Multi-harmonic Analysis Using Magnitude-Squared Coherence and Its Application to Detection of Auditory Steady-State Responses

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Abstract. The detection of auditory evoked brain responses is an important task in hearing science, especially in the role of investigation of hearing thresholds. Objective Response Detection (ORD) techniques aim to identify the presence of evoked potentials based purely on statistical principles that perform an automatic hypothesis test in the frequency domain and the Magnitude-Squared Coherence (MSC) is a well-known and very efficient uni-variate ORD technique. The use of q-sample tests, which, in addition to the fundamental frequency, also includes higher harmonics in the detection has shown trends to better detection of ASSRs performance. The database used in this work contains ASSRs that were collected when evoked by amplitude modulation of pure tones delivered binaurally at 70 dB SPL to 24 volunteers with normal hearing thresholds. This paper analyses the detection of response using a multi-harmonic approach combining the fundamental frequencies, 84 and 88 Hz, and its six next harmonic frequencies. A detection threshold was estimated using a Monte Carlo simulation. Both the detection rate and area bellow the detection curve increased using q-MSC techniques when compared to the one-channel and one-harmonic technique. The best results trends to be using a mean value (mean q-MSC) up to the third harmonic frequency, with an increase of 7.4% of detection rate mean, statistically proven with McNemar test, and the mean area bellows the detection curve increased 24.37%, statistically proven with t paired test, for the 14 channels compared.

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1 Introduction

The auditory evoked potential (AEP) is a type of signal, that can be measured through Electroencephalography (EEG), considered as a brain response due to an acoustical stimulus. EEG is a very useful non-invasive clinical tool to measure and monitor vital brain activities from newborns to adults, and it can be used for both medical and research application to an investigation of hearing thresholds [2,17]. The evoked potentials with constant both, phase and amplitude, during a long period of time it is considered as steady-state responses (SSRs) [20].

The auditory steady-state responses (ASSRs) have shown that it can provide a demonstration that sounds have been processed by the brain and it is important in objective audiometry studies [18]. Some parameters of human hearing sensitivity can be estimated by audiological tests based on ASSRs data, principally due to the fact that multiple stimulus responses can be simultaneously assessed, and so the ASSRs can be objectively detected using statistical tests using objective response detection (ORD) techniques to achieve them [21]. According to [5], ORD has several potential goals: It can be useful to remove an observer from a neonatal intensive care screening; an automatic controlled false positive rate can be set; it is proved to have performance superior to human observers in some cases; and can provide hidden useful information that can be used in training needed human observers.

In 1984, [13] introduced the ORD technique known as Phase Coherence (PC) in the analysis of ASSRs. [27] applied the PC as a way to predict auditory threshold in adults with normal hearing. In 1987, [19] applied the T^2 Hotelling test [14] and the PC to ASSRs. In 1989, [3] introduced the use of the Magnitude-Squared Coherence (MSC), an ORD technique that uses the phase and magnitude components of the response and stimulus in order to identify the frequencies that contribute to the AEP. In a later work in 1990, [4] applied the MSC to a filtered AEP with the called Optimal 'Wiener' Filter considered to be an auspicious process when compared to a low signal-to-noise ratio (SNR) non-filtered version. Similar work papers comparing ORDs techniques came up later [5–7,11,12]. Recently, [8,26] compared the univariate (MSC) and multivariate magnitude-squared coherence (MMSC) in the detection of ASSRs.

Detection rate is the rate achieved based on statistical comparison between signal and noise powers in the evoked potential measured, and is an rate highly used in several papers [1,7,9,10,26] in order to measure responses.

According to [1], the ASSR is also represented by several relevant higher harmonics in the frequency domain and the use of the fundamental frequency and its first harmonic in a q-sample test leads to significantly higher detection rates and shorter detection times in comparison to a one-sample test, which uses the information of the fundamental frequency only. [15] shown that weighted averaging is a useful technique to gave the best signal-to-noise ratios.

This paper investigates the use of a q-MSC, which is a technique that combines higher levels of harmonics in order to increase detection rates from ASSRs collected and compare the results to the regular MSC test.

