

Evaluating Electromagnetic Railway Environment Using adaptive Time-Frequency Analysis

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Abstract—With the current introduction of new technologies in railway signaling, the railway electromagnetic environment is becoming more and more complex. Indeed, the characteristics of the signals used in these systems are very different both in time and frequency domains. Because of this wide range of very different signals to evaluate, time-frequency representations already used in electromagnetic compatibility studies, do not perfectly enable us to easily and quickly process, with a sufficient flexibility, these signals. In this letter, these methods are briefly recalled and discussed. Some limits regarding their use in the electromagnetic environment analysis considered are identified and a more flexible time-frequency analysis method is proposed. By applying it to synthesized and recorded signals, we show that time and frequency resolutions are easily adapted to fit the particular considered subsystem and adjusted according to the disturbance or radio communication signal to examine.

Index Terms—Time-frequency analysis, electromagnetic compatibility, railway communication, signaling systems

I. INTRODUCTION

Due to the different high power and signaling systems operated at the same time in a railway system, the corresponding electromagnetic environment is very rich in terms of signals and interferences that have to be compatible between them. Moreover, the harmonization of the railway system in Europe called European Railway Traffic Management System (ERTMS), also developed in other regions of the world, has introduced new techniques. ERTMS signaling is based on spot communication and localization using balises laid along the track, and on continuous radio communication using a digital cellular radio system for voice and data exchanges between trains and control centers [1]. Track circuits are used to detect the presence of trains running over blocks [2]. Some relevant time and frequency technical characteristics of these systems are given in Table I. Steady and transient signals generally evaluated regarding these subsystems are listed in the last column. We deduce from table 1 that a frequency range between a few kHz and almost

1 GHz must be examined and that signal durations from a few

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nanoseconds to several milliseconds have to be considered.

Therefore, analyzing electromagnetic interferences (EMI) over such a wide range of signals requires an adequate and flexible time-frequency analysis process. Besides, for an EMC study,

TABLE I
TECHNICAL CHARACTERISTICS OF RAILWAY SIGNALING SYSTEMS

Railway subsystem	Frequency band	Signal bandwidth	Elementary Signal duration	Main threats
Balise	4.234 MHz	282 kHz	1.77 μ s	Some μ s transient interferences.
Digital radio	900 MHz	200 kHz	3.7 μ s	Adjacent cellular phone network interference. Some ns transient interferences: pantograph/catenary contact...
Track circuit	2 kHz	29 Hz	Few ms	Harmonics and some ms transients in the rail return current.

EMI must be considered regarding the filtering characteristics and the temporal dynamics of the system to protect and not the EMI sources. For this reason, an analysis method that gives a representation of the EMI as perceived by the railway subsystem studied is needed in order to evaluate the impact of these EMI on the subsystem. Thus, the analysis method has to take into account the different characteristics of the railway subsystem especially its behavior in the time and the frequency domains.

This paper is organized in five sections. The second section briefly discusses time-frequency analysis methods relevant to this study. The third section describes the proposed analysis method. Section 4 presents and analyzes results applying the proposed method to a synthesized signal and then to a recorded real railway signal. Finally, section 5 concludes this article.

II. TIME-FREQUENCY ANALYSIS METHODS

Measured signals or disturbances can be represented in the time or in the frequency domain separately. Nevertheless, in many studies, these one domain representations are not sufficient. This is also the case to solve some electromagnetic compatibility (EMC) complex problems. Indeed, using either time or frequency domain alone leads to the loss of some important characteristics of the signal. On the one hand, the time representation does not allow observing the different frequencies or the spectral characteristics of some disturbances. On the other hand, the instants of appearance or disappearance of some phenomena are not visible in the

spectral representation.

For these reasons, the use of time-frequency representations is primordial in many EMC analyses. Indeed, this representation allows observing evolutions of the analyzed signal spectrum through time. With this feature, electromagnetic interferences, such as transient phenomena, can be characterized by the determination of their duration, instant and repetition of appearance or, the covered frequency bandwidth. This way, their potential impacts on the railway system can be estimated.

A. Classical Methods

Different types of time-frequency analyses exist and present various characteristics. They are ranked in two main categories: linear and quadratic.

