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DEVELOPMENT AND VALIDATION OF A TEST SYSTEM FOR MEASURING THE ACOUSTIC SIGNATURE OF CHEMICAL, BIOLOGICAL, RADIOLOGICAL AND NUCLEAR PERSONAL PROTECTIVE EQUIPMENT ENSEMBLES

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An acoustic measurement system was developed and validated for assessing the acoustic signature of commercially available chemical, biological, radiological and nuclear (CBRN) personal protective equipment (PPE). Current commercial CBRN PPE standards don't consider the minimization of acoustic signatures required for tactical operations. An acoustic signature includes all noise created by the wearer and the PPE that could lead to audible detection by a potential adversary. Many CBRN respiratory PPE design features increase the acoustic signature and can make stealth operations more challenging or impossible. The developed noise measurement system matched the specifications stated in the Department of Defense (DoD) Noise Limit Standard (MIL-STD-1474D) and used a free field microphone (Type 40AF, G.R.A.S., Denmark) mounted in an anechoic chamber. A data acquisition device (NI-PCI-4461, National Instruments, Austin, TX) coupled with a program developed in LabVIEW 8.6 (National Instruments, Austin, TX) recorded the sound pressure and calculated the decibel levels at 1/3 octave intervals from 50 to 10,000 Hz. Verification tests measured different tones and decibel levels with the developed system and a sound level meter simultaneously. The results demonstrated that the system could detect frequencies within the range of human hearing and compared favorably with the sound level meter.

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PREFACE

The Department of Homeland Security Science and Technology Directorate sponsored the production of this material under Interagency Agreement #M02398/Contract No. HSHQDC-06-X-00394 with the U.S. Army Edgewood Chemical Biological Center. The work was started in January 2009 and completed in September 2009.

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1. INTRODUCTION

Law enforcement officers and special operations personnel increasingly rely on chemical, biological, radiological, and nuclear (CBRN) personal protective equipment (PPE) to provide protection against hazards while completing operations. For example, tactical law enforcement operations use CBRN PPE during covert laboratory response, barricaded CBRN terrorist response, downed officer evacuation under hazardous atmospheric conditions, and other operations.[1] During operations that require CBRN PPE wear, it is imperative that officers are able to perform their missions in a manner as similar as possible to those not performed in a CBRN environment. This is especially important in operations requiring stealth.

A minimized acoustic signature is required for tactical stealth operations and is not addressed in current CBRN PPE standards. An acoustic signature includes all noise created by the wearer and the PPE that could lead to audible detection by a potential adversary. For instance, PAPR blowers are noisy and virtually render the breathing system unusable where stealth is required.[2] Additionally, reports indicate that common Level B and C suit materials such as Tyvek® and Tychem® create a noticeable crinkly sound.[3] Many CBRN respiratory PPE design features (e.g., blowers, low oxygen warning signals, amplified breathing noises, etc.) increase the acoustic signature and can make stealth operations more challenging or impossible.

A noise limit design criteria standard (MIL-STD-1474D) published by the Department of Defense (DoD) states acoustic signature limits below which a potential adversary will not detect the sound source.[4] The DoD refers to the limits as nondetectability limits in the standard. Additionally, the standard establishes acoustical noise limits, recommends testing requirements and measurement techniques. The established acoustical noise limits are given in decibels (dB) at 1/3 octave frequencies from 50 to 10,000 Hz at different distances from a sound source (i.e., higher sound levels are allowable for sound sources further away).

The purpose of this study was to develop and validate a test system based on the DoD Aural Nondetectability standard capable of quantitatively measuring the acoustic signature of different CBRN PPE ensembles on test volunteers. A developed and validated test system could objectively measure the acoustic signature of different CBRN PPE combinations that would assist in the selection of appropriate ensembles for use in tactical operations. In addition, the quantitative measurement of current equipment creates a baseline for future tactical CBRN PPE designs.

