Fall 2014

Measurement of Field Complex Noise Using a Novel Acoustic Detection System

Jun Qin
Southern Illinois University Carbondale, jqin@siu.edu

Pengfei Sun
Southern Illinois University Carbondale, sunpengfei@siu.edu

Jacob Walker
Southern Illinois University Carbondale, walkerjacob1393@yahoo.com

Measurement of Field Complex Noise Using a Novel Acoustic Detection System

Jun Qin, PengFei Sun, and Jacob Walker
Department of Electrical and Computer Engineering
Southern Illinois University Carbondale
Illinois, USA

***Abstract*— This paper represents our recent experimental measurement study of the complex noise in industrial fields, using a novel acoustic detection system and wavelet transform algorithms. Noise induced hearing loss (NIHL) continues to be one of the most prevalent occupational hazards in the United States. Number of research on NIHL showed a complex noise could produce more hearing loss than an energy-equivalent continuous or impulsive noise alone. Many workplaces in varied industries are subjected to the high level complex noise (i.e., high-level impulsive noise mixed with continuous Gaussian noise). The current noise measurement guidelines and devices (e.g., conventional sound level meters) are based on the equal energy hypothesis (EEH), which states that loss of hearing by exposure to noise is proportional to the total acoustic energy of the exposure. However, the EEH does not accurately rate the impulsive noise and the complex noise. Therefore, the conventional sound level meter may not be able to accurately assess the complex noise in industrial fields. In this project, a new waveform profile based noise measurement system has been developed for evaluation of the high level complex noise in industrial fields. The system consists of four ½" condenser microphones, and it can simultaneously detect and record four waveforms of the complex noise with high sampling rate (125 KHz). In addition, a wavelet transform based signal analysis algorithm has been modified and implemented to characterize the complex noise. Pilot field measurements have been conducted in selected local coal mining fields (e.g., wet coal preparation plant and dry coal handling plant) using the developed system. The preliminary results showed that the system successfully detected and recorded waveforms of complex noise in industrial fields. The modified algorithm can decomposed the complex noise signals and display the detailed features in the time-frequency joint domain. The key parameters of complex noise can be determined, and the hazardous complex noise in industrial fields can be identified. In addition, when measuring the equivalent A-weighted averaged sound pressure level, the developed system is comparable to a conventional sound level meter.**

Keywords—noise induced hearing loss; complex noise, noise measurement, wavelet transform; time-frequency domain characterization.

I. INTRODUCTION

Noise induced hearing loss (NIHL) continues to be one of the most prevalent occupational hazards in the United States. Typical workplaces are often subjected to a complex noise environment in which high-level impulsive noise mixed with continuous Gaussian noises are embedded [1]. A number of animal studies showed that interaction effect between impulsive and broadband noises may actually exacerbate the NIHL [2]. For example, an exposure to a complex noise was observed to produce a much greater permanent threshold shift (PTS) and more extensive hair cell losses than an exposure to only an energy equivalent continuous or impulsive noise alone would have caused.

The noise measurement guidelines and standards, such as ISO-1999-1990 and ANSI S3.44-1996, are designed based on the equal energy hypothesis (EEH). This theory regards that NIHL depends on the total acoustic energy of the noise exposure [1]. In addition, conventional sound level meters (SLMs) are developed based on the EEH. These SLMs commonly use condenser microphones to detect the noise signals, and take A-weighted equivalent sound pressure level (SPL), L_{Aeq}, as criterion to evaluate the noise exposure levels. However, a number of studies showed that the impulsive noise and the complex noise could not be accurately rated by the EEH [2, 3]. Furthermore, L_{Aeq} could not reflect that frequency discrepancy in hearing loss evaluation. Other studies also suggested that new noise metrics were needed for evaluation of the risk of high level complex noises [4-11]. Therefore, new noise measurement systems and noise metrics (e.g. the time-frequency domain characteristics, Kurtosis, etc.) were needed for accurate assessment of complex noises in industrial workplaces.