2 Methodology

2.1 Database

The database used in this work was collected at *Nucleo Interdisciplinar de Analise de Sinais* located at the Department of Electrical Engineering in Federal University of Vicosa (NIAS-UFV). This dataset contains EEG signal data from 24 volunteers (8 females and 16 males) with normal hearing and ages ranging from 20 to 43 years old. For each volunteer, the stimuli were presented binaurally and the carriers always the same for both ears with carrier frequencies of 500, 1000, 2000, 4000 Hz, with modulation frequencies of 84 Hz for the left ear and 88 Hz for the right one [26]. The EEG signal collected contains data of 14 electrodes ($C_z; P_z; F_z; O_z$; F3; F4; C3; C4; T3; T4; P3; P4; T5 and T6) arranged on the scalp of each volunteer according to the 10–20 International System [24]. The signals were sampled in a sampling frequency of $f_s = 1250\,\text{Hz}$ and windowed in a 1024 windowing points for an offline analyze (0.8192 s each window) and processed up to 600 windows (total time of 491.52 s).

2.2 Magnitude-Squared Coherence (MSC)

The MSC technique, introduced in 1989 by [3], appeared promising for purposes of objectively identify stimulus-response relationships in the frequency domain. The MSC indicates the linearity involving the component of the harmonic stimulus and the response obtained by the EEG, and can be estimated by using the following equation [3]:

$$\widehat{MSC}(f) = \frac{|\sum_{i=1}^{M} Y_i(f)|^2}{M|\sum_{i=1}^{M} Y_i(f)|^2} \tag{1}$$

Where M is the number of windows, Y_i is the Discrete Fourier Transform (DFT) of the i-th window and '$\widehat{\ }$' refers to estimate value. The $\widehat{MSC}$ value ranges from 0 to 1. For the null hypothesis (H_0) and in order to check whether or not you have a detected response, the MSC value must be compared to a threshold, called critical value, and it is calculated by [23]:

$$MSC_{crit} = 1 - \alpha^{\frac{1}{M-1}} \tag{2}$$

where α is the significance level. To reject the (H_0), the $\widehat{MSC}$ value must be greater than MSC_{crit}, indicating detection of response.

2.3 The q-MSC

The data analysis for the q-Samples cases, averaged and product of the MSC, proposed in this paper is related to the fact of the ASSR present an energy in the fundamental frequency and its harmonics [1]. So this paper introduces the use of an averaged MSC (aMSC) and product MSC (pMSC) q-Sample test, and are calculated by the following equations:

$$aMSC_k = \frac{\sum_{h=1}^{H} MSC_i(f_h)}{H} \tag{3}$$

$$pMSC_k = \prod_{h=1}^{H} MSC_i(f_h) \tag{4}$$

where k is k-th averaged MSC calculated, H is the number of harmonics tested, i, h is h-th frequency harmonic with h = 1 being the fundamental. Both, aMSC and pMSC values, range from 0 to 1.

The result of aMSC in Eq. 3 is given by the sum of combined MSC divided by number of harmonics involved, and the result of pMSC in Eq. 4 is given by the product of MSC into number of harmonics involved.

2.4 Critical Value

The values of $aMSC_{crit}$ and $pMSC_{crit}$ were estimated by using 100,000 iterations of Monte Carlo simulation, with a significance level of $\alpha = 5\%$, generating signals to be applied on both, aMSC and pMSC techniques. The corresponding critical value is the result of the quantile of 5% lower values $(1 - \alpha)$, as a function of values of windows and number of signals [9,10,22].

2.5 Performance of the Detectors

The techniques were done in the frequency domain, with a fixed significance level (α) of 5% for the Monte Carlo simulation, then the aMSC and pMSC were estimated in the fundamental frequencies of 84 Hz and 88 Hz and its next 5 harmonics, according to Eqs. 3 and 4, and compared to the value of the calculated threshold, $aMSC_{crit}$ and $pMSC_{crit}$, for each sweep.

For the detection rate estimation, values of 1 or 0, were assigned to values of each of the methods when the Eqs. 1, 3 and 4 value was, respectively, greater or smaller than the corresponding MSC_{crit} value for each window [15].

The criterion for deciding whether or not to have a false positive was, for detection of response at defined rejection frequencies. In both cases, the rejection fundamental frequency is 79 Hz and 85 Hz and its next 5 harmonics, these values were defined based on criteria during data acquisition [26].

In order to evaluate the performance of the detectors, the detection and false positive rate on the M = 600 windows, and the area below the detection curve were estimated. The value of the area takes into account the size of the analyzed signal, giving an indication of how fast the detector improves with the increase of the window size.

