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Characterizing impulsive noise with A-weighted sound pressure, kurtosis, and higher order statistical moments

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Permanent hearing loss and tinnitus are the first and second most common disabilities for current members and veterans of the US armed services. The recently finalized Military Standard 1474E for noise uses the peak sound pressure level, A-weighted equivalent level and the Auditory Hazard Assessment Algorithm for Humans (AHAAH) model. An alternate approach uses the kurtosis statistic to indicate the extent of impulsiveness of the sound pressure waveform. This paper discusses how the characterization of impulsive noise by the A-weighted equivalent level can be supplemented with kurtosis. Impulsive noise is processed in the time domain using A-weighting filters and one-third octave band filters. Each one-third octave band has its own analysis time window that is the maximum of five wave periods or 0.01 seconds. For all one-third octave bands, the sound pressure waveform is processed using a time step of 0.01 seconds. Overlapping of the analysis time windows may occur below 500 Hz. The short time step provides a higher temporal resolution for modelling the acoustic reflex. A dataset of fifty previously collected acoustic waveform stimuli are used to test the signal processing methods. The dataset was originally collected by SUNY-Plattsburg, New York and USAARL in Fort Rucker, AL.

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1 METHODS FOR ANALYZING IMPULSIVE NOISE

Impulsive noise has a greater potential to cause hearing loss than continuous noise of the same A-weighted sound pressure level[1-2]. Several metrics are currently used to characterize the risk of hearing impairment due to impulsive noise exposure. The recently finalized military standard, MILSTD 1474E, uses 3 different metrics to characterize the potential for hearing impairment, including sound pressure peak level L_{peak} (dBP re 20µPa), Auditory Hazard Assessment Algorithm for Humans (AHAAH) which is measured in Auditory Hazard Units (*ARU*s), and the 100 ms equivalent A-weighted sound pressure level with A-duration correction $L_{\mathrm{IAeq100ms}}$ (dBA re 20µPa rms).[3] Another approach using the fourth central standardized statistical moment, kurtosis, is the subject of current research.

This paper discusses supplementing the A-weighted sound pressure level with kurtosis and higher-order centered standardized statistical moments. Familiar digital filters in one-third octave bands are used in the time domain. Analysis time windows of one second are commonly used. However, a goal of this research is to understand the acoustic middle ear reflex. The purpose of the short time window is to characterize the individual impulsive noise events and the continuous noise between the impulsive events with a time resolution shorter than the latency of the acoustic reflex. The time step has a fixed length that is chosen to be short enough (approximately 0.01 seconds) to model the acoustic middle ear reflex and the quiet time between impulses.

Previous research using the kurtosis of the sound pressure used analysis time windows of approximately 40 seconds.[4-6] Long time windows are used because kurtosis of occupational noise exposure waveforms approaches an asymptotic limit with time. Kurtosis and other higher order statistical moments depend on the time length of the analysis time window. If the time window is long enough, then the distribution of the sound pressure will be approximately the same from one time step to the next, and the value of the kurtosis metric will be almost identical from one time step to the next. In this paper, the approach of characterizing individual impulsive noise events with both a short time step (0.01 seconds) and a short analysis time window (maximum of 5 wave periods and 0.01 seconds) will be investigated.

2 ACOUSTIC REFLEX

When activated, the acoustic reflex provides some protection against hearing loss due to impulsive noise.[7] To better understand the role of the acoustic reflex, future work will model the acoustic reflex in impulsive noise. The signal processing described in this paper is established to satisfy the requirements of modelling the acoustic reflex.

In humans, the acoustic middle ear reflex is the contraction of the stapedius muscles in both ears when a sound is presented to either ear. The ipsilateral stimulated ear tends to exhibit a slightly stronger response, and the threshold of the acoustic reflex is also lower in the ipsilateral ear. By contracting the stapedius muscle, the impedance of the middles ear changes and reduces the sound transmission to the cochlea preferentially for lower frequencies than for higher frequencies.[8] Humans with normal hearing generally have an acoustic reflex threshold of 85 dBA. As the stimulus increases in intensity, the contraction of the stapedius muscles increases, which increases the sound reduction in the cochlea. The signal to contract the stapedius muscles travels through both the afferent and efferent systems and has a latency that decreases from approximately 25 ms to 125 ms. As the intensity of the stimulus increases, the latency decreases. [8-10]

The rate of activation and the total level of attenuation achieved by the acoustic reflex depend on many factors of the excitation stimulus, including the sound pressure level, frequency content, and type of noise (sinusoidal, white noise, or broadband impulse).[8-10] The time to activate the acoustic reflex varies from 0.025 seconds to approximately 0.125 seconds. A time window of 0.01 seconds is short enough to resolve the lower bound on the rate of activation of the acoustic reflex. In future work, a time step of 0.01 seconds will be used in modeling the middle ear acoustic reflex.

3 FORMULAS FOR ANALYSIS TIME WINDOWS AND OVERLAP

In time-frequency analysis there is a tradeoff between the step size in time and the step size in frequency to accurately estimate the parameters of interest as a function of both time and frequency. In this paper, the time step and analysis time window are shortened so that individual events or non-events can be characterized at a time resolution faster than the human middle ear acoustic reflex. If the analysis time window is too short, then the parameters cannot discern between a sinusoidal wave, white noise, and a broadband impulse. If the analysis time window is too long, then the behavior of the acoustic reflex will be obscured. Statistical moments are used as the parameters of interest for characterizing the events. Estimating the standard deviation, kurtosis, and higher order moments requires approximately 5 wave periods. This choice provides approximately enough information to differentiate between white noise, a sinusoidal wave, and a broadband impulsive event. The exact number of wave periods needed for analyzing the data needs further research.