In this study, we developed a novel acoustic measurement system to collect the field complex noise data. Unlike the convenient SLMs, the developed system could record the pressure waveforms of noise signals with high sampling rate up to 125 kHz, and it included an acoustic test fixture to emulate the structure of human ear canals. A wavelet transform (WT) based algorithm was used to characterize the noise signals measured in fields. In addition, new noise metrics, including WT based equivalent SPL $L_{WTeq}(\omega)$ and Kurtosis $kurt(\omega)$, were proposed for the accurate assessment of the risks of complex noises in industry workplaces.

II. METHODS AND MATERIALS

A. *Noise measurement system*

A waveform profile based noise measurement system has been developed in this study. As shown in Figure 1, the system consists of an acoustic test fixture (GRAS 45CA) with two ½-inch pressure condenser microphones assembled, two ½-inch free-field condenser microphones, a 4-channel microphone signal conditioning amplifier, a 16-bits data acquisition device (NI DAQ USB6254), and a laptop. The test fixture is used to emulate human ear canal structure. Two assembled ½-inch pressure microphones are used to record acoustical pressure waveforms in the ear cannel, while the other two ½-inch free-field microphones are used to record the pressure waveforms in free field. A user interface is developed using LabVIEW software to control the system, and record the waveforms of complex noise signals.

After development, the system was validated using varied noise signals, including pure tone noise, Gaussian noise, and complex noise. Gaussian and complex noises were simulated and generated by a digital noise exposure system. The SPL of varied noise signals were simultaneously measured by the develop system and a conventional SLM. The validation results indicate that the developed system is comparable with the SLM. In addition, the developed system has higher sensitivity and precision than the SLM.

B. *Field measurement*

The developed noise measurement system has been used to conduct field measurements in a coal preparation plant. Figure 1B shows the setup of the developed system in a field measurement. In each field measurement, a conventional SLM has been used for a quick noise level measurement at different locations in the plant. Three locations were selected for the comprehensive measurement using the developed system, including Level 1 nearby the entrance of the plants as background noise measurement, Level 3½ nearby the screen bowl as the highest averaged SPL point, and Level 4 nearby the DR screen at the highest peak SPL point. At each selected location, five noise signals (5 minutes time duration) were measured and recorded by the developed system for further signal analysis. A conventional SLM was also used to measure SPLs of noise in the field, and it was compared with the developed system.

C. *Wavelet transform technology for noise analysis.*

In the conventional noise evaluation methods, the noise signals are characterized in either the time domain or the frequency domain. However, time and frequency are relevant to each and change simultaneously. Therefore a transient signal, such as impulsive or complex noise, needs to be better characterized in the time-frequency (T-F) domain. The wavelets transform, which uses various kernel functions to decompose signals, is suitable for analysis of transient signals.

