

Time-Frequency Analysis of High-Intensity, Fast Transient Noise from Power Tools by Analytic Wavelet Transform

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1. INTRODUCTION

It is well known that impulsive noise is inherently more dangerous than steady state noise. This is due to the fact that our auditory system's adaptation to high-level sound requires some time to be activated, and also is ineffective at high frequencies¹. Impulsive noise on construction sites is generated by tools with an impact mechanism, such as power wrenches and jack hammers. While other types of impulsive noises from military or residential sources occur intermittently and last only for a short duration, impact tool noises last for a long period of time, exposing workers to high-intensity sound. According to various studies, between 16% and 50% of construction workers suffer from significant noise induced hearing loss (NIHL)². While a method for quantitative analysis of the health risk of impact power tool noises is urgently needed, most past studies on impulse noises are on annoyance issues related to the military noises³⁻⁶ and residential noises⁷.

It is our long-term goal to develop a method for quantitative assessment of the health risk of being exposed to high-intensity impulsive sound. One basic difficulty related to the task lies in the measurement and analysis of the noise characteristics. It is evident that current noise measurement practices, which are based on the steady state, time-averaging concepts, are not suitable for the purpose. We propose use of the analytic wavelet transform (AWT). The AWT is well suited for transient signal analysis by virtue of being a type of wavelet analysis⁸. It also provides all the quantities that have been used in conjunction with the Fourier transform. For example, magnitudes and phases, frequency components, auto and cross power spectra can be defined in the transient sense. This is an important advantage because all the metrics and concepts that have been used traditionally, for example the sound pressure level (SPL) and octave analysis, can be utilized in the transient analysis. Noise signatures measured from two commonly-found power tools are used as examples to demonstrate applications of the AWT. The tools chosen are an electric impact wrench that generates highly impulsive sound, and a jig saw that generates a relatively steady state sound.

3. BASIC MEASUREMENT AND INSTANTANEOUS SPL

Figures 1 and 2 show time histories of the sound pressures measured from an electric impact power wrench and a jigsaw. The power wrench generates impacts using a rotary hammer driven by an electric motor. Almost 45 impacts are produced per second, thus a series of very fast high level impulsive sounds are induced as shown in Figure 1. The jigsaw's sound is much smoother compared to the impact wrench as seen in Figure 2 since it does not involve any impact mechanism. Discussions on internal mechanisms and frequency domain noise analyses of the tools are found in⁹. The overall sound pressure level (SPL) measured is 92 dB for the impact wrench and 78 dB for the jigsaw. By definition, these levels represent time-averaged values; therefore do not always properly represent the actual risk involved with the sound.

One way to assess a transient sound may be using the instantaneous SPL. A problem is to define *instantaneous* SPL. Envelope analysis by the Hilbert transform¹⁰ may be an option. The procedure is;

$$A(t) = \left(p(t)^2 + p_h(t)^2 \right)^{1/2} \quad (1)$$

where, $p(t)$ is the signal, the instantaneous sound pressure in this case, and $p_h(t)$ is the Hilbert transform of $p(t)$ that can be obtained as;

$$p_h(t) = F^{-1} \left[-j \operatorname{sgn}(f) P(f) \right] \quad (2)$$

where, F^{-1} is the inverse Fourier transform, sgn is the signum function and $P(f)$ is the Fourier transform of $p(t)$. Then, the instantaneous SPL is defined as;

$$SPL(t) = 20 \log_{10} \frac{\frac{1}{\sqrt{2}} A(t)}{P_{ref}} \quad (3)$$

Figures 3 and 4 are instantaneous SPLs obtained applying the above procedure to the impact wrench and the jig saw sounds. Although smooth envelopes are not obtained because they are not modulated sounds, it is seen that the peak instantaneous SPL of the impact wrench reaches 115 dB, about 25 dB higher than the averaged SPL. This becomes much smaller in the jigsaw, which shows only about 6 dB difference. Obviously the SPL in the traditional time-averaged definition will significantly underestimate the risk involved with highly impulsive sounds such as shown in Figure 1.

The instantaneous SPLs shown in Figures 3 and 4 are not truly instantaneous because they include the time response characteristics of the measurement instrument's chain. Even if it is possible to obtain, the instantaneous SPL alone is not sufficient information. Spectral information is also necessary, because the response of the human auditory system is frequency dependent. The Hilbert transform calculates the instantaneous frequency, which is a single value that averages all the frequency components. Therefore, a time-frequency analysis such as the short time Fourier transform (STFT), Wigner-Ville distribution or wavelet transform becomes necessary.