2. METHODS

2.1 Sound Measurement System

The sound measurement test system conformed to the specifications stated in the DoD Noise Limit Standard MIL-STD-1474D.[4] The complete sound measurement system diagrammed in Figure 1 used an anechoic chamber, a free field microphone with a power supply, a data acquisition device, a closed-circuit television (CC-TV), an intercom, and a light display silent metronome. The anechoic chamber measured approximately 3 x 3 m in length and width and approximately 2 m in height. The free field microphone (Type 40AF, G.R.A.S., Denmark) was mounted at a height of 1.2 m in one corner of the chamber and a rubber mat was placed in the opposite corner. The 1 m^2 mat was provided to cushion subjects from the metal grate flooring. A line was placed on the mat at a distance of 2 m from the microphone. The location of the 2 m line allowed enough room for a subject to perform simple movements without being obstructed by the anechoic chamber walls and conformed to the recommended measurement distance stated in the standard.

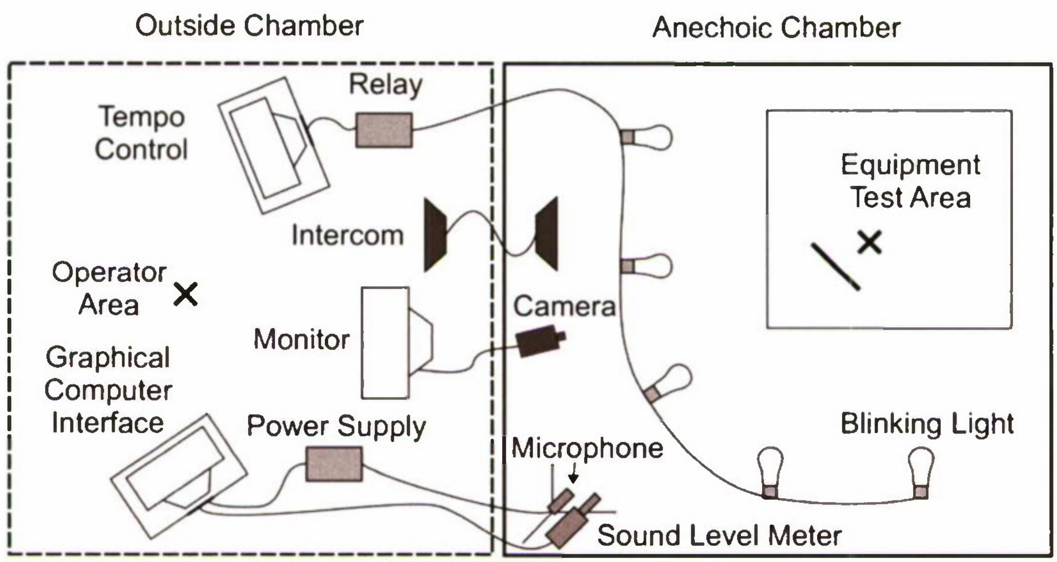

Figure 1. Schematic of the Sound Measurement Test System

The microphone was connected to a power supply (Type 12AK, G.R.A.S., Denmark) located outside of the anechoic chamber. The power supply provided power and the excitement voltage to the microphone. An analog output on the power supply provided an AC voltage related to the sound pressure observed by the microphone. The output was attached to a data acquisition device (NI-PCI-4461, National Instruments, Austin, TX). The data acquisition device was a computer mounted/ controlled card with the ability to measure analog voltage at rates as fast as 200,000 Hz. The data acquisition card and subsequent data storage was controlled by a computer program created in Labview 8.6 (National Instruments, Austin, TX).

A sound level meter (Model 322, Center Technology Corporation, Taiwan) was mounted in the chamber below the microphone. The meter was also attached to the data acquisition card. The A-weighted dB level of the sound level meter was displayed and recorded along with the measurements made on the microphone.