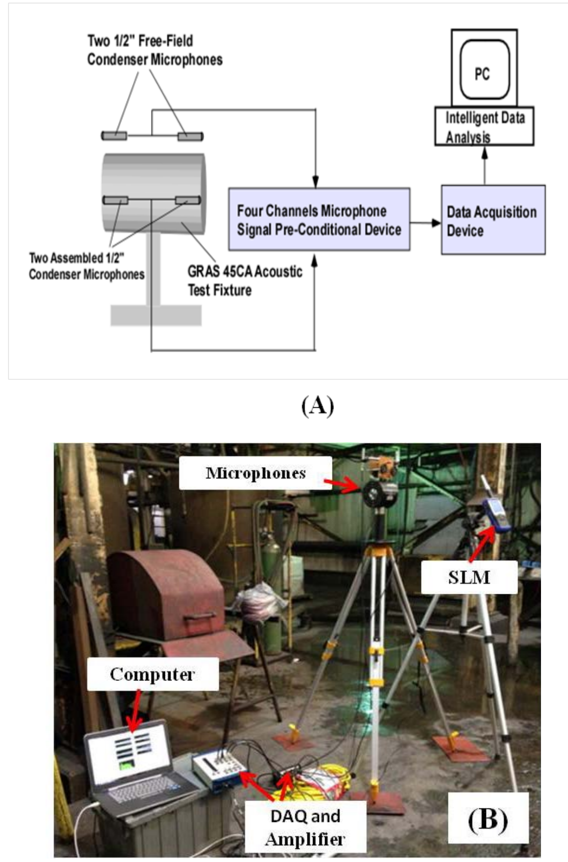

FIG.1: (A) Schematic diagram of the developed noise measurement system, and (B) a photograph of system setup in a field measurement at a coal preparation plant.

Continuous wavelet transform (CWT) which decomposes a signal *f(t)* in the T-F domain can be defined as follows [12,13]:

$$W(a,b) = \int_{-\infty}^{\infty} f(t)\frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right)dt \qquad (1)$$

where $\psi(t)$ is the wavelet kernel function along with the continuous scaling parameter *a* and the time shifting parameter *b*. *W(a, b)* refers to the CWT coefficient.

The signal *f(t)* can be obtained from the wavelet coefficients by the inverse WT, only when it satisfies the admissibility condition ($C_\psi < \infty$):

$$f(t) = C_\psi^{-1}\int_{-\infty}^{\infty}\int_{0}^{\infty}\frac{\mathrm{d}a\mathrm{d}b}{a^2}W(a,b)\psi(t) \qquad (2)$$

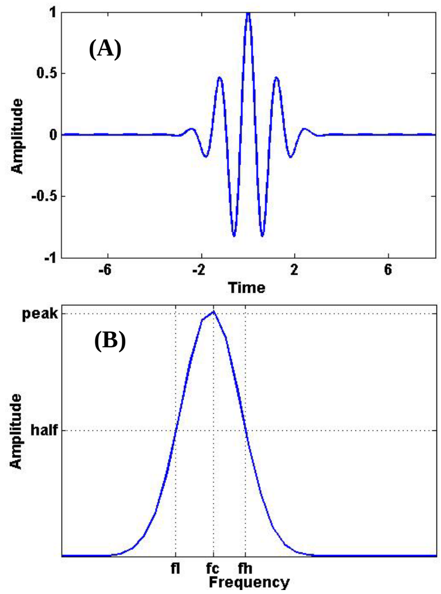

FIG. 2 (A) the time history and (B) the amplitude spectrum of the Morlet wavelet.

where constant value C_ψ is defined by:

$$C_\psi = 2\pi \int_{-\infty}^{\infty} d\omega \left|\hat{\psi}(\omega)\right|^2 |\omega|^{-1} \qquad (3)$$

where $\hat{\psi}(\omega)$ is the Fourier transform of the wavelet kernel function $\psi(t)$. Equation 3 requires that $\hat{\psi}(0)$ =0, which equals to $\int \psi(t)dt = 0$, and wavelet kernel functions have a zero average in the time domain [13]. In addition, after normalization, $\int |\psi(t)|^2 dt = 1$ is required as well.

To normalize wavelet kernel function $\psi(t)$, a wavelet atom $\phi_\gamma(t)$ is proposed:

$$\phi_\gamma(t) = \psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \qquad (4)$$

where γ is a multi-index parameter referring to a and b.

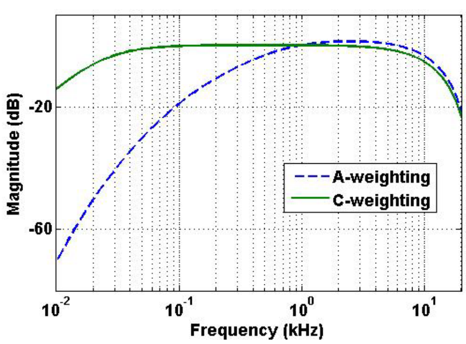

FIG. 3 illustration diagram of the frequency responses of A-weighting and C-weighting filters.