3 Results

In this section, we present the results of the multi-harmonic detection rate and area bellow the detection curve in comparison with one-channel and one-harmonic detection rate, up to a window M = 600.

As the data used were real EEG signals, only the results with a false positive rate less than or equal to 5.73% were analyzed, instead of the false-positive rate of less than or equal to 5%, usually used in similar studies. So, the only criterion chosen to determine whether a result will be analyzed is whether it has a false positive rate of less than or equal to 5.73%.

Figures 1 and 2 shows, respectively, the results of the mean detection rate and mean area bellow the detection curve for each h number of harmonics utilized.

Figures 3 and 4 shows, respectively, the detection rate graphs for the electrode with the best responses analysed (F_z) found utilizing the mean (aMSC) and product (pMSC) techniques, for up the six first harmonics. From these results, the areas below the detection curves were calculated. These areas are dimensionless values directly correlated with detection time, and are better explained in Sect. 4.

For the significance testing of the differences between the detection rates found for the best q-sample case (three-sample) and one-sample within and between the subsamples, McNemar's test [25] was applied. For significance testing of differences between areas bellow the detection curve, the t-paired test was applied [16].

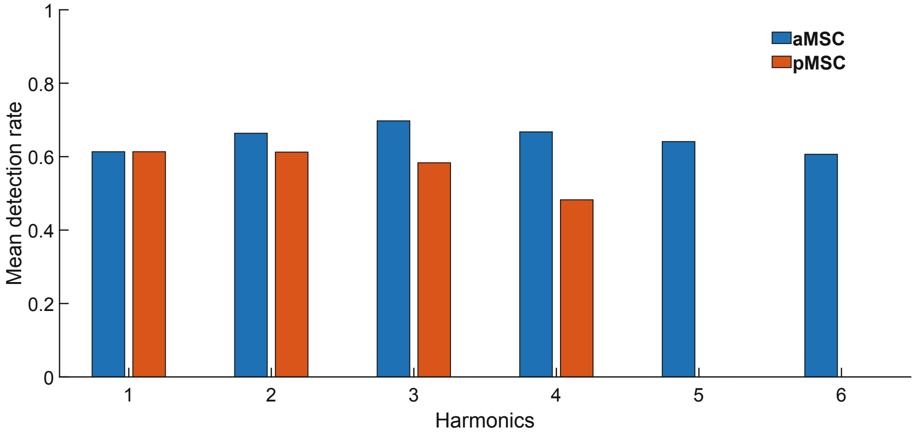

Fig. 1. Average detection rates for one-channel and multi-harmonic tests for each of the first six harmonics of the spectrum of the modulation frequencies. Mean detection rate is the simple average of the channels used, with false positive rate lower than 5.73%.

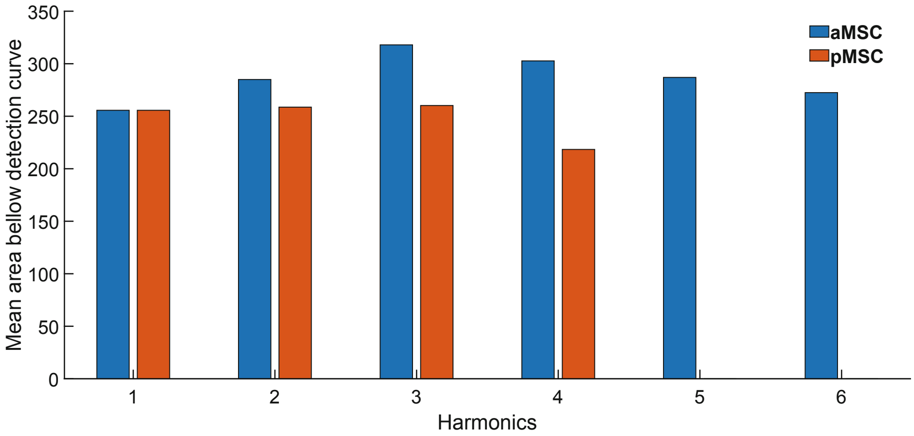

Fig. 2. Average area bellow the detection curve for one-channel and multi-harmonic tests for each of the first six harmonics of the spectrum of the modulation frequencies. Mean area bellow the detection rate curve is the simple average of the channels used, with false positive rate lower than 5.73%.

