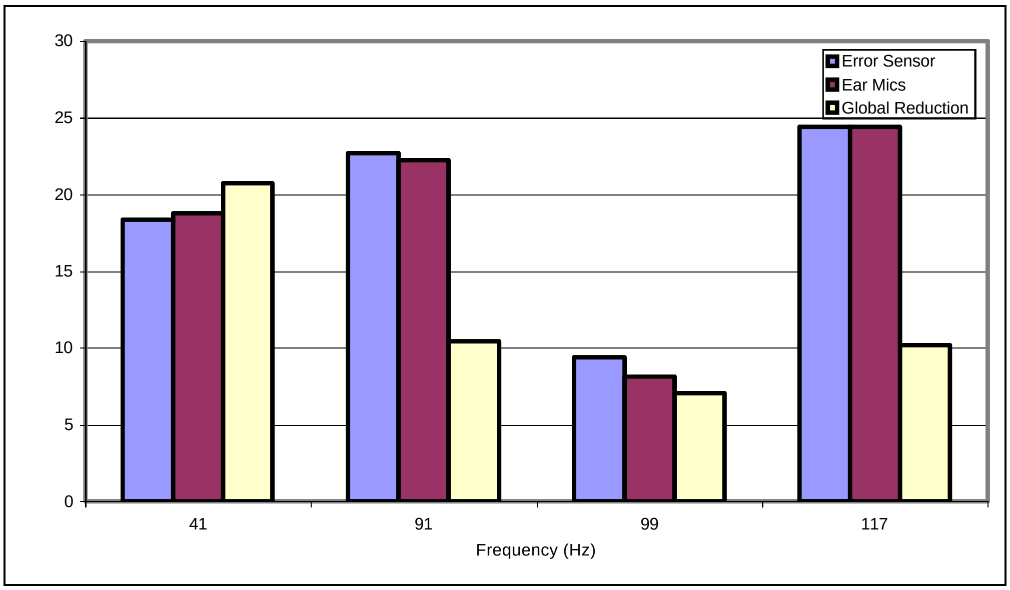

Figure 5.3. Attenuation of static engine tones, comparing noise reduction achieved at various locations inside the cab.

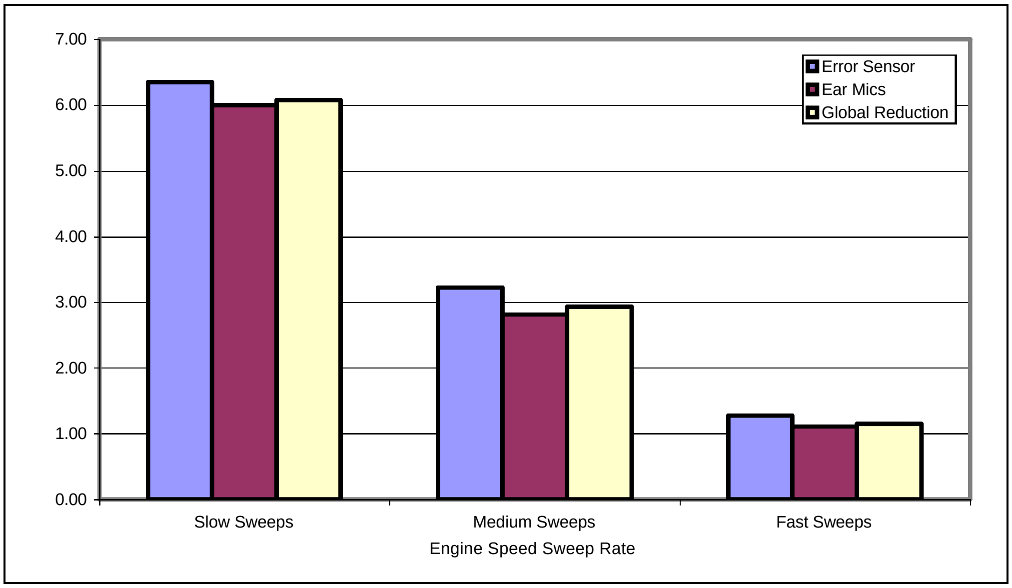

Figure 5.4. Reduction in L_{eq} achieved during different recorded engine speed sweeps at various locations inside the cab.

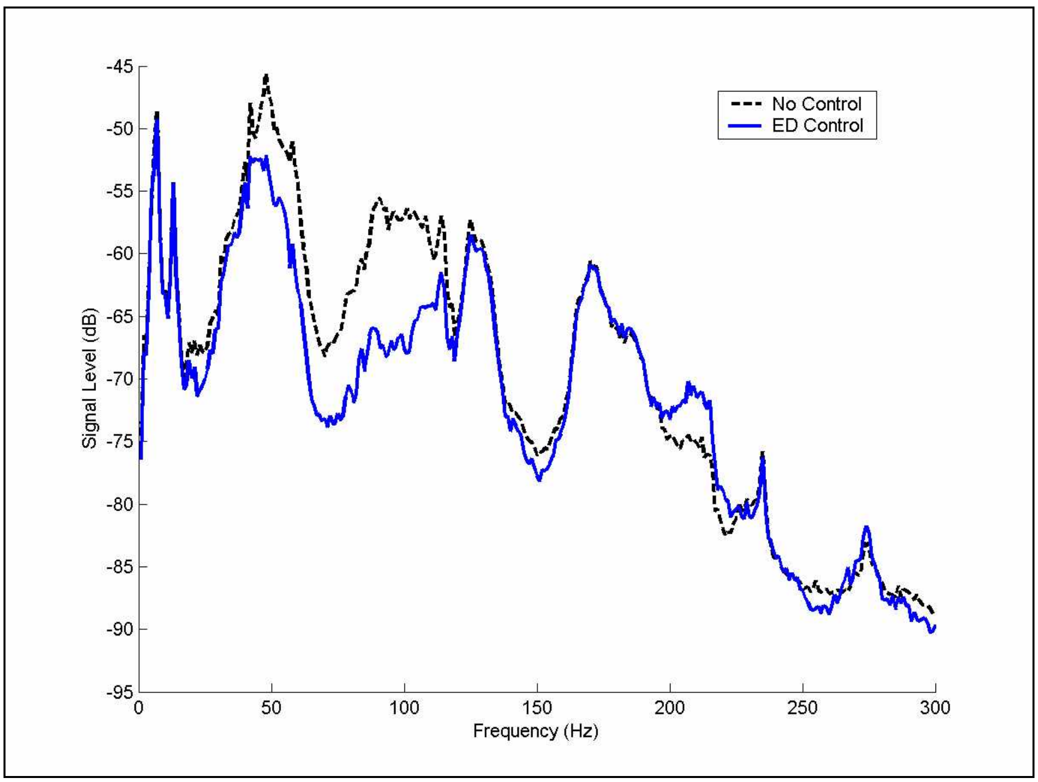

Figure 5.5. Time-averaged spectrum of recorded engine noise, measured by the left ear microphone with and without ANC, using slow engine speed sweeps.