Morlet wavelet was used in this study for noise analysis. Morlet wavelet was derived from the Gaussian function, and it can be defined as:

$$\psi_{mor}(t) = \frac{1}{(\tau^2\pi)^{1/4}} \exp\left(\frac{t^2}{2\tau^2}\right) \exp(j\eta t) \qquad (5)$$

where τ is the parameter to control the frequency bandwidth, and η represents the central frequency of this kernel function.

Figure 2A shows the time history of the real part of the kernel functions of Morlet wavelet. Morlet wavelet is symmetric about y-axis in the time domain. The frequency spectrum of the Morlet wavelet function is shown in Figure 2B, in which the f_c is central frequency, and the f_l and f_h refers to the low and high frequency boundaries at half amplitude, respectively. As described in Equation 5, the f_l and f_h can be defined and adjusted by the parameter τ, and the f_c is controlled by the parameter η. In the frequency domain, it behaves like band-pass filters, and can extract the localized frequency details of transient signals.

Furthermore, the WT yields out the decomposition of the acoustic signal, and its coefficients alternatively can be represented in the sound pressure level (SPL) as:

$$SPL(b)_a = 10\log 10\left(\frac{w_s(b)w_s(b)^*}{2P_{ref}^2}\right) \qquad (6)$$

where $P_{ref} = 20\times 10^{-6}$ Pa.

D. *Characterization of complex noise*

Filters with frequency-dependent gain have been introduced to mimic the frequency response of the human auditory organ. The A-weighting and C-weighting filters are most commonly used for noise evaluation. Figure 3 shows the frequency responses of the A-weighting and C-weighting filters. The A-weighting filter has narrower bandwidth than the C-weighting filter. Specifically, at frequencies less than 1000 Hz, the A-weighting filter quickly decays, while the C-weighting filter doesn't decay. Consequently, an A-weighted noise metric such as L_{Aeq} does not count low frequency components in a noise signal. Such a metric is not suitable for accurate evaluation of the complex noise, which contents strong low frequency components. In contrast, the C-weighting filter is relatively flat within the normal audible frequency range, and it should be considered as a more suitable metric for the evaluation of the complex noise in workplaces.

TABLE I. SUMMARY OF DIFFERENT NOISE LEVELS MEASURED AT THREE LOCATION IN THE FIELD.

Locations	L_{Aeq}, dB	L_{Ceq}, dB	L_{pmax}, dB
Level 1	92.25	105.24	114.40
Level 3½	99.79	108.34	118.58
Level 4	95.13	115.07	122.97

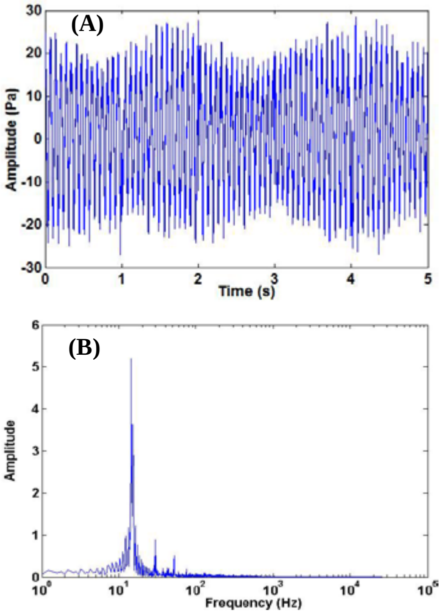

FIG.4 (A) waveform with five second duration and (B) amplitude spectrum of a representative complex noise signal measured in the field.

In this study, new noise metrics have been proposed to evaluate the complex noise measured in mining fields. These metrics include C-weighted equivalent SPL $\boldsymbol{L_{Ceq}}$, WT based equivalent $\boldsymbol{L_{WTeq}}$, peak SPL $\boldsymbol{L_{pmax}}$, and Kurtosis $kurt(\omega)$.