The analysis time window must have a starting time, duration, and stopping time. The time offset is needed for calculating the starting times for the analysis time window for each one-third octave band and is given by

$$T_{\text{offset}}\left(f_{\text{band}}\right)=\max\left(T_{\text{ar}},\,\frac{N_{\text{band}}}{f_{\text{band}}}\right), \tag{1}$$

where T_{offset} is the offset time for each third octave band, T_{ar} is the time resolution for the acoustic reflex (0.01 seconds), N_{band} is the number of bands used in the analysis time window, and f_{band} is the center frequency of the third octave band. The maximum time offset is

$$T_{\text{offset,max}}=\max\left(T_{\text{offset}}\left(f_{\text{band}}\right)\right)\,. \tag{2}$$

We choose the time overlap between analysis time windows to be the same as the acoustic resolution time to satisfy the goal of modelling the acoustic reflex. This is also the size of the time step in time-frequency analysis. The formula is given by

$$T_{\text{overlap}}=T_{\text{ar}}=T_{\text{time step}}\,, \tag{3}$$

where T_{overlap} is the overlap time in seconds and $T_{\text{time step}}$ is the step size in time. The starting time for each analysis time window in each one-third octave band is given by

$$T_{\text{start}}\left(f_{\text{band}},n\right)=T_{\text{offset,max}}-T_{\text{offset}}\left(f_{\text{band}}\right)+nT_{\text{overlap}}\,. \tag{4}$$

where n is the number of the n^th analysis time window. The number of time steps in a finite time interval when starting with the maximum offset is given by

$$N_{\text{time steps}}=floor\left(\frac{T_{\text{interval}}-T_{\text{offset,max}}}{T_{\text{time step}}}\right)+1\,, \tag{5}$$

where $N_{\text{time steps}}$ is the number of time steps in a time interval T_{interval} (s).

Figure 1 depicts a stimulus being windowed by 23 one-third octave bands from 125 Hz to 20 kHz. The time overlap is 0.01 seconds, and the one-third octave bands have an analysis time window length of the maximum of 5 wave periods of the one-third octave band and 0.01 seconds.

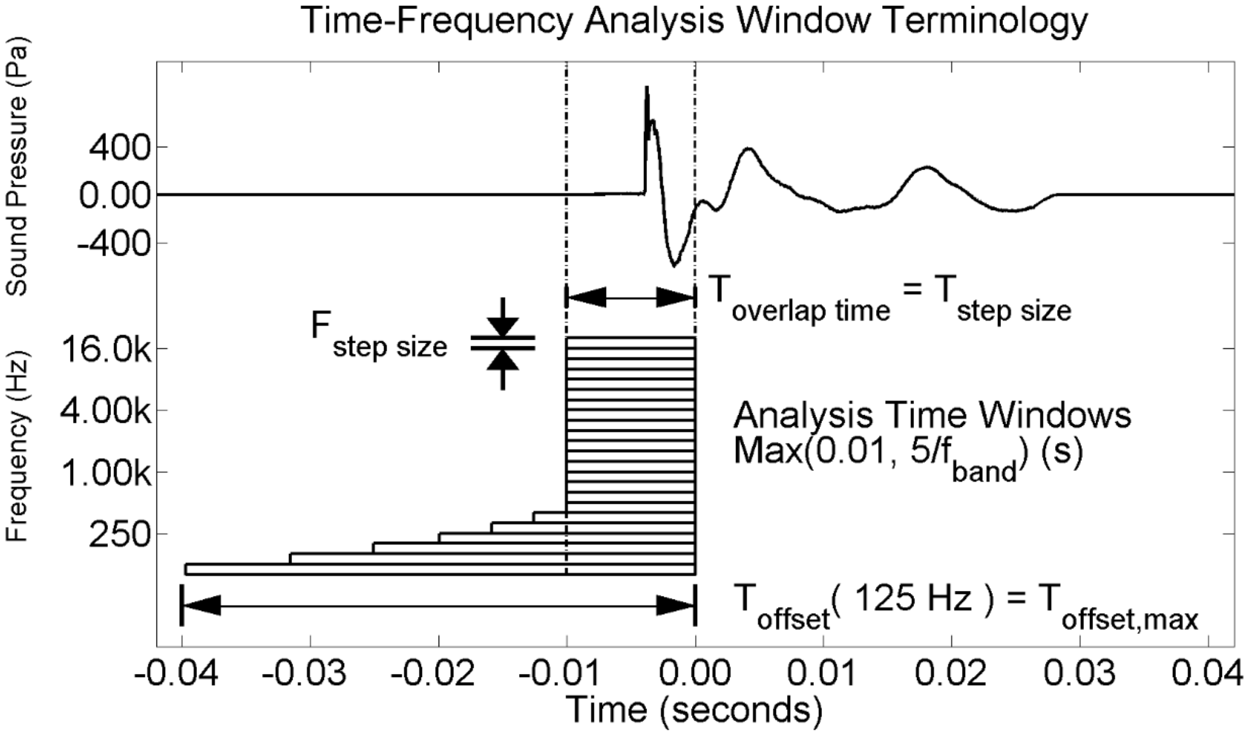

Fig. 1 – A sound pressure waveform from a stimulus is overlaid with the one-third octave band analysis time window, time step size, and frequency step size. The time overlap is 0.01 seconds and each one-third octave band has an analyis time window of length maximum of 0.01 seconds and 5 wave periods.