Quadratic time-frequency analyzes, such as Wigner-Ville or Choi-Williams distributions, perform well in terms of time and frequency resolutions. However, the cross term interferences between the different signal components make them not fully suitable for analyzing complex signals [3].

Linear time-frequency representations are more commonly used in EMC analysis, especially the short-term Fourier transform (STFT) and the wavelet transform. Their processes consist in cutting time signals into successive time segments and computing the spectrum associated to each segment.

In the case of STFT, the spectrum is computed within a sliding window defined by its shape and duration [4]. In this method, the time and frequency resolutions are dependent on one another. When the frequency resolution is improved, the time resolution is lowered, and vice versa. Moreover, time and frequency resolutions are static regardless of the analyzed frequency, which can be problematic knowing that signals and disturbances have different temporal and spectral characteristics according to their frequency ranges [5].

Continuous Wavelet Transform (CWT) permits adapting time and frequency resolutions according to the frequency analysis [6]. Indeed, the frequency resolution is improved when the analyzed frequency is high and the time resolution is low. At low frequencies, time resolution is improved and frequency resolution is lowered [7].

B. Synthesis and limits

Discrete versions of the STFT and CWT are generally employed to analyze discrete signals. In the case of STFT, the short-term fast Fourier transform (STFFT) is used to reduce the calculation time. The windowing principle is kept, but instead of calculating the classical Fourier transform, the FFT algorithm is applied to each segment. FFT algorithm allows saving an important computation time but it causes limitations in terms of time and frequency resolution choice [8]. Indeed, besides the fact that FFT does not offer much choice in terms of analysis window width [9], the number of the analyzed frequencies depends directly on this width. Consequently, the adaptation of the time and the frequency resolutions to our railway requirements is not perfect, especially when the analysis is focused on a very narrow frequency band and needs a high frequency resolution.

Regarding the wavelet transform, the discrete wavelet transform (DWT) is based on the use of successive low pass and high pass filters. Filters whose cutoff frequencies are

divided by two after each step are applied to the analyzed signal and the number of samples is also divided by two after each step [10]. Because of these successive steps, the frequency resolution of the analysis is improved after each filtering, but the time resolution becomes lower after each operation. At low frequencies, the frequency resolution is high while the time resolution is poor, and vice versa. Thus, it imposes a relationship between analysis frequency, time and frequency resolutions. For our EMC analysis, the time and frequency resolutions have to be adapted on demand over a wide range regarding the railway subsystem studied and the nature of the disturbances threatening the system. The classical time-frequency analysis methods do not allow optimizing the resolutions for the studied system or the analyzed disturbances. Thus, a method offering more flexibility in terms of time and frequency resolutions is proposed.

III. PROPOSED METHOD

The proposed method allows adapting time and frequency resolution according to different parameters, such as the frequency band of the subsystem studied, the width of the communication channels, the time characteristics of useful signals or disturbances. It also offers the possibility to choose and limit the analyzed frequency band, unlike the FFT which realizes the computation over the whole spectrum. It also permits operating a single analysis tool correctly adapted to systems operating simultaneously at low and high frequencies.

This method is composed of two main steps. In the first one, the signal is transposed from the time domain to the frequency domain. In the second one, a windowing operation is applied to the obtained result by calculating the convolution with a sliding window. The separation of these two steps allows having independent time and frequency resolutions.

A. Step 1: Transforming into the frequency domain

In this step, the time domain data are multiplied by a series of sinusoids from a starting frequency $F1$ to a final frequency $F2$ (1), unlike the classical STFT where this operation is done over the entire spectrum.

$$\bar{x}(i, f) = x(i) \exp\left(-\frac{j2\pi fi}{F_s}\right), \quad F1 \leq f \leq F2 \quad (1)$$

where \bar{x} is a provisional result, F_s is the sampling rate, and f the analyzed frequency. f scans the $[F1 F2]$ frequency band with a 1 Hz minimum step. This feature allows improving the potential frequency resolution by adapting the number of analyzed frequencies to the studied railway subsystem. The actual frequency resolution is determined in the next step and permits avoiding interferences between different frequencies in the final result of the analysis.

The step 1 is standard for each studied railway subsystem regardless the aim of the analysis. The computation is done once for all over a fixed frequency band with a known frequency step. The analysis time and frequency settings are done in the next step and allow extracting information about permanent or transient disturbances.