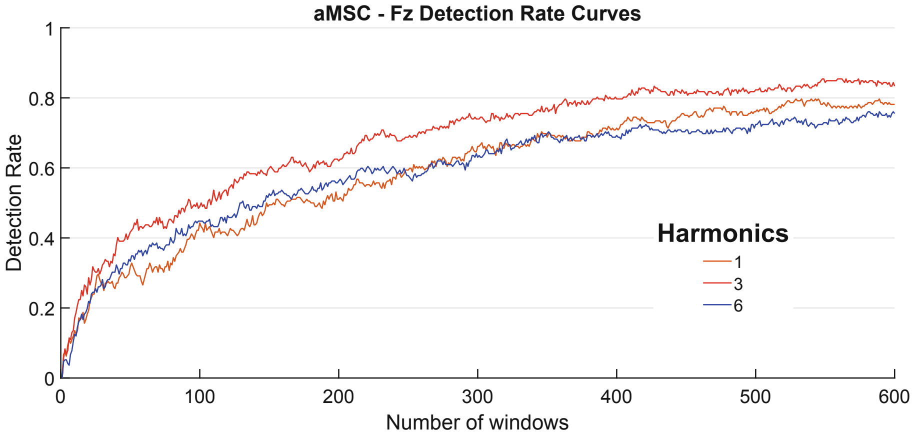

Fig. 3. F_z detection curves utilizing the aMSC technique in the case of a q-Sample test. The Figure shows the comparison between detection curves of one-Sample, three-Sample and six-Sample using the aMSC technique. The respective detection rate values, at M = 600, found were 0.78, 0.83 and 0.75. The respective area bellow of each detection curve found were 353.79, 406.18 and 351.95

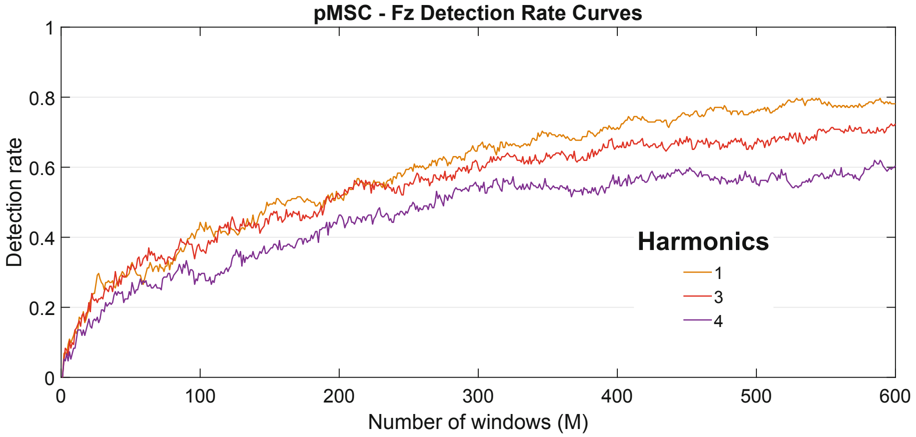

Fig. 4. F_z detection curves utilizing the pMSC technique in the case of a q-Sample test. The Figure shows the comparison between detection curves of one-Sample, three-Sample and four-Sample using the pMSC technique. The respective detection rate values, at M = 600, found were 0.78, 0.72 and 0.60. The respective area bellow of each detection curve found were 353.79, 327.42 and 275.76

4 Discussion and Conclusion

The F_z electrode, positioned in the sagittal plane of the frontal midline of the skull, is systematically present in all the best-analyzed cases. The detection rate increases with the course of the examination time. The results from aMSC three-Sample test led to better results when compared to the one-Sample MSC, with a 7.4% improvement in detection rate and up to a 24.37% increase in the area below the detection curve. A larger area below the detection curve can lead to a higher detection rate for window values than the analyzed one, that is, a better response for smaller windows. The use of the pMSC did not generate improvements in the detection rate, besides that it also led to an increase of the false positive rate, which even removed them from the analysis for a greater number of combined harmonics.

As a conclusion, the results from this study has shown that ASSRs is also present in several higher harmonics of the carrier frequency. However, it is important to note that the best results are not in the higher harmonic evaluated. As demonstrated in this work, the use of available information hidden in higher harmonics in a q-sample test leads to higher detection rates and shorter detection times in comparison to one-sample test.

Possible future works include the use of multiple channels combined with multiple frequencies utilizing the MSC.

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