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Assessment of a hand tremor based on analysis of the accelerometer signal

Abstract*. This paper presents the method developed for the assessment of a tremor based on analysis of the output signals from a 3-axis accelerometer placed on the index finger of the right hand. Firstly, the signal representing only acceleration caused by involuntary movement of the hand is determined. The tremor frequency is obtained as the dominant frequency of the PSD estimated for short segments of this signal by using the AR model. The presented method allows us to evaluate variability of tremor frequency in typical neurological tests.*

Streszczenie. *W artykule opisano metodę opracowaną do oceny drżenia na podstawie analizy sygnałów wyjściowych z trójosiowego akcelerometru, który został umieszczony na palcu wskazującym prawej ręki. Najpierw wyznaczany jest sygnał reprezentujący tylko przyśpieszenie wywołane mimowolnym ruchem ręki. Częstotliwość drżenia jest określana jako dominująca częstotliwość PSD estymowanej dla krótkich segmentów tego sygnału na podstawie modelu AR. Prezentowana metoda umożliwia ocenę zmienności częstotliwości drżenia w typowych testach neurologicznych. (**Ocena drżenia ręki na podstawie analizy sygnału z akcelerometru**).*

Keywords: accelerometer, tremor frequency, wavelet analysis, spectral analysis.
Słowa kluczowe: akcelerometr, częstotliwość drżenia, analiza falkowa, analiza widmowa.

Introduction

A human tremor is defined as an unintentional, rhythmic, oscillatory movement of one or more parts of a body. A tremor is produced by alternating or synchronous contractions of reciprocally innervated agnostic and antagonistic muscles [1, 2].

A tremor can be classified depending on its etiology, phenomenology, location and frequency. It occurs both in healthy individuals and as a symptom of a movement disorder, most often of neurological origin.

Physiological tremor, present in healthy persons is usually invisible because of its low amplitude. The enhanced physiological tremor is characterized by increased amplitude due to the influence of stress, fatigue, emotion, drug, etc. The frequency of physiological tremor will change from proximal to distal parts of an upper limb (e.g. the tremor frequency is 7–10 Hz at a wrist and 12–30 Hz at a metacarpophalengeal joint) [1].

Rest tremor occurs for example while sitting with arms supported against gravity. Rest tremor presence is a good criterion for the diagnosis of Parkinson's disease because this kind of tremor is usually not associated with other pathologies. Parkinson's tremor of a hand reminds the so-called "pill rolling" movement and its frequency occurs in the 4–6 Hz frequency range. Rest tremor often increases with mental stress or contra lateral movements but it disappears with action (i.e. when a voluntary movement is performed) and during sleep.

Essential tremor is the most common neurological movement disorder, being twenty times more prevalent than Parkinson's disease [3]. Up to 22% of elderly population suffers from this tremor which maximally affects hands. Essential tremor is characterized by the so-called action tremor which is divided into postural and kinetic tremor. Postural tremor appears when a subject voluntarily maintains a position against gravity (e.g. holding arms outstretched). As far as kinetic tremor is concerned, it occurs during voluntary movement. Frequency of essential tremor ranges widely from 4 to 12 Hz.

To sum up, the main features of each tremor are amplitude and frequency, which are used to recognize the kind of a human tremor and help to assess its severity. Tremor frequency is mostly dependent on the pathophysiological mechanism. Amplitude of tremor shows short as well as long term variability, which is also modified by the progress of disease and the effectiveness of treatment.

There are various tremor assessment techniques [2–6]. Archimedes spiral drawing and handwriting are the most popular subjective clinical methods used by neurologists. However, accelerometry provides objective measure of tremor frequency and amplitude so it is generally accepted as a gold standard [2, 7, 8].

Most of the reported studies consider the tremor signals collected by accelerometer to be stationary.

Determination of tremor frequency and amplitude is often done in frequency domain using the methods based on Fourier transform (FFT, PSD) [9,10]. For example, the tremor frequency is determined as the peak (i.e. the dominant frequency) in the PSD, while the tremor amplitude can be estimated from the area under this peak.

As alternatives, time-domain algorithms based on thresholds [10], parametric identification methods [11], STFT, and techniques based on empirical mode decomposition (EMD) [12] have been proposed in the literature.