4 COMPARING FILTERS

The Labview Advanced IIR Filter Design Virtual Instruments (programs) were used to realize the third octave band filters. The filters were tested to assess conformance with ANSI S1.11-2014.[11] The Labview digital filters were compared using three types of measurements described in ANSI S1.11-2004. The three types of measurements were exponential sinusoidal sweeps, sinusoidal attenuation curves, and the reverberation decay times. Computer simulations were used to compare the filters. The effective band width measurement was not performed. The exponential sinusoidal sweeps had a frequency range of 80 Hz to 31.5 kHz and a duration of 10 seconds. The sinusoidal attenuation curves were calculated for each of the one-third octave bands. The reverberation decay times used 1.0 seconds of inverse-f noise at an amplitude of 1.0 Pa followed by 1.0 seconds of inverse-f noise at an amplitude of 0.1 μPa. A running average of the squared sound pressure was applied using a window of duration of 0.10 seconds. Linear regression was applied from 10 dB down to 70 dB down the decay curve.

Five filter types (Butterworth, Chebyshev, Inverse Chebyshev, Elliptic, and Bessel) were compared with the three types of tests. Six different analog-equivalent odd filter orders (3, 5, 7, 9, 11, 13) were used. The analog filter orders are equivalent to digital filter orders are 6, 10, 14, 18, 22, and 26. The filters were realized using digital techniques and were tested using 26 sampling rates from 4 kHz to 1 MHz. This yielded a 5x6x26 array of 23 one-third-octave band filters.

Figures 2a and 2b show the attenuation curves for the Butterworth filter in one-third octave bands at 1000 Hz and 4000 Hz center frequencies for a sampling rate of 100 kHz. All of the filter orders have attenuation rates that satisfy the Class 1 and Class 2 requirements of ANSI S1.11-2014 at the 100 kHz sampling rate. The other filter types were tested, but they did not perform as well as the Butterworth filters. For brevity, only the results of the Butterworth filters are shown.

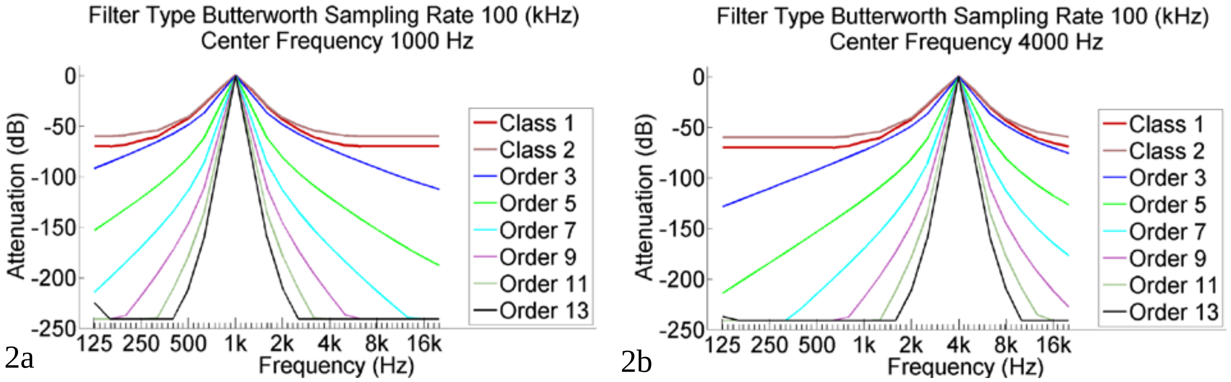

Fig. 2 – Attenuation of Butterworth one-third octave band digital filters with center frequencies of 1000 Hz and 4000 Hz. All of the filter orders of the Butterworth one-third octave band filters meet the Class 1 and Class 2 requirements of ANSI S1.11-2014 at the 100 kHz sampling rate.

Figures 3a and 3b illustrates the results of the exponential sweep and the reverberation time testing for the Butterworth filters at a 100 kHz sampling rate. In Figure 3a, the measurement error of the exponential sweep increases as the filter order decreases. The measurement errors of the exponential sweep are within the Class 1 interval ±0.4 dB for all filter orders. In Figure 3b, the reverberation time at low frequencies increases as the filter order increases. ANSI S1.11-2014 does not specify required reverberation times. The advantage to having a shorter reverberation time is that the filters will have less influence on the results of the reverberation time measurement. The 5th order Butterworth filter provide a satisfactory compromise between measurement error and reverberation time and satisfies these requirements of the standard.