The operator controlled the test from outside the chamber to decrease any chance of nuisance noise. Thus, a way for the operator to monitor and communicate with the test subject was created. A CC-TV was created by connecting a black and white camera inside the chamber to a television and power supply outside the chamber allowing the operator to monitor the subject. An intercom was wired into the chamber to allow communication between the operator and subject. Thus, the operator could communicate clearly with the subject, and the subject could communicate with the operator, while the operator monitored the subject from outside the anechoic chamber.

Because subjects may be asked to perform simple movements, a guide was created to ensure performed exercises would occur at the same relative speed (i.e., a metronome). The silent system relied on a string of miniature lights. Power to the lights was controlled by a relay (Model SSRL240DC25, OMEGA, Stamford, CT). Voltage applied to the relay, which turned the lights on, was applied with another computer controlled data acquisition device (NI-PCI-6036E National Instruments, Austin TX). A computer program written in Labview 6.0 (National Instruments, Austin, TX) turned the lights on and off at an operator set rate. The blinking of the lights provided a steady beat to the subject within the chamber.

2.2 Sound Measurement Software

A graphical computer interface created in Labview 8.6 controlled the data collection, analysis, and storage. Basic Labview functions were required to sample the voltage output of the microphone and convert it to sound pressure. The processing of the sound pressure into A-weighted 1/3 octave bands required functions from the Sound and Vibration Suite (Version 6.0, National Instruments, Austin, TX). The Sound and Vibration Suite contained a library of powerful functions for sound and vibration processing. A graphical user interface enabled the operator to continually control, monitor, and record the audible signature of PPE ensembles.

Once started, the Labview program automatically performed a continual series of operations. The output voltage of the microphone power supply was continually sampled at a rate of 50,000 Hz, which was more then enough to allow for the detection of sound frequencies up to 10,000 Hz. A saved calibration value converted the sampled voltage values to sound pressure (Pascal [Pa]). The calibration value was determined daily by placing a 1,000 Hz 94 Decibel (dB) sound source (Type

4231, B&K, Denmark) at the microphone. The sensitivity of the microphone changed little and remained at approximately 50 mV/Pa.

The sampled sound pressure values proceeded into a 1/3 octave analysis function. The function transformed the sound pressure values from the time domain to the frequency domain and simultaneously split the frequency values into 1/3 octave bands from 50 to 10,000 Hz. The sound pressure values were converted from Pa to dB. A reference value of 20 μPa (the threshold of human hearing) was used. The output (dB values of 24 frequency bands from 50 to 10,000 Hz) was processed by an A-weighted filter function. Because human sound perception is sensitive to frequency (generally more sensitive at 5,000 Hz), the applied A-weighted filter standardized the frequency band dB levels. Thus, a measured value of 100 dB at 500 and 5,000 Hz would be perceived by the human ear as the same loudness.

While the data sampling and conversion was continually operating, the operator monitored the dB levels of the frequency bands, controlled the file descriptions, controlled the file recording, and even listened to sound within the chamber with the graphical user interface (GUI) shown in Figure 2. The "Test Description and Record" box was used to name, describe, and save data. The subject number, exercise list, and condition list were used along with the date to name the saved file. Repeat files were automatically sequentially numbered, so that all file names were unique. In addition, the description boxes including the comments box were placed in the header of the data file. The record button was set to save data for 30 s after being pressed. The sound pressure data was saved in a wave file (.wav extension), while the frequency bands were recorded in a separate data file (.txt extension) at a rate of 50 Hz. Both files had the same name with different extensions. The "Third-octave Analysis" graph displayed the real-time dB frequency bands along with the total band power. The max dB value for each band and the max total band was also displayed. For reference, a nondetectability limit and an ambient noise level (both from the military standard) could be plotted. The nondetectability, ambient noise level, and reset of the max were controlled in the "Third-octave Analysis Control" box. The max was also reset anytime the record button was pressed. The "Chamber Monitoring Controls" allowed the operator to listen to the sound generated in the chamber at an appropriate volume. The "Calibration" box showed when the device was last calibrated and the value of that calibration.