Decomposition of acceleration into gravity and inertial acceleration using a measurement unit was investigated as an alternative to commonly used direct spectral analysis of measured acceleration [13].

This paper presents a novel method for assessing the variability of hand tremor frequency and amplitude during typical neurological tests. This method is based on off-line analysis of the acceleration signal which corresponds to fluctuations of acceleration representing only involuntary movement.

Data acquisition

To record a tremor signal during various tasks, a small accelerometer was attached to the index finger of the right hand. The ADXL325 a 3-axis accelerometer with signal conditioned voltage outputs was used. This sensor measures the static acceleration of gravity in tilt-sensing applications, as well as a dynamic acceleration resulting from motion, shock, or vibration. The dynamic range of this sensor is $\pm$ 5g.

The accelerometer output voltage signals were sampled at 100 Hz and digitized using a 14-bit ADC. All tremor data acquired by the module NI USB-6009 was sent into a computer and stored.

An example of simulated Parkinson's tremor is illustrated in Fig.1.

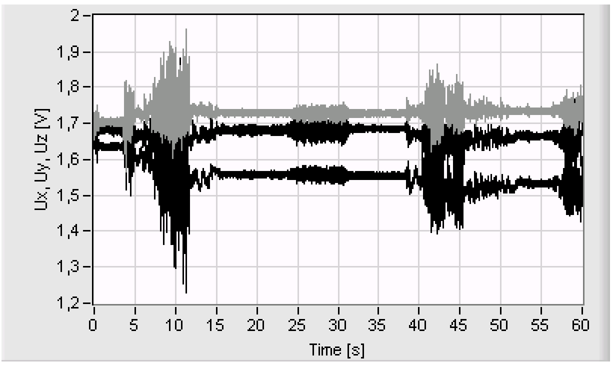

Fig.1. The 3-axis accelerometer output voltage signals recorded during simulation of Parkinson's tremor (i.e. "pill rolling" movement)

Method

The algorithm developed for determining hand tremor frequency and amplitude is shown in Fig. 2.

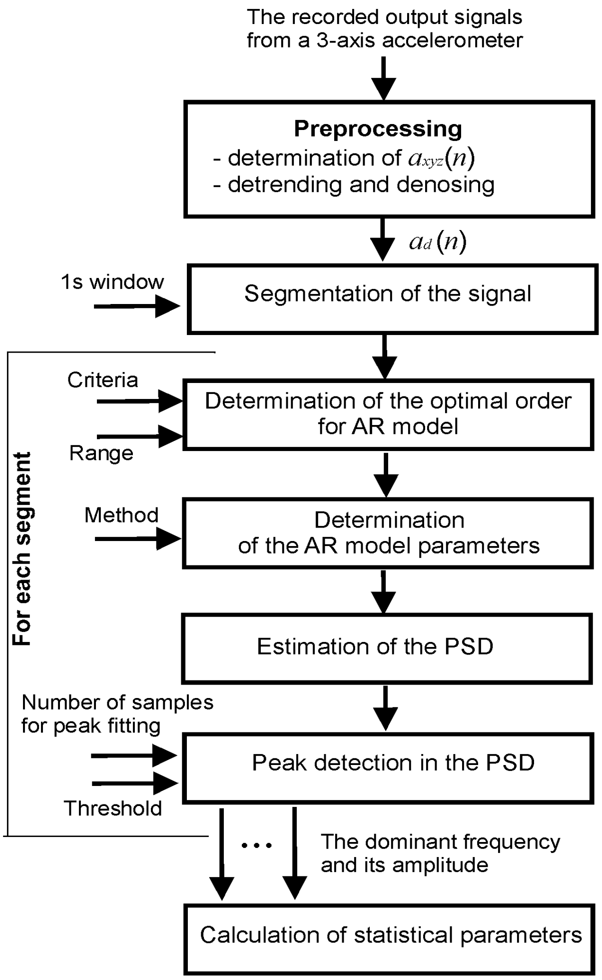

Fig.2. The algorithm for determining hand tremor frequency and amplitude based on analysis of the output signals from a 3-axis accelerometer

Firstly, the accelerometer output voltage signals representing acceleration in *x*, y, z direction are converted into g unit, where g represents gravitational acceleration (1 g = 9.81 m/s^2).