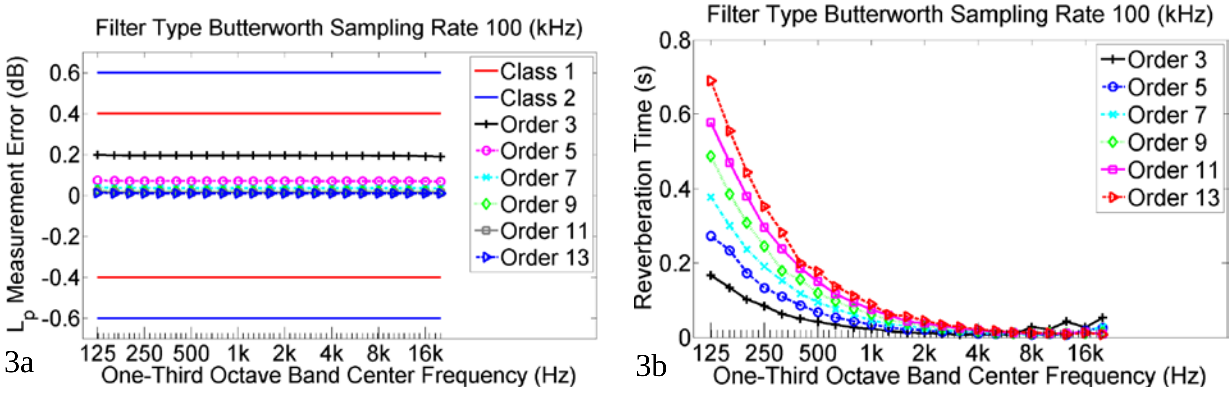

Fig. 3 – On the left (3a) is the measurement error of the sound pressure level (dB re 20µPa rms) of the third octave band filters for an exponential sweep from 80 Hz to 31.5 kHz. On the right (3b) are the third octave band filter reverberation times.

5 APPLICATION TO BLAST DATA

Fifty stimuli from a previously collected animal noise exposure study from the Jaycor Project Number 2997-28[12] were used to understand the robustness of the signal processing with respect to changes in the filter order. A total of 900 chinchillas were exposed to high-level impulse noise to investigate hearing loss due to blast overpressure. Chinchillas have similar hearing mechanisms to humans however, they are more susceptible to hearing loss.[13] The data were collected at two facilities. At the Auditory Research Laboratories at the State University of New York (SUNY) in Plattsburgh, NY, 689 chinchillas in 102 groups with 18 different stimuli were processed. At the United States Army Aeromedical Research Laboratory (USAARL) in Fort Rucker, AL, 311 chinchillas in 35 groups with 32 different stimuli were processed.[12]

The goal of robust design is to optimize a process by controlling variables that can be controlled so that the results are incentive to variables that cannot be controlled or may change. A researcher may decide to use a different filter order for a given task. So the chosen fitter type and statistical moments should be robust with respect to changes in the filter order.

The goal of robust signal processing design in this paper is to choose a digital filter type (Butterworth), analysis time window duration, and test statistics (moments) that completely characterize the distribution of the sound pressure and are insensitive to changes in the filter order, so that any filter order can be chosen and the chosen statistical moments will not be affected by the choice of filter order. The results of the signal processing are the estimated statistical moments of the sound pressure at each of the one-third octave bands for each time step.

The blast stimuli were processed to understand the robustness of the estimated statistical moments with respect to the filter orders, and to understand the correlations of the estimated statistical moments with respect to the sequence of time steps. The stimuli were zero padded so that each impulse noise event occurred at approximately 0.5 seconds and the total length of the waveform is one second. Since processing zeros causes the estimated moments to be zero, inverse-f noise with exponent 1 and amplitude 0.002 Pa was added to the stimuli to improve signal processing. The inverse-f noise added approximately 44 dB of noise across the frequency bands from 125 Hz to 20 kHz. The inverse-f noise improved signal processing with only negligible influences on the impulsive noise event.

To determine if the derivative of the sound pressure with respect to time provided additional explanatory information, the fifty stimuli were processed as both the sound pressure and the derivative of the sound pressure with respect to time. The stimuli were processed by first applying an A-weighting filter in the time domain, then applying digital one-third octave band Butterworth filters in 23 bands from 125 Hz to 20 kHz. For the one-third octave bands, six filter orders (3, 5, 7, 9, 11, 13) were tested. Five numbers of wave periods (5, 7, 10, 15, 20) were tested, where the durations of the analysis time windows depended on the durations of the analysis time windows were the maximum of the number of wave periods or 0.01 seconds. The time step was 0.01 seconds. The first ten statistical moments were calculated for each of the 97 time steps. This yielded a 50x2x23x 6x5x10x97 array of data.

To express the results in more familiar terms, the standard deviation of the sound pressure is often expressed as the sound pressure level using the formula

$$L_{\mathrm{p}} = 10\log_{10}\left(\frac{\sigma_{\mathrm{p}}^{2}}{\sigma_{\mathrm{ref.}}^{2}}\right), \tag{5}$$

where $\boldsymbol{\sigma_{ref} = 20\mu\mathrm{Pa}}$ and σ_p^2 is the square of the standard deviation of the sound pressure. The nth centered standardized statistical moment level can be expressed using the formula

$$L_{\mu_n} = 10\log_{10}\left(\frac{\mu_{\mathrm{n}}/\sigma_{\mathrm{p}}^{\mathrm{n}}}{(\mathrm{n}-1)!!}\right), \tag{6}$$

where $\mu_{\mathrm{n}} = \sum_{\mathrm{i}=1}^{\mathrm{i}=\mathrm{N}} (x_{\mathrm{i}} - \mu)^{\mathrm{n}}$ is the nth centered moment, (n-1)!! is the double factorial function of n-1, and $\sigma_{\mathrm{p}}^{\mathrm{n}}$ is the standard deviation of the sound pressure raised to the nth power. The kurtosis of the sound pressure is the fourth centered standardized statistical moment of the sound pressure with a reference value of $(4-1)!!=3$.

Figures 4a and 4b show the results of processing the sound pressure of stimulus 1 using the 1000 Hz center frequency one-third octave band for moments 2 (standard deviation) and 4 (kurtosis) respectively for six orders of filters. The six filter orders show similar results. With the number of wave periods set to 5, then the $T_{\mathrm{offset,max}}$ is 0.04 seconds and there are 97 overlap time steps. Plots of the even-numbered higher moments are similar to the kurtosis plot in Figure 4a for all values of the number of wave periods from 5 to 20. As the number of wave periods increases the $T_{\mathrm{offset,max}}$ increases and the number of time steps decreases. Plots of the derivative of the sound pressure with respect to time are not shown, but are very similar to the plots of the sound pressure.