4. TIME-FREQUENCY ANALYSIS BY ANALYTIC WAVELET TRANSFORM

The wavelet transform is ideal for analysis of transient signals because it uses variable time-frequency atoms. It uses shorter wavelets to decompose faster components of the signal and longer wavelets to decompose slower components⁸. Such a concept is shown in terms of the Heisenberg box in Figure 5. The transform is well suited especially for impact noise analysis because the noise has flat frequency components in the high frequency range which change very fast in time. Given the measured data, the size of the time-frequency atom is always constant, which states that the time and frequency resolutions cannot be improved simultaneously. In comparison to the AWT, the STFT uses the same Heisenberg box at all time-frequency points, which generally results in the lack of the time resolution for high frequency components and lack of the frequency resolution for low frequency components. In addition to the advantage related to the variable time-frequency atom, analytic wavelet transform is especially useful in sound analysis because it calculates both the magnitude and the phase of the time-frequency components of the signal as the Fourier transform does. This allows virtually all concepts in Fourier analysis to be defined and utilized, for example the auto and cross power spectra, all in the transient sense.

The AWT is briefly explained here, while reference⁸ may be used for more details. A mother wavelet for the analytic wavelet transform can be constructed as;

$$\psi(t) = g(t)e^{j\eta t} \quad (4)$$

where, g is the wavelet window function. The Fourier transform of $\psi(t)$ is $\hat{\psi}(\omega) = \hat{g}(\omega - \eta)$. To make $\psi(t)$ analytic, $\hat{\psi}(\omega)$ has to be made zero at negative frequencies. This means η needs to satisfy the condition that for $|\omega| > \eta$, $g(\omega) = 0$.

Usually the wavelet ψ defined as in equation (4) is analytic only in approximate sense because its Fourier transform is not completely zero in $\omega < 0$. The kernel of the transform can be obtained by scaling and translating the mother wavelet;

$$\psi_{u,s}(t) = \frac{1}{\sqrt{s}} \psi\left(\frac{t-u}{s}\right) = e^{-i\xi u} g_{s,u,\xi}(t) = \frac{1}{\sqrt{s}} g\left(\frac{t-u}{s}\right) e^{i\xi(t-u)} \quad (5)$$

where, s is the scale. Then, the analytic wavelet transform of the signal $p(t)$ is defined by the following convolution integral.

$$Wp(u,s) = \langle p(t), \psi_{u,s} \rangle \quad (6)$$

As it may be seen from equation (6), the AWT may be interpreted roughly as a Fourier transform with a moving time window of scale dependent size.

The center frequency of the transformed result is given as:

$$\eta_{u,s} = \frac{1}{2\pi} \int_0^\infty \omega |\hat{\psi}_{u,s}(\omega)|^2 d\omega = \frac{\eta}{s} \quad (7)$$

where, $\eta = \frac{1}{2\pi} \int_0^\infty \omega |\hat{\psi}(\omega)|^2 d\omega$ is the center frequency of the mother wavelet. The distribution around $\eta_{u,s}$ is given as:

$$\sigma_\omega(u,s) = \frac{1}{2\pi} \int_0^\infty \left(\omega - \frac{\eta}{s}\right)^2 |\hat{\psi}_{u,s}(\omega)|^2 d\omega = \frac{\sigma_\omega^2}{s^2} \quad (8)$$

where, $\sigma_\omega = \frac{1}{2\pi} \int_0^\infty (\omega - \eta)^2 |\hat{\psi}(\omega)|^2 d\omega$ is the distribution of the mother wavelet. This distribution defines the width of the frequency band. If the continuous wavelet is used, the scales can be chosen so that the center frequencies and distributions coincide with any proportional bands. Complex coefficients are obtained by the result of the wavelet transform defined in equation (6), which represent the energy density of the signal at the time-frequency point. Therefore, the transform result can be interpreted like the Fourier coefficients in a transient sense; hence the auto-power spectrum and SPL can be defined the same way as in the FFT analysis.