Generally, the equivalent SPL $\boldsymbol{L_{eq}}$ can be defined as [4]:

$$L_{eq} = 10\log 10\left(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \frac{p_A^2}{p_0^2} dt\right) \tag{7}$$

where p_0 is the reference pressure level 20uPa. p_A is the acquired sound pressure in Pa. The time period for data samples ranges from t_1 to t_2.

When applying the A-weighting and C-weighting filters to the acoustic signals, equivalent SPL are described as $\boldsymbol{L_{Aeq}}$ and $\boldsymbol{L_{Ceq}}$, respectively. In addition, the WT based equivalent SPL is proposed to reveal the time history of the different frequency components. The WT based $\boldsymbol{L_{WTeq}}$ is calculated as a function of frequency as [9]:

$$p_{eq}(\omega) = \sqrt{\frac{1}{T}\int_0^T (p(\omega,t))^2} \tag{8}$$

where $p(\omega, t)$ is the time histories of sound pressure obtained at central frequencies for each 1/3 octave band. $\boldsymbol{L_{WTeq}}(\omega)$ can be calculated as [9]:

$$L_{WTeq}(\omega) = 10\log 10\left(\frac{p_{eq}(\omega)^2}{p_{ref}^2}\right) \tag{9}$$

The peak SPL $\boldsymbol{L_{pmax}}$ is defined as [4]:

$$L_{p\max} = 20\log 10\left(\frac{p_{peak}}{p_{ref}}\right) \tag{10}$$

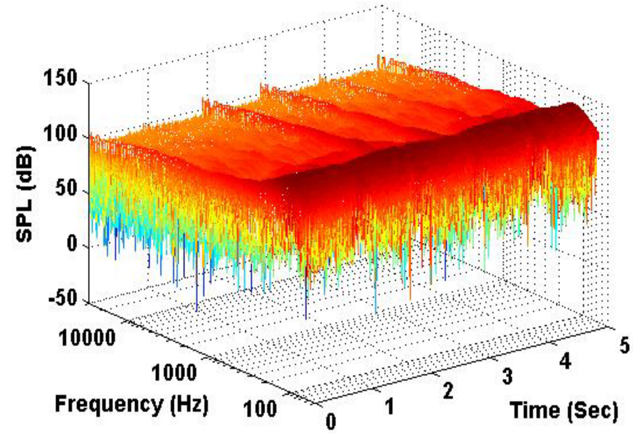

FIG.5 T-F representation of the SPL of a representative noise signal measured in the field.

The statistical metric Kurtosis is a parameter to describe the impulsiveness and the spectral composition of a complex noise. The Kurtosis directly reflects the strength and skewness of the peak pressure, which are usually taken as the metric to assess the risk of hearing loss.

Generally, it can be defined as the ratio of the fourth moment to the squared second moment. In this study, the Kurtosis as a function of frequency is calculated from the SPL time history of each wavelet scale [9].

$$Kurt(\omega) = \frac{\frac{1}{N}\sum_{t=1}^{t=N}(p(\omega,t) - \overline{p(\omega,t)})4}{(\frac{1}{N}\sum_{t=1}^{t=N}(p(\omega,t) - \overline{p(\omega,t)})^2)^2} \tag{11}$$