2.3 PPE Sound Measurement Test Procedure

The operation of the test system for PPE testing was straightforward. The subject entered the chamber wearing the PPE of interest. With the microphone on, software running, and mini-lights blinking, the operator communicated to the subject to perform an exercise in sync with the blinking lights. The operator selected the appropriate subject, exercise, and equipment configuration descriptors on the GUI. Any additional comments were added to the comment box. The operator confirmed that the subject was performing the appropriate exercise by watching on the CC-TV. The sound pressure and dB frequency bands were recorded for 30 s in files named for the descriptors selected. After 30 s, the test was complete. The operator prompted the subject to move on to the next exercise or PPE ensemble.

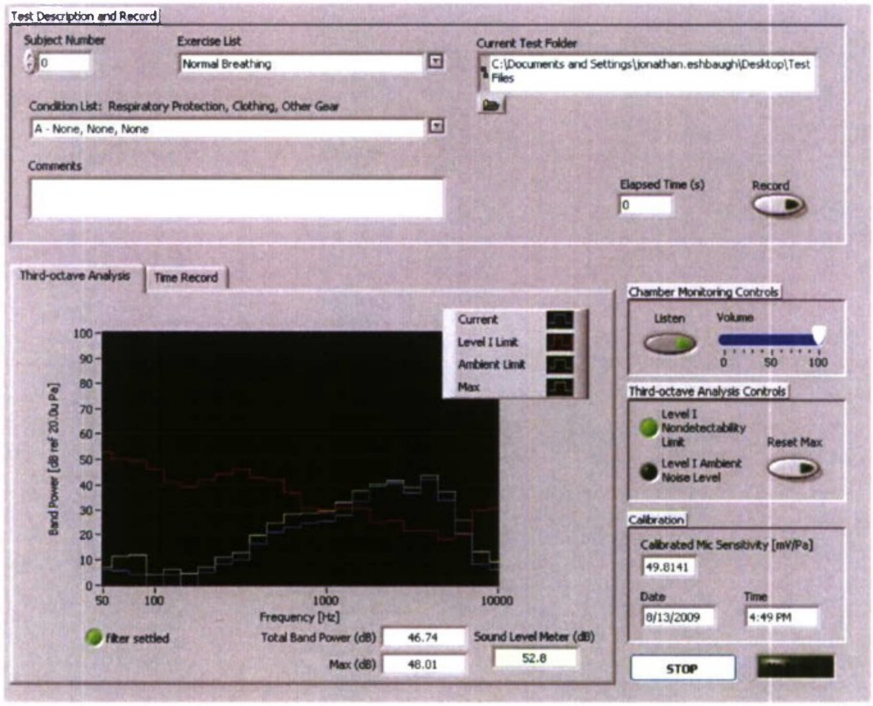

Figure 2. Sound Measurement System Graphical User Interface (GUI)

2.4 Sound Measurement System Verification

To verify that the test system could accurately detect different frequencies and different dB levels at those frequencies, a speaker was placed within the chamber and attached to an amplifier and computer. The computer produced test tones from 50 to 10,000 Hz at ten different intervals (50, 100, 300, 800, 1k, 2k, 4k, 5k, 8k, and 10k Hz). The test was repeated twice (for a total of three tests) at different amplification levels.

In addition to the single test tones, pink noise was generated by a noise generator (Type 1405, B&K, Denmark). The pink noise power is inversely related to frequency; thus, as frequency increases, power decreases resulting in equal energy across all octaves. The pink noise generator was attached to an amplifier, which was attached to the speaker. The pink noise was adjusted to approximately 60 dB, which is similar to the level used for respirator mask communication tests.[5]

3. RESULTS AND DISCUSSION

The frequency response of pure tones at three different amplification levels is shown in Figure 3. The sound measurement system detected the different sound levels at all frequencies. The frequency response curves were almost exactly the same at the three amplification levels except that they were separated by a constant dB. This was expected, because the increase in amplification was applied equally across all tones. The measured curve peaked at approximately 5,000 Hz. The overall curve was the result of the A-weighted filter. The A-weight filter mimics human hearing and thus, diminishes the sensitivity below 1,000 Hz and above 6,000 Hz. As expected, the highest measured dB levels were within the 1,000 to 6,000 Hz range. The peak and small variations from a smooth curve are most likely due to the frequency response of the speaker and amplifier. A flat frequency response from a speaker and/or amplifier is virtually impossible to achieve.