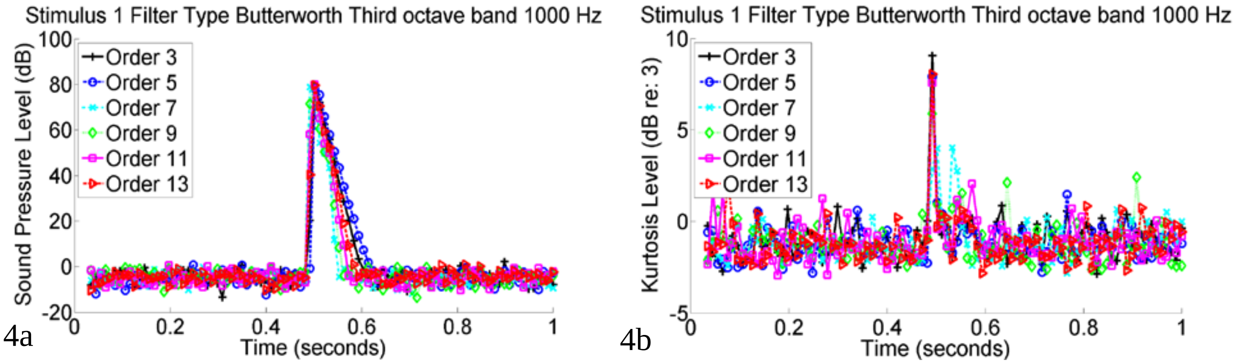

Fig. 4 – On the left (4a) are 97 time steps of the standard deviation expressed as sound pressure level. On the right (4b) are the 97 time steps of the kurtosis expressed as kurtosis level.

The odd higher-order moments are not shown, but they are briefly described here. The estimated values of the odd-order moments for the 97 time steps are generally close to zero except near the impulsive noise event, where the estimated values of the odd moments can be positive or negative. Different filter orders have positive or negative estimates of the odd moments, and the relationship appears to be random. For this reason, the odd statistical moments do not appear to be useful in characterizing one-third octave band time waveforms.

5.1 Blast Data Parameter Robustness across Filter Orders

To characterize the sound pressure distribution with the fewest number of estimated moments and the shortest analysis time window, it is desirable to determine how sensitive the first ten statistical moments are with respect to the filter orders. For each of the fifty stimuli and each of the 10 moments, the proportion of 95% confidence intervals of the estimated mean value across the six filter orders containing zero was calculated for each one-third octave band and time step. The 95% confidence intervals assume the values of the moments across the six filter orders are approximately distributed as a student t-distribution with 4 degrees of freedom.

Figures 5a and 5b show the proportions of the 95% confidence intervals that include zero for each of the ten statistical moments and fifty stimuli. In Figure 5a, moments 2, 4, and 6 have a much higher proportion of 95% confidence intervals not including zero than moment 8 and 10. This suggests that the standard deviation of the estimates grows faster for moments above 4 than the mean. Moments 8 and 10 have more variance with respect to the mean and are more sensitive to changes in the filter order. In Figure 5b, almost all of the odd moments include zero in every 95% confidence interval. This suggests that the odd moments may be randomly distributed or equal zero. In regression analysis, the explanatory variables are assumed to be constants that must be significantly different than zero. The odd-moments are not suitable for use in regression analysis as explanatory variables. The even moments especially moment 2 and 4 are more likely to be useful in regression analysis.

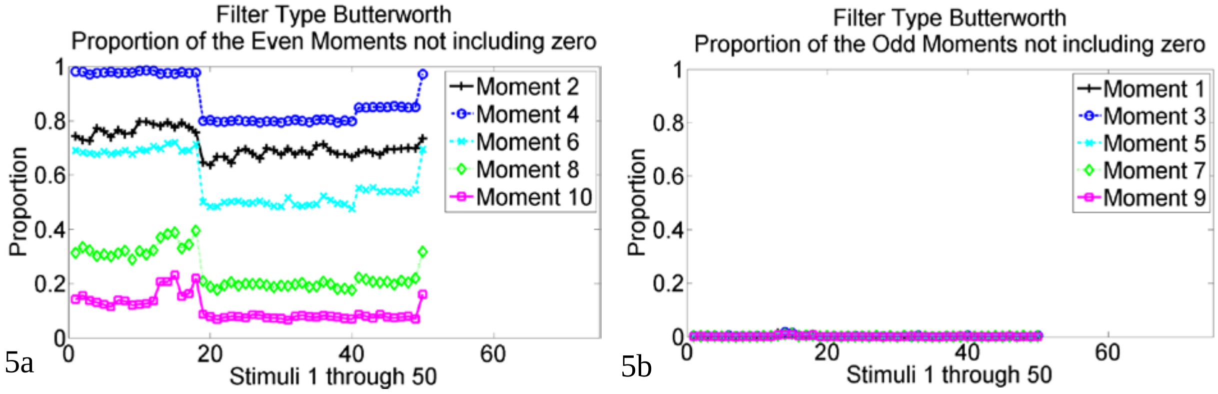

Fig. 5 – On the left (5a) is the proportion of the estimated even moments not including zero. On the right (5B) is the proportion of the estimated odd moments not including zero. Moments 8 and 10 and the odd moments have less of a proportion of 95% confidence intervals not including zero, so they are more likely to be zero.