III. RESULTS AND DISCUSSION

A. *Noise waveform and spectrum using regular FFT.*

The $\boldsymbol{L_{Aeq}}$, $\boldsymbol{L_{Ceq}}$, and $\boldsymbol{L_{pmax}}$ of the complex noise measured by the developed system at three locations in the field are summarized in Table 1. At all three locations, the C-weighted SPL $\boldsymbol{L_{Ceq}}$ are about 10 dB higher than the A-weighted SPLs $\boldsymbol{L_{Aeq}}$. Moreover, Figure 4 shows a representative waveform (5 second time duration) and amplitude spectrum of a noise signal measured in the field. It shows the noise signal measured in the field is a complex noise (Non-Gaussian noise). In the amplitude spectrum, higher amplitudes can be found at low frequency range (< 100Hz). It indicates that the complex noise measured in the field contains very strong low frequency components. Such low frequency components are not counted into the $\boldsymbol{L_{Aeq}}$ due to the frequency response of an A-weighting filter. While these low frequency components are included in C-weighted SPL calculation. This is the main reason that causes 10 dB difference between $\boldsymbol{L_{Ceq}}$ and $\boldsymbol{L_{Aeq}}$ summarized in Table 1. The $\boldsymbol{L_{Aeq}}$ is the metric currently used in government regulation for assessment of the complex noise in mining fields. It is generally considered appropriate for continuous Gaussian noise but not for complex noise. Such criteria may significantly underestimate the risk of high level complex noise in mining fields.

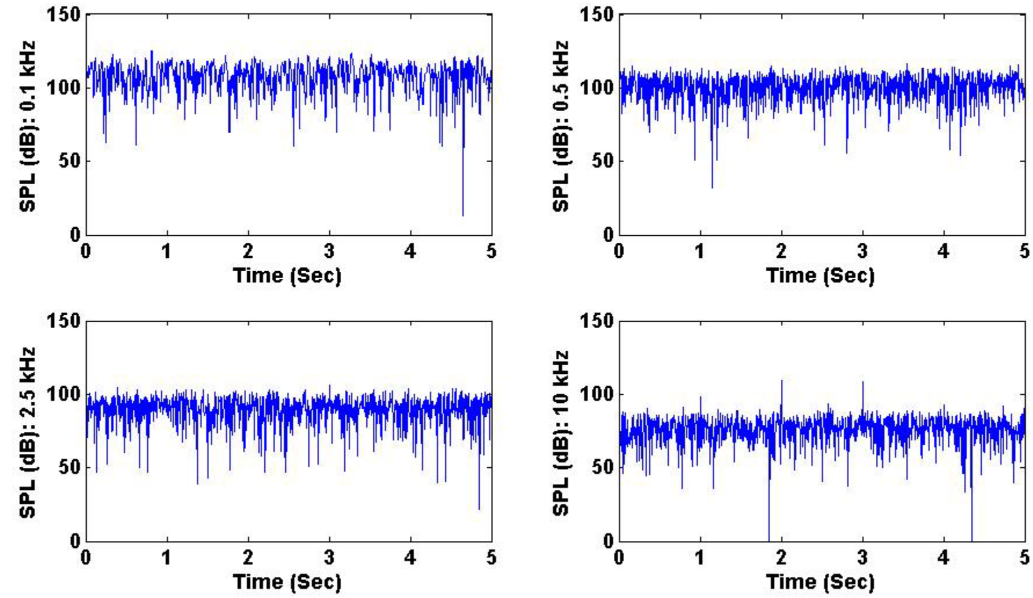

FIG.6 Time history of the 1/3 octave SPL components of a field noise signal. Each time history was obtained by applying the AWT to the noise with the center frequency at the frequency shown in the figure. For example, 0.5 kHz time history shown in the figure approximates the field noise that passed through a 1/3 octave filter of 0.25 kHz center frequency.

B. *AWT based noise characterizaiton*

The Morlet WT was applied to decompose the measured noise signals into the T-F domain. In order to decompose the noise signal following the characteristic of human hearing system, the central frequencies and bandwidths on the frequency axis were adjusted according to 1/3 octave bands in the WT. At each scale, the SPL is integrated along the time axis based on the wavelet coefficients. Figure 5 shows the T-F representation of SPL of a noise signal measured by the developed system in the field. The 3D structure in the T-F domain reflects the distribution of SPL of the noise signal.