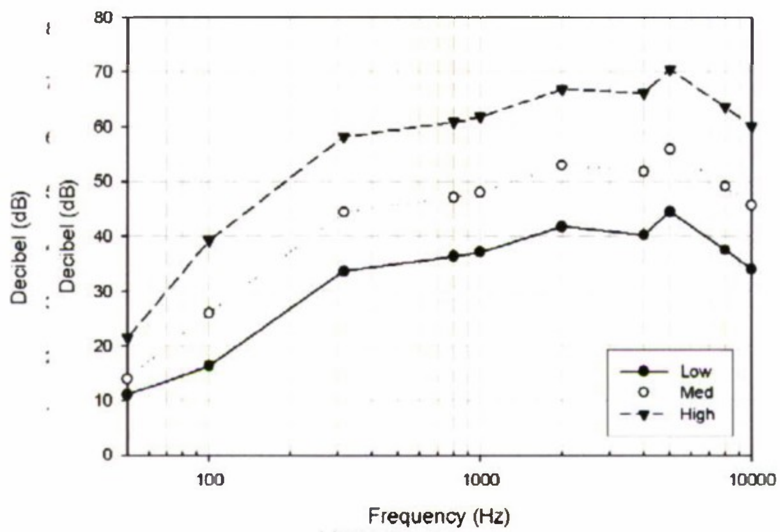

Figure 3. Frequency Response of Pure Tones at Three Amplification Levels

The frequency response of the pure tones from the medium loud test was plotted with the total band level during the tone measurement and the sound level meter value during the tone measurement in Figure 4. The sound level meter agreed with the total band power at almost every test tone. Only at the lower tones that were below 30 dB did the sound level meter and total band dB levels differ noticeably. This most likely occurred because the sound level meter only has a detection range from 30 to 130 dB.

The total band power and sound level meter values from all test levels (low, medium, and high) were plotted in a regression plot shown in Figure 5. Only frequencies from 300 to 8,000 Hz were used. The lower frequencies were below the

30 dB threshold of the sound level meter, and the highest frequency was not in the recommended sound level meter frequency range. The plotted values and their trend line remained close to the identity line. Furthermore, a statistical regression test [6] confirmed that the slope and intercept of the trend line and the identity line were not significantly different. Thus, the total band dB measured with the microphone system was the same as the sound level meter measured dB at each test tone.

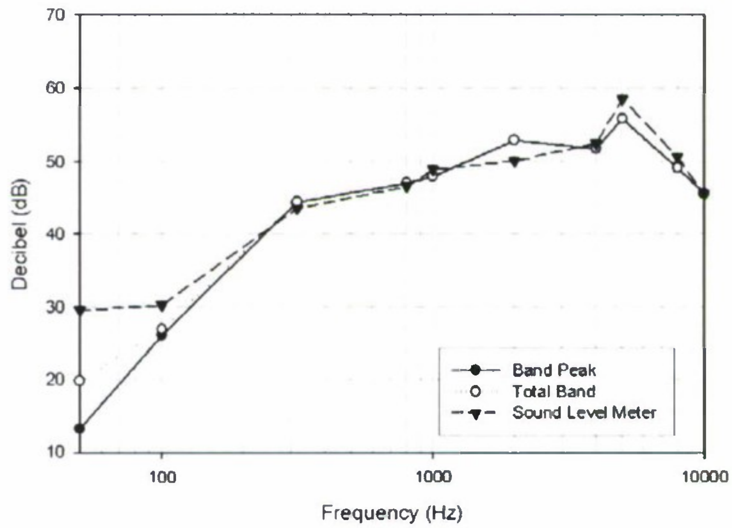

Figure 4. Band Peak, Total Band, and Sound Level Meter Frequency Response of Pure Tones at Medium Amplification