The results shown in Figures 5a and 5b are similar to the results for the wave periods 5, 7, 10, 15, and 20. Additionally, the results are similar for the derivative of the sound pressure with respect to time. In statistical regression, the explanatory variables are treated as constants and must have a mean that is large relative to the variance. This means that the odd moments and moments 8 and 10 may not be useful in statistical regression. The statistical moments 2, 4, and 6 may be useful in statistical regression analysis.

5.2 Blast Data Parameter Correlations across analysis time windows

It is desirable to identify the fewest number of estimated statistical moments that characterize the distribution of the sound pressure and the derivative of the sound pressure with respect to time. If two moments are highly correlated then the higher moment explains the same information as the lower order moment and the higher order moment can be discarded from the analysis. The Pearson correlations of the statistical moments across the sequence of time steps for the sound pressure and derivative of the sound pressure were investigated. The correlation of the moments of the sound pressure for the even moments were calculated for each of the filter orders and number of wave periods in the analysis time windows.

Figures 6a and 6b displays contour plots of the correlations as a function of one-third octave bands along the x-axis and stimulus number from 1 to 50 along the y-axis. Figure 6a shows the correlation between the standard deviation and the kurtosis of the sound pressure across the 97 time steps. The standard deviation and kurtosis have only weak correlation at the low frequencies $\left(f_{\text{band}} < 2\,\text{kHz}\right)$, but the correlation becomes much stronger for high frequencies $\left(f_{\text{band}} > 4\,\text{kHz}\right)$. Figure 6b on the right shows the correlation between the kurtosis and the 6th centered standardized statistical moment of the sound pressure across the 97 time steps. The kurtosis and the 6th centered standardized statistical moment are highly correlated for all of the one-third octave bands in all of the fifty stimuli. Although not illustrated in this paper, the kurtosis is also highly correlated with the 8th and 10th centered standardized statistical moments of the sound pressure across the 97 time steps.

The correlation between the even moments of the derivative of the sound pressure with respect to time are very similar to Figures 6a and 6b. The correlations between the even moments for sound pressure and the correlations between the even moments for derivative of the sound pressure with respect to time are very similar for the different filter orders and for the different number of wave periods in the analysis time windows.

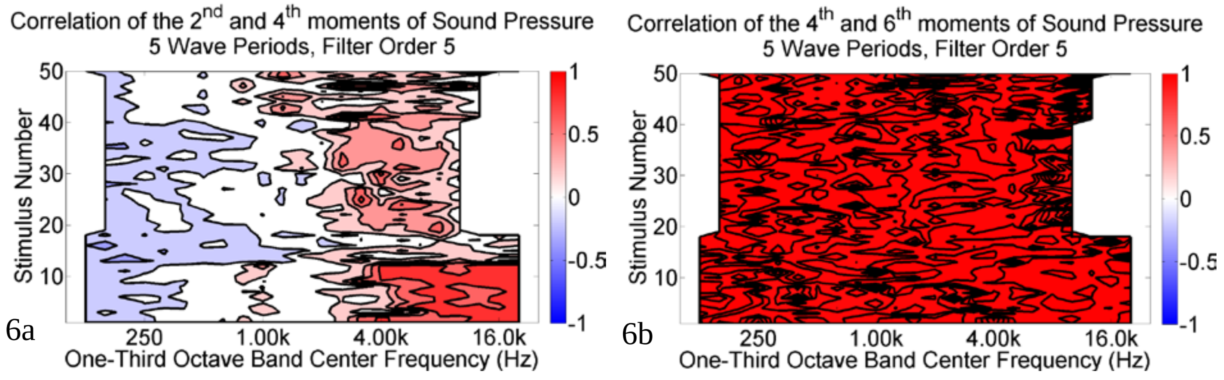

Fig. 6 – On the left (6a) is the correlation between the estimated standard deviation and kurtosis of the 97 time steps of the sound pressure. On the right (6b) is the correlation between the estimated kurtosis and the 6th centered standardized moment of the of the 97 time steps of the sound pressure. Both plots used a Butterworth filter of order 5 with an analysis time window of 5 wave periods.

Figure 7a displays a contour plot of the correlation of the standard deviation of the sound pressure and the standard deviation of the derivative of the sound pressure with respect to time.

These two standard deviations are highly correlated for each one-third octave band and stimulus. Figure 7b displays a contour plot of the correlation of the standard deviation of the sound pressure and the kurtosis of the derivative of the sound pressure with respect to time. The standard deviation of the sound pressure and kurtosis derivative of the sound pressure are only weakly correlated. This suggests that the standard deviation of the sound pressure and the derivative of the sound pressure with respect to time cannot both be used in a regression analysis because they are highly correlated.