Figure 6 shows the time-frequency plot of the impact wrench obtained by the AWT. Gaussian wavelet is used as the time window of the mother wavelet. 1/12 octave band setup is used for the frequency. Notice that the logarithmic scale is used in the frequency axis. The transform decomposes the time variation of the frequency components very nicely, capturing instantaneous peaks in the high frequency side very much in detail. Such a clear representation is due to the inherent advantage of the wavelet transform that uses variable size time windows. The advantage becomes clear if we compare the time-frequency plot obtained for the same signal using the short time Fourier transform (STFT) shown in Figure 7. STFT is essentially applying the Fourier transform repeatedly as the time window is moving. The transform does not capture high frequency details of the signal very well. The time window in the high frequency side is much longer than that of the AWT, thus effectively averages the sharp signal peaks toward a lower value. If the time window size is decreased to improve the time resolution at the high frequency range, the frequency resolution will suffer, obscuring the information in the low frequency side. The frequency resolution in the STFT shown in Figure 7 is already too low (notice that the frequency axis is in the logarithmic scale). Figures 8 and 9 are AWT and STFT results applied to the jigsaw sound in Figure 2. Figure 8 shows a much more detailed temporal change in the high frequency range.

The AWT result in Figure 6 may be considered an instantaneous 1/12 octave representation of the sound. Any typical operations conducted in traditional FFT analysis can be implemented in the same way. For example, A, B or C weighting can be easily applied at each time-frequency points. A curve that will be obtained by cutting through the surface while fixing the time can be interpreted as the 1/12 octave band spectrum at that particular instant. Obviously 1/3 octave or full octave bands can also be set up by choosing the appropriate wavelet window. A curve that will be obtained by cutting through the surface while fixing the frequency point can be interpreted as the time history of the corresponding 1/12 octave frequency component. We plan to use these features to relate measured metrics to physiological characteristics. For example the response time at different frequencies, response locations in the basilar membrane or other physiological quantities may be related to these metrics.

5. POSSIBLE STRATEGIES TO RELATE TIME-FREQUENCY METRIC AND PHYSIOLOGICAL DAMAGE

Applying the AWT to a transient noise signal has many potential advantages as discussed earlier. Probably the most important advantage is that the transform decomposes the temporal and spectral characteristics of the sound in a way similar to what our auditory system does. For example, the dependency of the temporal response of the basilar membrane is well documented¹, which is represented in the AWT by the effect of using scale dependent time windows. As stated, our eventual goal is to develop a procedure to relate the time-frequency metrics of the highly transient noise and the risk of physiological damages. Extensive studies on reported cases and physical models of the cochlea, basilar membrane and hair cell-nervous system interactions will be necessary to bridge the gap of knowledge between the signal analysis and physiology.

6. SUMMARY AND CONCLUSIONS

Using two types of portable power tools as examples, it is explained that a time-frequency analysis is necessary to properly characterize highly impulsive sound. Between the two tools, the noise generated by the impact wrench is more highly transient compared to the jigsaw noise. It is shown that the characteristics, and therefore the related risks, of such noises cannot be severely underestimated unless accurate time-frequency analysis is utilized. We propose the analytic wavelet transform as an ideal signal analysis tool to characterize such highly transient sounds. It is explained that the transform provides the advantages of both the wavelet transform and the Fourier transform. The transform can be interpreted as a transient spectral analysis, which will open up many interesting applications. While the transform can be used to study the response characteristics of any dynamic system, it is especially useful in acoustics applications because of its resemblance to the way our auditory system processes sound signal. It is our long-term plan to develop a method for quantitative risk assessment of impact noise induced hearing loss. This work summarizes the first stage of this long term effort.

7. ACKNOWLEDGMENTS

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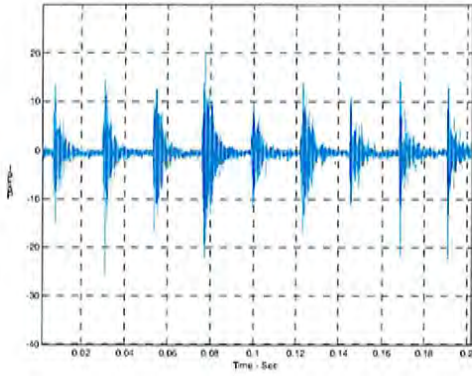