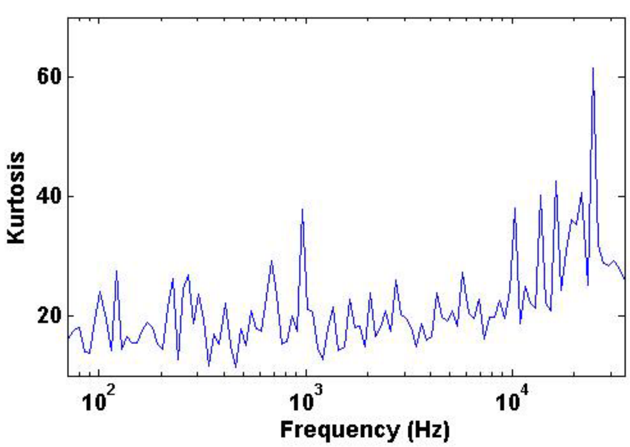

FIG.7 the frequency distribution of Kurtosis of a noise signal measured in the field.

The SPL time histories of a field noise signal at selected 1/3 octave bands (central frequencies at 100, 500, 2500, and 10000 Hz) are illustrated in Figure 6. The lowest frequency band centered at 100 Hz contains higher energy around 120dB level. Correspondingly, the highest frequency spectrum centered at 10 kHz shows lower energy around 90dB level. However, the SPL distribution for 10 kHz demonstrates several high peaks more than 110dB. Those peaks cannot be found in the power spectrum obtained by regular FFT, but they may cause hearing loss.

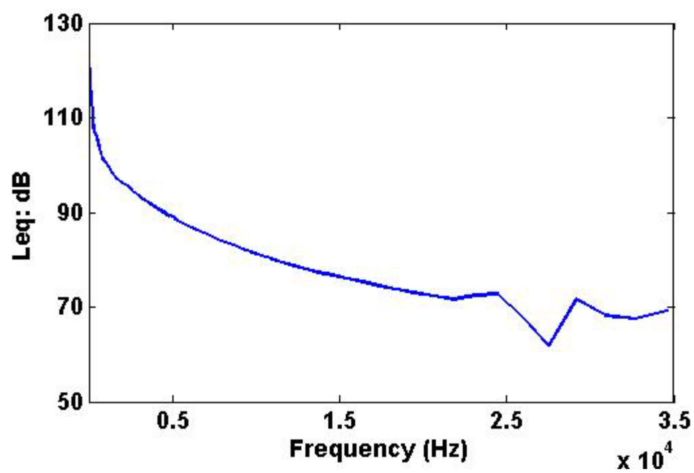

FIG.8 the frequency of the WT based equivalent SPL $L_{WTeq}(\omega)$ of a noise signal measured in the field.

C. *WT based new nosie metrics:* $L_{WTeq}(\omega)$ *and Kurtosis*

Kurtosis was proposed as a new noise metric to assess the complex noise. According to Equation 11, the Kurtosis $kurt(\omega)$ as a function of frequency can be calculated from pressure wavelet coefficients $p(\omega, t)$ in the T-F domain. Figure 7 shows the frequency distribution of Kurtosis of a noise signal measured in the field. Overall, the Kurtosis at entire frequency range is greater than 3, which is the Kurtosis value of the Gaussian noise. It indicates the noise signal measured in the field is a non-Gaussian complex noise. In addition, the Kurtosis is increasing from 20 to 60 with the frequency increasing. It means that the noise signal contents impulsive components, specifically, at high frequency.