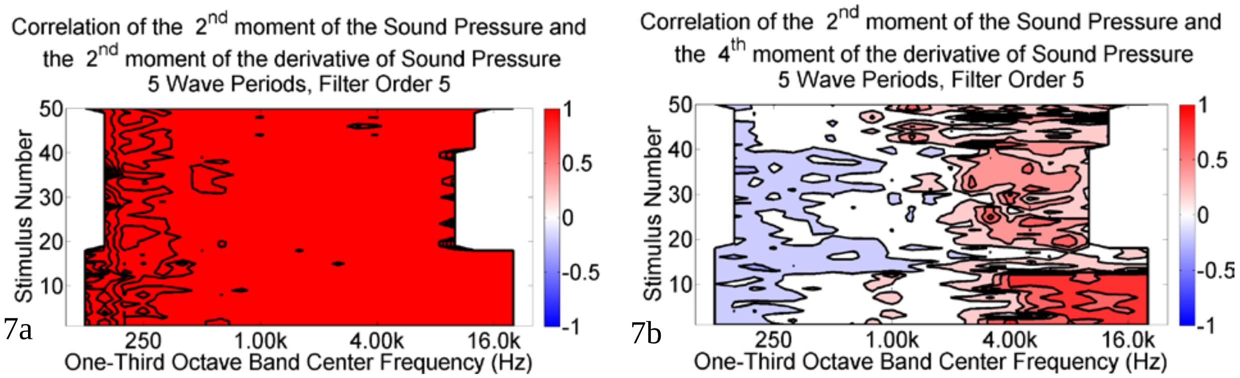

Fig. 7 – On the left (7a) is the correlation between the standard deviation of the sound pressure and the standard deviation of the derivative of the sound pressure with respect to time. On the right (7b) is the correlation between the standard deviation of the sound pressure and the kurtosis of the derivative of the sound pressure with respect to time. Both plots used a Butterworth filter of order 5 with an analysis time window of 5 wave periods.

Figure 8a displays a contour plot of the correlation of the kurtosis of the sound pressure and the kurtosis of the derivative of the sound pressure with respect to time. These two quantities are highly correlated for each third octave band and stimulus. Figure 8b displays a contour plot of the correlation of the kurtosis of the sound pressure and the standard deviation of the derivative of the sound pressure with respect to time. These two quantities are only weakly correlated. This suggests that the kurtosis of the sound pressure and the kurtosis of the derivative of the sound pressure with respect to time cannot both be used in a regression analysis since they are highly correlated.

The moments of the sound pressure and derivative of the sound pressure are highly correlated and contain the same information so only the sound pressure is needed. The odd moments, and moments 8, and 10 of the sound pressure are not likely to be useful in regression analysis. Moments 6, 8, and 10 are highly correlated with moment 4, so moments 6, 8, and 10 are not needed. The 2nd and 4th moments of sound pressure are only weakly correlated. Consequently the standard deviation and the kurtosis of the sound pressure are likely to be useful in regression analysis and are the only moments of the sound pressure that need to be considered in regression analysis.

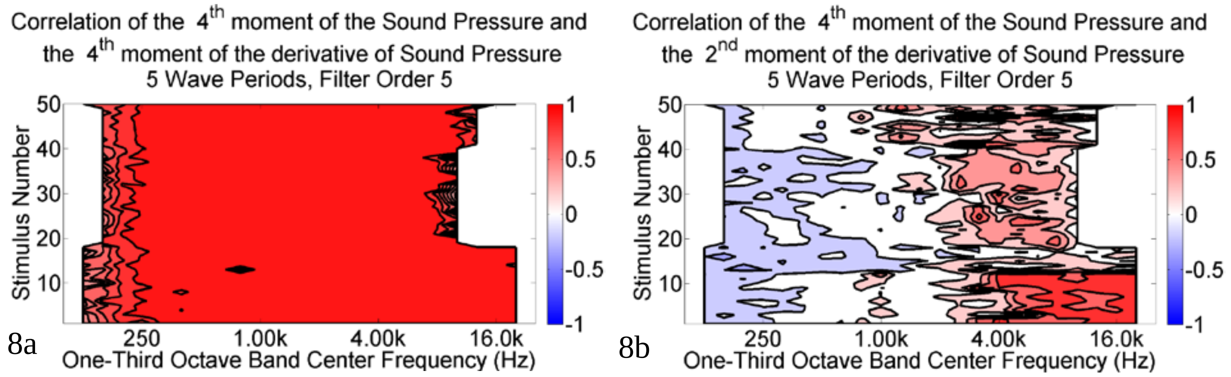

Fig. 8 – On the left (8a) is the correlation between the kurtosis of the sound pressure and the kurtosis of the derivative of the sound pressure with respect to time. On the right (8b) is the correlation between kurtosis of the sound pressure and the standard deviation of the derivative of the sound pressure with respect to time. Both plots used a Butterworth filter of order 5 with an analysis time window of 5 wave periods.

6 DISCUSSION AND CONCLUSIONS

The 5th order Butterworth filters satisfy the sinusoidal attenuation test and the exponential sweep test, and have good reverberation time performance. Additional testing is needed to fully verify conformance of the filters with ANSI S1.11-2014.

This paper suggests that sound pressure level and sound kurtosis level are sufficient to characterize impulsive noise events when conditioning on third octave bands from 125 Hz to 20 kHz with analysis time windows for each band being the maximum of 5 wave periods and 0.01 seconds with a time step of 0.01 seconds. This approach is based on the method of statistical moments. This method did not consider the temporal effect of rise time or fall time. The method of moments with short time steps and short time windows provides a detailed characterization of the time waveform distributions; however, additional temporal characteristics may be needed.

The analysis time windows had at least 5 wave periods which caused the length of the analysis time windows at low frequencies $\left(f_{\text{band}} < 500\,\text{Hz}\right)$ overlap since they were longer than the time step, 0.01 seconds. More computer simulations of tonal impulses especially at low frequency $\left(f_{\text{band}} < 500\,\text{Hz}\right)$ are needed to determine the fewest number of wave periods for estimating the statistical moments.