B. Step 2: Convolution

In this step, convolution with a sliding window is applied to

\bar{x} in order to obtain the time-frequency representation. The choice of the convolution window is important in order to reach the required flexibility. For time varying windows, such as Hamming or Gaussian [11], the weight associated to a sample within one window is not constant and depends on the duration of the window. Consequently, this weight is also modified in operations shifting samples in the window. This makes the relationship between two neighboring windows a bit complex, which increases the computation time. Although it introduces significant side lobes, the rectangular window manages this operation very simply i.e. a shift only means deleting the first sample and adding a new one [12].

In (2), $X(k, f)$ is the result of the first convolution with a rectangular window, which width is w . Since $\prod_w(k + \frac{w}{2})$ is equal to 1 between k and $k + w$, the value of $X(k, f)$ is the sum of $\bar{x}(i, f)$ over the same interval.

$$X(k, f) = \frac{\sum_{i=1}^N \bar{x}(i, f) \prod_w(k + \frac{w}{2})}{w} \quad (2)$$

$$= \frac{\sum_{i=k}^{w+k} \bar{x}(i, f)}{w}$$

In order to obtain the next value, $X(k+1, f)$, and instead of recalculating the sum again over the whole window length, the algorithm only retrieves $\bar{x}(i, f)$ and adds $\bar{x}(i+1+w, f)$ as described in (3). This reduces again significantly the computation time and provides a good flexibility.

$$X(k+1, f) = \frac{\sum_{i=k+1}^{k+1+w} \bar{x}(i, f)}{w}$$

$$= \frac{\sum_{i=k}^{w+k} \bar{x}(i, f) + \bar{x}(k+w+1, f) - \bar{x}(k, f)}{w} \quad (3)$$

$$= X(k, f) + \frac{\bar{x}(k+w+1, f) - \bar{x}(k, f)}{w}$$

C. Multi-convolution

Although the rectangular window allows more flexibility in time and frequency resolutions with fast convolution calculation, it has the significant disadvantage of producing high level side lobes in the frequency domain, altering the processed signal. In order to reduce side lobes, we apply the convolution algorithm several times. Indeed, the convolution of two rectangular windows gives a triangular window, and by realizing several successive convolutions with the same

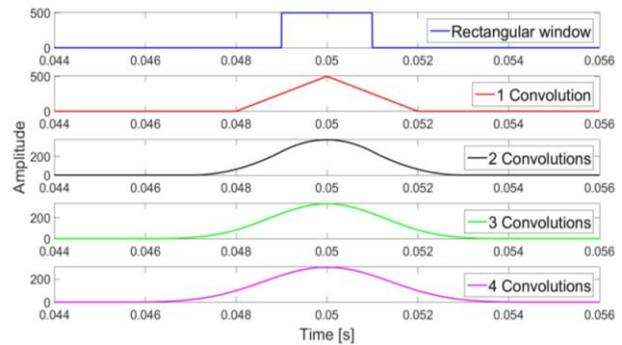


Fig. 1. Evolution of the temporal shape of the applied analysis window according to the successive convolutions.

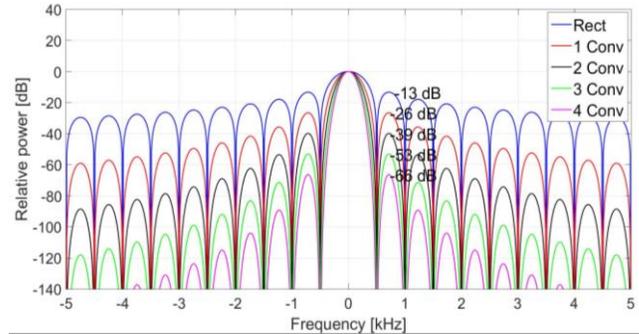


Fig. 2. Evolution of the analysis window spectrum according to the successive convolutions.

rectangular window, the quality of the results approaches those obtained using a Gaussian window. Fig. 1 shows the equivalent analysis window after applying up to 4 convolutions, using a 2 ms width rectangular window.

In the frequency domain, since the shape of the equivalent window is changing with multi-convolutions, the spectrum is also evolving. Fig. 2 shows the spectra of analysis windows presented in Fig. 1. We notice that the side lobes of the spectra are reduced by the successive convolutions. However, a side effect of the multi-convolution exists, and Fig. 1 shows that the width of the window is enlarged after each convolution.