Another new metric proposed in this study is the WT based equivalent SPL $\boldsymbol{L}_{WTeq}(\omega)$, which can be calculated from pressure wavelet coefficients according to Equations 8 and 9. Figure 8 illustrates the frequency distribution of $\boldsymbol{L}_{WTeq}(\omega)$ calculated from a noise signal measured in the field. The results indicate that the $\boldsymbol{L}_{WTeq}(\omega)$ is a function of frequency, and it decreases with the frequency increasing. $\boldsymbol{L}_{WTeq}(\omega)$ reflects the averaged energy at different 1/3 octave bands. As shown in Figure 8, the energy is concentrated at the lower frequency bands (less than 500 Hz). It is also can be found that the $\boldsymbol{L}_{WTeq}(\omega)$ of high frequency bands ranging from 5 kHz to 12 kHz are above 85dB level. In addition, the $\boldsymbol{L}_{WTeq}(\omega)$ could be associated with hearing loss at different frequency bands in the cochlear, and it will be a meaningful metric for the evaluation of complex induced noise loss.

IV. Conclusion

In this study, we developed new noise measurement system and proposed new noise metrics for the investigation of the complex noise in high noisy industry fields. The developed system not only can measure the noise levels, but also can record detailed waveform of noise signals in the field. The system has been successfully validated both in our lab and in a coal mining field. Moreover, the Morlet WT algorithm has been applied to characterize the complex noise measured in the field. Such technology can provide detailed information of a complex noise in the T-F domain, and lead to the development of new noise metrics. In addition, new noise metrics for the evaluation of the complex noise have also been proposed and discussed in this paper. The preliminary results demonstrated the proposed new metrics can more accurately evaluate the risks of high level complex noise. In our future work, a new metric evaluating system will be established, and more field measurements will conducted in varied industrial fields (e.g., coal preparation and handing plants, surface mines, and other industrial fields).

Acknowledgment

This project was funded by the Illinois Clean Coal Institute with funds made available by the State of Illinois**.**

References

[1] X.D. Zhu, and J. Kim, "Application of analytic wavelet transform to analysis of highly impulsive noises," Journal of Sound and Vibration, vol.294, pp. 841-855, July 2006.

[2] W. A. Ahroon, R. P. Hamernik, et al., "COMPLEX NOISE EXPOSURES - AN ENERGY ANALYSIS, " Journal of the Acoustical Society of America, vol.93, pp. 997-1006,1993.

[3] R. P. Hamernik, W. Qiu, et al., "Hearing loss from interrupted, intermittent, and time varying non-Gaussian noise exposure: The applicability of the equal energy hypothesis," Journal of the Acoustical Society of America vol.122, pp. 2245-2254, 2007.

[4] D. Havelock, S. Kuwano, and M. Vorländer, Handbook of signal processing in acoustics (Vol. 1). NY: Springer, 2008.

[5] R. P. Hamernik, and W. Qiu, "Energy-independent factors influencing noise-induced hearing loss in the chinchilla model," Journal of the Acoustical Society of America, vol.110, pp.3163-3168, 2001.

[6] R. P. Hamernik, W. Qiu, et al., "Cochlear toughening, protection, and potentiation of noise-induced trauma by non-Gaussian noise," Journal of the Acoustical Society of America vol.113, pp.969-976, 2003.

[7] J. Starck, E. Toppila, et al., "Impulse noise and risk criteria, " Noise & Health, vol.5, pp. 63-73, 2003

[8] J. Kim, et al., "Time-frequency characterization of hand-transmitted, impulsive vibrations using analytic wavelet transform," Journal of Sound and Vibration, vol.308, pp. 98-111, Nov 2007.

[9] X. Zhu, et al., "Development of a noise metric for assessment of exposure risk to complex noises," The Journal of the Acoustical Society of America, vol.126, pp.703-712, 2009.

[10] D. Henderson, and R.P. Hamernik, "Impulse noise–critical review," Journal of the Acoustical Society of America, vol.80, pp.569-584, 1986.

[11] R.P. Hamernik, et al., "Audiometric and histological differences between the effects of continuous and impulsive noise exposures," Journal of the Acoustical Society of America, vol.93, pp.2088-2095. 1993.

[12] I. Daubechies, Ten Lectures on Wavelets. Philadelphia: SIAM, 1992.

[13] S. Mallat, A wavelet Tour of Singal Processing. Academic Press, 1997.