The first ten statistical moments were estimated; however only moments 2, 4, and 6 were statistically much different than zero. The odd-centered standardized statistical moments may not be statistically different than zero. Most of the 95% confidence intervals of the estimated values of the odd moments for each time step include zero. Different filter orders have positive or negative signs for the estimates of the odd moments, and the relationship appears to be random. For this reason, the odd centered standardized moments do not appear to be useful for characterizing sound pressure waveforms. The even-centered standardized statistical moments may be different than zero. The moments 2, 4, and 6 are statistically far from zero. Moments 8 and 10 are statistically closer to zero than moments 2, 4, and 6. This suggests that moments 8 and 10 have more variability with respect to the mean values than moments 2, 4, and 6. In statistical regression, the explanatory variables are treated as constants and must be far from zero. The moments 8 and 10 have too much variance with respect to the mean for regression analysis.

The even-numbered higher order centered standardized statistical moments (6, 8, and 10) are highly correlated with the 4th centered standardized statistical moment (kurtosis) and do not provide additional information for analysis of data. The standard deviation and kurtosis are only weakly correlated below 2 kHz, but are highly correlated above 4 kHz. Consequently, the standard deviation and kurtosis (moments 2 and 4) are sufficient to characterize the distribution of the third octave band time waveforms.

The sound pressure and the derivative of the sound pressure with respect to time are highly correlated, to the extent of being nearly collinear. Either sound pressure or the derivative of sound pressure with respect to time, but not both, can be used to analyze time waveforms. The sound pressure is simpler and more commonly used, so future work will use the sound pressure.

The signal processing techniques described in this paper can be applied to animal and human data sets by using the standard deviation and kurtosis statistics with a third octave bands from 125 Hz to 20 kHz with analysis time windows for each band being the maximum of 5 wave periods and 0.01 seconds with a time step size of 0.01 seconds. The standard deviation and kurtosis of the sound pressure are appropriate for use as explanatory variables in a regression analysis. Consequently the A-weighted sound pressure can be supplemented with kurtosis of the sound pressure waveform to better understand impulsive noise.

7 FUTURE WORK

Future work will focus on a time series model of the acoustic reflex and recovery during quiet times between impulsive noise exposures. A time series model of cumulative hearing loss in the animal and human ears can be developed and regressed against a datasets of animal and human hearing loss data. The ultimate goal of the research is to produce a model that relates the cumulative noise exposure to the risk of hearing impairment in humans.

8 ACKNOWLEDGEMENTS

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9 REFERENCES

1. ISO 1999 (1990). Acoustics - Determination of occupational noise exposure and estimation of noise induced hearing impairment, *International Organization for Standardization*, Geneva, Switzerland

2. Davis, R. I., Qiu, W., Heyer, N. J., Zhao, Y., Qiuling Yang, M. S., Li, N., ... & Yao, D. (2012). The use of the kurtosis metric in the evaluation of occupational hearing loss in workers in China: Implications for hearing risk assessment. *Noise and Health*, 14(61), 330

3. MIL-STD-1474E (2015). Design criteria standard noise limits, United States Department of Defense: Accessed on 2015/05/08, Available at http://www.arl.army.mil/www/pages/343/MIL-STD-1474E-Final-15Apr2015.pdf

4. Lei, S. F., Ahroon, W. A., & Hamernik, R. P. (1994). The application of frequency and time domain kurtosis to the assessment of hazardous noise exposures. *The Journal of the Acoustical Society of America*, 96(3), 1435-1444

5. Zhao, Y. M., Qiu, W., Zeng, L., Chen, S. S., Cheng, X. R., Davis, R. I., & Hamernik, R. P. (2010). Application of the kurtosis statistic to the evaluation of the risk of hearing loss in workers exposed to high-level complex noise. *Ear and hearing*, 31(4), 527-532

6. Goley, G. S., Song, W. J., & Kim, J. H. (2011). Kurtosis corrected sound pressure level as a noise metric for risk assessment of occupational noises. *The Journal of the Acoustical Society of America*, 129(3), 1475-1481

7. Coles, R. R. A., Garinther, G. R., Hodge, D. C., & Rice, C. G. (1967). *Criteria for assessing hearing damage risk from impulse-noise exposure* (No. HEL-TM-13-67). Human Engineering Lab Aberdeen Proving Ground MD.

8. Silman, S. (Ed.). (1984). *The acoustic reflex: Basic principles and clinical applications*. Academic Press. pp 303-316

9. Møller, A. R. (2000). *Hearing: its physiology and pathophysiology*. Academic Press. pp343-346

10. Musiek, F. E., & Baran, J. A. (2007). *The auditory system: Anatomy, physiology and clinical correlates*. Boston: Pearson. pp 202-206

11. ANSI S1.11-2014 (2014). American National Standard Electroacoustics - Octave-band and Fractional-octave-band Filters - Part 1: Specifications (a nationally adopted international standard). *American National Standards Institute, Acoustical Society of America, New York*

12. Hamernik, R. P., Patterson Jr, J. H., & Ahroon, W. A. (1998, August). Use of animal test data in the development of a human auditory hazard criterion for impulse noise. *Plattsburgh, NY: State University of New York at Plattsburgh. Auditory Research Laboratory Report*. Final Report DAMD17-96-C-6007

13. D. Henderson & R.P. Hamernik, *Occupational Medicine: State of the Art Reviews*, Hanley & Belfus, Inc., 1995 Accessed on 2015/05/08, Available at http://faculty.plattsburgh.edu/roger.hamernik/cds_344/pdf_files/henderson2.pdf