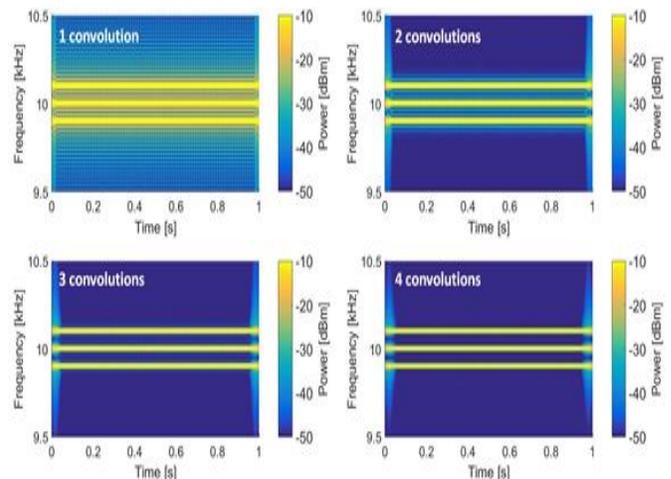


Fig. 3. Time-frequency representations obtained after 1, 2, 3 and 4 successive convolutions

IV. RESULTS

A. Results using a synthesized signal

In order to study the impact of the multi-convolution on the result, the method is applied to a 1 s duration synthesized signal, sampled at 25 kSa/s and composed of three unmodulated sinusoids at 9.9, 10 and 10.1 kHz. Fig. 3 shows time-frequency representations of this signal, obtained with 1, 2, 3 and 4 successive convolutions, respectively. The window width used is 1,000 points, which corresponds to 40 ms. The analyzed frequency band ranges from 9.5 kHz to 10.5 kHz and the frequency step is 5 Hz. Fig. 3 shows that by using only one convolution the frequency resolution is limited and significant level side lobes appear beside each frequency component. By increasing the number of convolutions, frequency resolution is improved and side lobes level decreases quite significantly.

B. Result on a measured signal

Then, the method is applied to a real signal recorded in the vicinity of a rail track during a high speed passing train. The sampling frequency is 5 GSa/s and the signal duration is 100 μ s. This signal, represented in Fig. 4, reveals the presence of a high amplitude transient, as compared to a relatively constant envelope of continuous signals.

In order to determine the impact of this transient on communication signals, the analysis parameters are fixed, according to values mentioned in Tab. 1. The analyzed frequency band ranges from 920 MHz to 950 MHz, using a 200 kHz frequency step. Fig. 5 shows the results obtained with two different analysis window widths and using three successive convolutions. In Fig. 5(a), the window width is 1,250 samples, corresponding to 250 ns. This duration is in the same range as transient phenomena in the cellular phone band [13]. Then, a transient is detected covering the whole cellular phone band. Thus, the temporal resolution is adequately adapted to analyze transient phenomena. However, due to the short analysis window used, frequency resolution is inappropriate to distinguish the activity over the different radio communication channels. In Fig. 5(b) the computational window is comparable to the elementary bit length used for the communication i.e. 3.7 μ s; its width is 12,500 samples, which corresponds to 2.5 μ s. Then, the frequency resolution is significantly improved and radio communication channels are visible, but transients are no longer detectable.

Thanks to both results, the power level of the transient can be compared to the radio signal power in order to determine if the transient can impact the communication quality. Fig. 6