Figure 1: Time History of the Impact Wrench

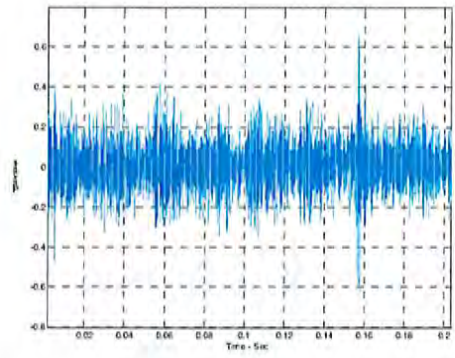


Figure 2: Time History of the Jigsaw

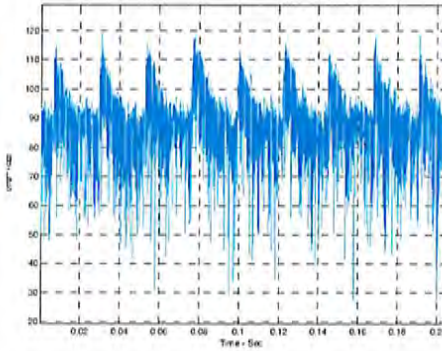


Figure 3: Instantaneous SPL of the Impact Wrench

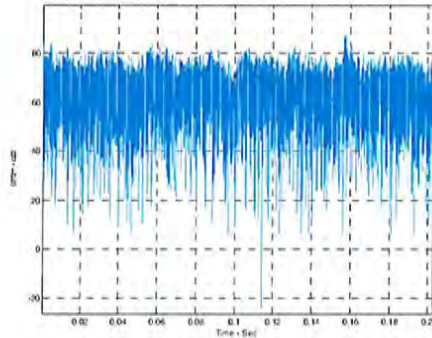


Figure 4: Instantaneous SPL of the Jig Saw

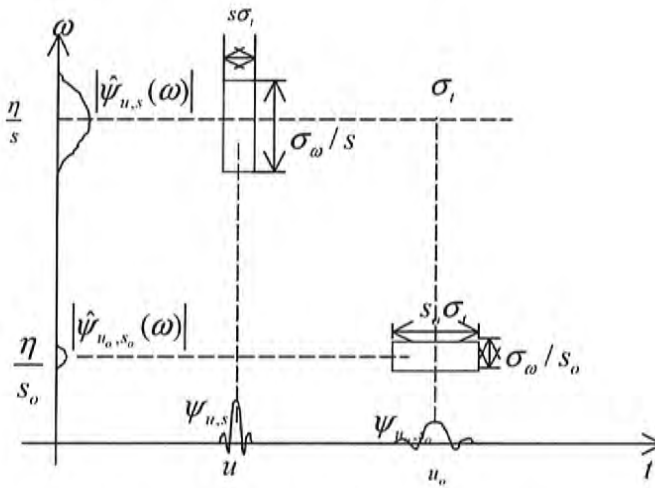


Figure 5: Heisenberg Box: Illustration of the Time-Frequency Atom of the Wavelet Transform

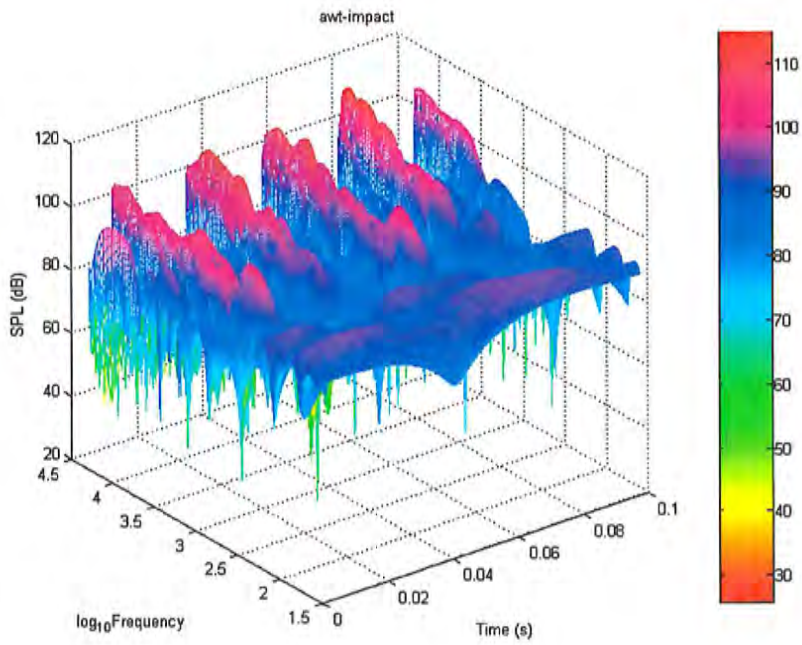


Figure 6: Transient 1/12 Octave Band Plot of the Impact Wrench Obtained by the Analytic Wavelet Transform