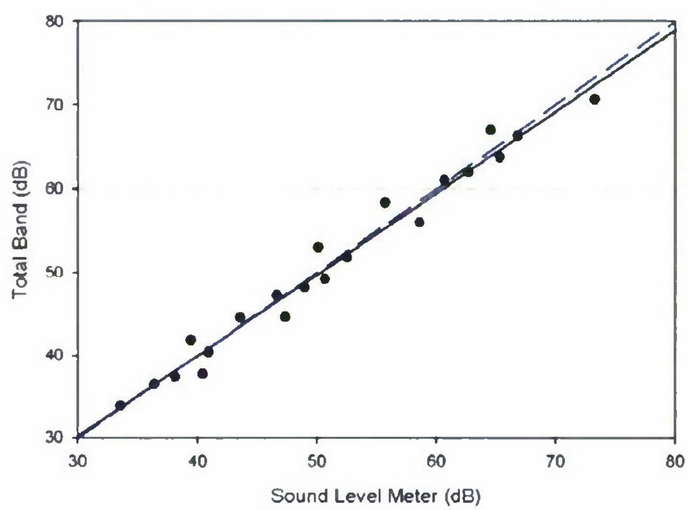

Figure 5. Regression Plot of Total Band and Sound Level Meter

The pink noise test results from the sound system are plotted in Figure 6. When produced in a sound system capable of nearly flat frequency response, pink noise has equal power across the octaves. Again, the system used to generate the sound did not have a flat frequency response and caused the small peaks and valleys seen in the plot. The total band power measured by the microphone was 57.5 dB, while the sound level meter measured 60.1 dB. The total band power measurement differed from the sound level meter measurement by < 3 dB. The total band power accounts for frequencies from 50 to 10,000 Hz, while the sound level meter accounts for frequencies from 31.5 to 8,000 Hz. The differences in the measurement ranges may account for the slight dB measurement difference. Additionally, the frequency responses of the microphones may be slightly different over the range of pink noise frequencies. Nevertheless, during the pink noise test, the measurement methods differed by < 3 dB.

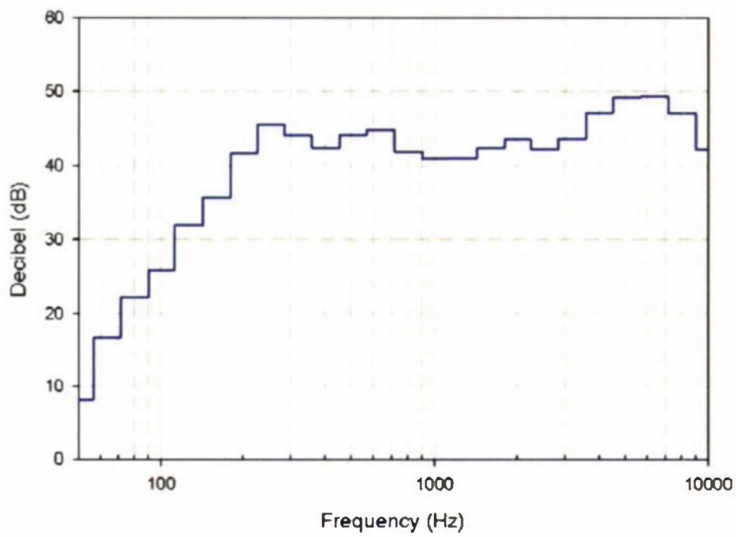

Figure 6. Pink Noise Measured 1/3 Octave

4. CONCLUSION

The sound measurement equipment and software were built to military standard specifications. The detection, analysis, and storage of sound data were accomplished in real-time with a simple user interface. With the addition of communication and monitoring components, the system was suitable for human subject testing of personal protective equipment. The verification tests demonstrated that the system could detect frequencies within the range of human hearing and compared favorably with a sound level meter used in other sound communication testing.

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