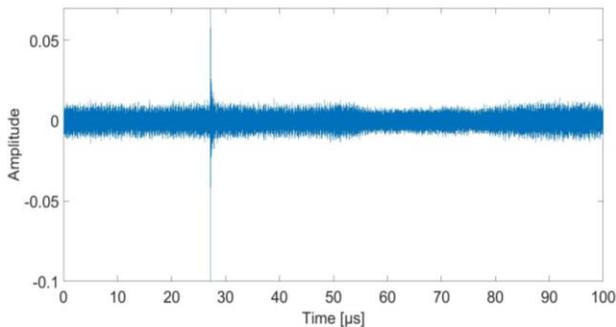


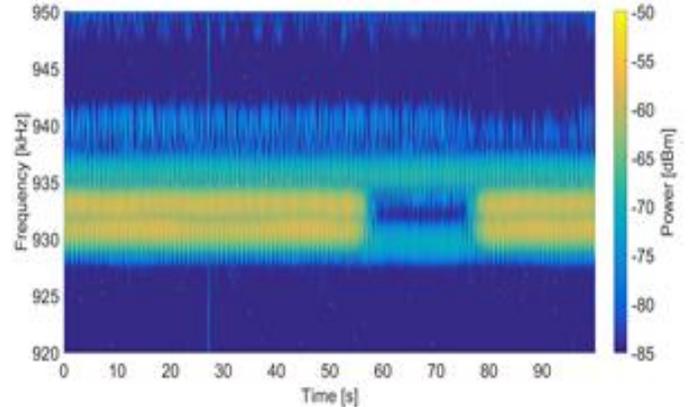
Fig. 4. Time domain representation of the analyzed signal.

compares the power of a 929.9 MHz radio signal measured with a 2.5 μ s window width, and the power level of a transient measured with a window of 250 ns. In order to obtain a relevant comparison, the power of the transient was measured at 924 MHz because no radio signal was detected at this frequency. The power of the transient is thus not affected by any other signal. Fig. 6 shows that the detected transient is less powerful than the useful signal by about 5 dB. That permits us to conclude that it has no major impact on the radio system. This result was not obvious starting from the time domain representation where the transient seems to be very powerful.

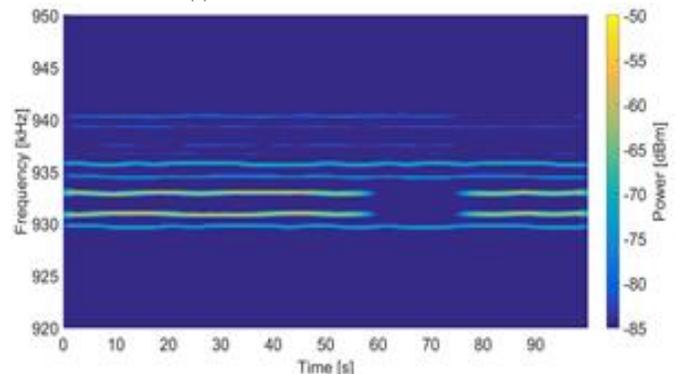
V. CONCLUSION

Time-frequency representations are very useful in EMC analysis. In some cases, as in the railway domain, time and frequency resolutions have to be very flexible due to the complexity of the electromagnetic environment to evaluate and the variety of the vulnerable systems' characteristics. Seeing that classical time-frequency methods do not offer such flexibility, we proposed a dedicated analysis method. Based on a rectangular window, this analysis permits optimizing time and frequency resolutions according to the system studied and the signals and disturbances analyzed.

The simplicity of the proposed process offers also the possibility of optimizing the algorithm complexity and reducing the computation time. This feature could be very useful especially with the recent development of real time time-frequency analyzers which are becoming commonly used in most of EMC studies.



(a) Result with a 250 ns window width



(a) Result with a 2.5 μ s window width

Fig. 5. Time-frequency representation of the radio communication frequency band with a 3 times rectangular window convolution

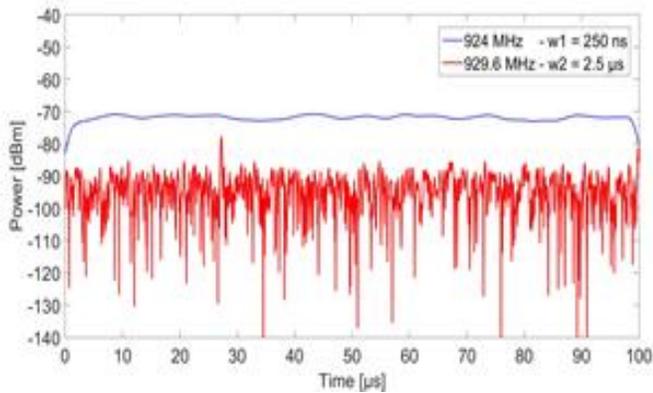


Fig. 6. Comparison between the power level of a useful signal (929.9 MHz) and a transient phenomenon.

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