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Reducing cross terms effects in the Choi–Williams transform of mioelectric signals

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ABSTRACT

This study aims at investigating the effect of removing the negative values of Choi–Wiliams distribution (CWD) related to the electromyogram (EMG) for visualization and instantaneous median frequency (IMF) estimation. Beyond the EMG signals from triceps surae and biceps brachialis, the CWD was applied in a simulated sinusoidal signal as like in stationary and non-stationary simulated EMG signals (SES). The CWD negative values of all simulated and EMG signals were removed. The IMF values were obtained for SES and EMG. The CWD IMF values from SES and EMG were thus compared with the IMF values from short time Fourier transform (STFT) by means of correlation. The suppression of negative values from the CWD reduced cross terms influence and improved visualization, as shown by the increased correlation coefficient between the IMF values. Before this suppression, the extracted IMF values showed large oscillation along the time, with various spurious values beyond 500 Hz, which disappeared after the suppression. Moreover, this procedure seems to be especially useful for non-stationary signals.

1. Introduction

The use of Fourier based methods, as fast Fourier transform (FFT) and short time Fourier transform (STFT), has been widely applied to identify the electromyogram (EMG) frequency contents in several contexts as fatigue, motor control and electric stimulation. An essential condition regarding the use of the Fourier transform (FT) is that the signal must be stationary [1–4].

The reduction of the signal window in which the Fourier transform is applied usually can solve the stationarity problem when one is dealing with the EMG related to isometric contractions. This window reduction, however, can be unhelpful in the range of 50–80% of the maximal voluntary contraction (MVC) of isometric signals [5] and in dynamic contractions [1,3]. Therefore, it is mandatory to test for signal stationarity before applying any Fourier based method. Otherwise, alternative time-frequency methods should be sought.

One of the most used time-frequency methods is the spectrogram, which is a Cohen class distribution member [6,7]. It is represented by the squared magnitude of STFT:

$$STFT[x(t)] \equiv X(\tau, \omega) = \int_{-\infty}^{\infty} x(t)\omega(t-\tau)e^{-j\omega t}dt \quad (1)$$

where $x(t)$ is the signal under consideration, $\omega(t)$ is a window function, τ is the time-lag and $X(\tau,\omega)$ is the Fourier transform of the function $x(t)\omega(t-\tau)$.

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The Choi–Williams distribution (CWD) is a time-frequency transform that has already been used in the EMG signal processing mainly in studies of muscular fatigue [1,4,8], uterine myoelectric activity [9] and injury prevention [10]. The CWD is a Cohen class member, which is related to parameters such as the instantaneous median frequency and the instantaneous power, which is the integral over all frequencies at each time [2]. The instantaneous median frequency (IMF) has been employed to monitor the CWD spectral parameters similarly to the conventional FT median frequency [1,4,8,11].

The CWD is given by:

$$D(t,f) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} R(t,\tau)\, e^{-(1/\sigma)(\Psi^2 \cdot \tau^2)} e^{-j2\pi\Psi(t'-t)} e^{-j2\pi f\tau} d\Psi\, dt'\, d\tau \quad (2)$$

where $R(t, \tau)$ is the instantaneous autocorrelation function for the time-lag τ, Ψ is the frequency-lag and $e^{-(1/\sigma)(\Psi^2 \cdot \tau^2)}$ is the exponential kernel that characterizes the CWD, whose effect is controlled by the scaling factor σ, which should be chosen between 0.1 and 10 [2]. Higher values approximate the CWD to the classical Wigner–Ville distribution.

Although the CWD can reduce the energy of cross terms, a significant amount of spurious values remains in the time frequency map, which may affect both quantitative and qualitative analysis [12]. This fact justifies the need of alternative methods for reducing the Choi–Williams cross terms interference.

Fan and Evans [13] suggested that only the positive values of Wigner–Ville distribution (WVD), other Cohen class member, should be taken into account, concerning that the negative values are exclusively due to cross terms. Beyond the study of Cardoso et al. [14], which extended such procedure to various Cohen class transforms applied to ultrasound signals, it was not found any study that has studied the effect of this proposal to the CWD from EMG signals.

Therefore, the comparison of the CWD spectral parameters under such conditions with classical Fourier based methods may contribute to elucidate if this procedure returns better information concerning the EMG spectral parameters.

Likewise, it would be interesting to evaluate the correlation between the CWD and the STFT among fatigue process, employing normalized IMF values. In this sense, the objective of this study was to investigate the effect of considering only the positive values of the CWD from EMG signals in order to estimate the IMF value and to compare with the classic FT median frequency.

2. Theoretical background

The theoretical evaluation of WVD presented by Fan and Evans [13] can also be applied to the CWD. Seizing the example used by Choi and Williams [2], regarding a signal $x(t)$ given by the sum of two sinusoidal waves with frequencies ω_1 and ω_2 and phases θ_1 and θ_2:

$$x(t) = A_1 e^{j(\omega_1 t + \theta_1)} + A_2 e^{j(\omega_2 t + \theta_2)} \quad (3)$$

Table 1 – Frequency contents of the Y(t) simulated signal and its respective magnitudes.

Time (s)	Frequency contents	Magnitude
Simulated signal Y(t)		
1	40	2
2	100	0.1
	125	1.3
	150	2.2
	175	3.5
	180	1.8
3	200	0.5
	240	2.2
	260	2
	280	2.4
	300	1.6
4	Chirp	4

the auto terms (AT) would be represented by:

$$AT = 2\pi \quad A_1^2\delta(\omega - \omega_1) + 2\pi \quad A_2^2\delta(\omega - \omega_2) \quad (4)$$

where δ is the Dirac delta function. Moreover, the cross-terms (CT) would be tied to the following expression:

$$CT = 2A_1A_2\cos[(\omega_1 - \omega_2)t + \theta_1 + \theta 2] \cdot \text{weight} \quad (5)$$

where weight represents the factor that reduces the magnitude of the cross terms and varies with the scale factor σ. The cosine in Eq. (5) determines whether the cross terms are negative or positive, since the A_1 and A_2 magnitudes are always positive.

Therefore, as in the WVD, the auto terms would present only positive values, in contrast to the cross terms, which could acquire positive or negative values. Thus, taking into account only positive values could reduce the influence of cross terms in the distribution.

Although this chosen signal $x(t)$ is much less complex than wide band EMG signals, this rationale makes composition of auto terms and cross terms clear and highlights the reasons for the proposed method.

3. Methods

3.1. *Simulated signals*

For better understanding the effect of ignoring negative values, the CWD (1) was first applied at a simulated signal $y(t)$ that was constructed (Table 1) by means of sinusoid waves sums with different frequencies and magnitudes and by a chirp function (Table 1) aligned in a vector form with a sampling frequency of 1000 Hz. The sigma value adopted was always 1 [1] and the window function was Hamming. The CWD was also applied to stationary and non-stationary simulated EMG signals (SES), with a sampling rate of 1000 Hz, as described in previous studies [15,16]. After that, the negative values of the time-frequency map from $y(t)$ and SES were replaced by zeros. The time-frequency maps from $y(t)$ and SES were constructed