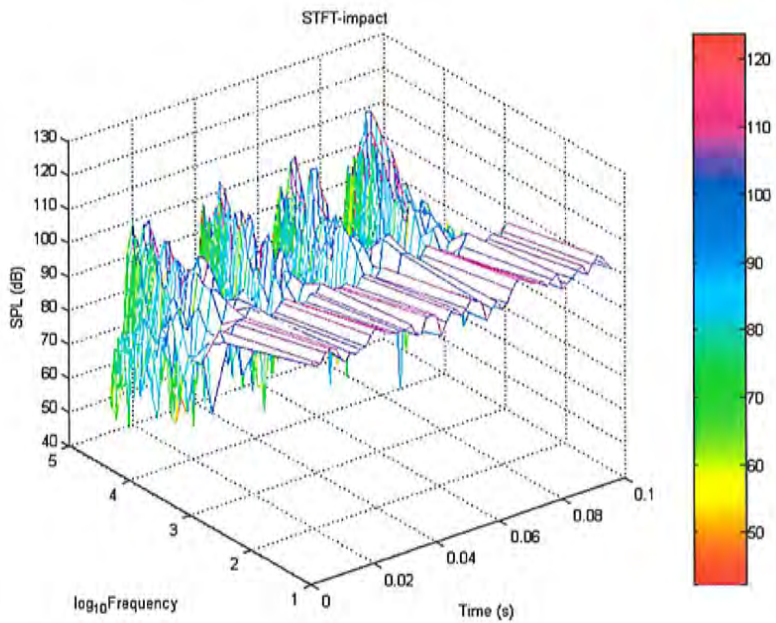


Figure 7: Time-Frequency Plot of the Impact Wrench Obtained by the Short Time Fourier Transform

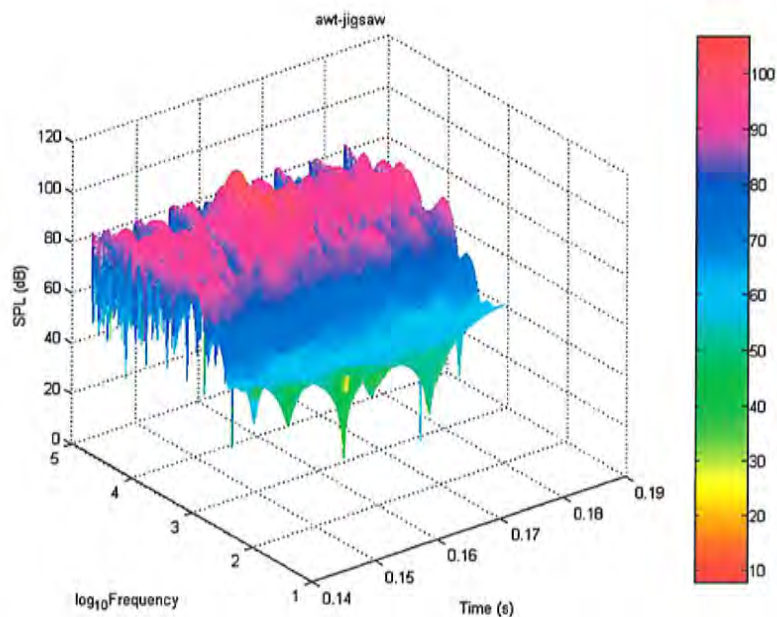


Figure 8: Transient 1/12 Octave Band Plot of the Jigsaw Wrench Obtained by the Analytic Wavelet Transform

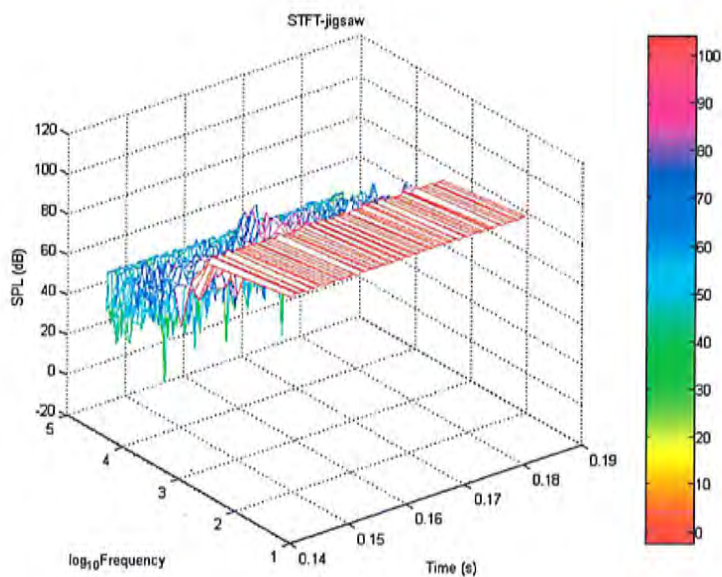


Figure 9: Time-Frequency Plot of the Jigsaw Obtained by the Short Time Fourier Transform

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