Then the absolute value of acceleration, $a_{xyz}(n)$ is calculated as follows:

$$a_{xyz}(n) = \sqrt{a_x^2(n) + a_y^2(n) + a_z^2(n)}\ . \tag{1}$$

If the accelerometer is not moved, it measures only the acceleration of gravity. During a hand movement, the accelerometer senses both the acceleration of the sensor and the acceleration of gravity. The acceleration of gravity must be subtracted from the absolute value of the acceleration. Furthermore, a voluntary hand movement (especially during drawing the spiral of Archimedes) appears as a nonlinear trend of the analyzed signal.

We assumed that only fluctuations of the acceleration are related to a hand tremor. In order to remove a low frequency component (with high amplitude) caused by hand movement while performing kinetic task, we applied the discrete wavelet transform (DWT). The signal $a_{xyz}(n)$ was decomposed by the DWT up to level six using Daubechies's orthonormal wavelet of order 10 (db10).

During the multiresolution decomposition performed according to Mallat's algorithm, an original signal is passed through a set of high-pass and low-pass filters [14]. The signals obtained as the results of this decomposition represent the original signal in different frequency bands. The details are the outputs of high pass filter and the approximate are from the low pass filter.

We assumed that the approximation at level six seems to be an acceptable estimate of a nonlinear trend including a DC component (see Fig. 3). The details at levels 1 and 2 represent mainly the noise.

Excluding the mentioned components from the analyzed signal during a signal reconstruction, the detrended and denoised signal, $a_d(n)$ is obtained (see Fig. 4).

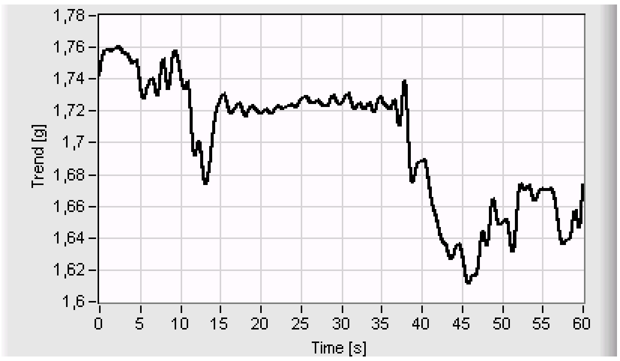

Fig.3. The nonlinear trend with a DC component extracted from the signal $a_{xyz}(n)$ for simulated Parkinson's hand tremor

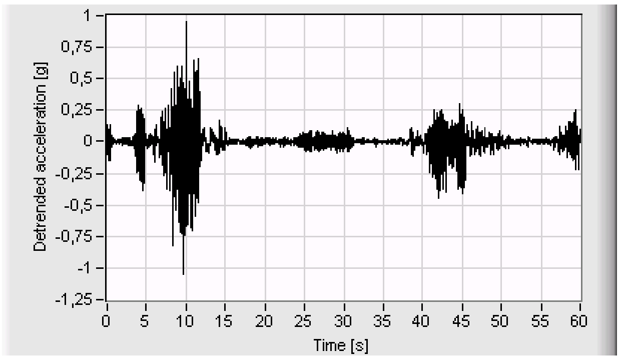

Fig.4. The detrended signal $a_{xyz}(n)$ obtained by wavelet analysis during simulation of Parkinson's tremor (i.e. "pill rolling" movement)

Next, the detrended signal, $a_d(n)$ is divided into equal segments by a 1-s moving window. These segments are non-overlapping. We assumed that each segment represents a stationary signal.

Finally, the tremor frequency is determined for each segment of the signal $a_d(n)$ as the dominant frequency in the PSD estimated via an autoregressive model (AR) using Burg's method.

Autoregressive techniques simplify a dataset representing a signal to a mathematical model dependent only on a small number of parameters.

An autoregressive (AR) model of order p represents the value of signal $x(n)$ by a weighted average of the previous signal values and some error $e(n)$ [15]:

$$x(n) = -\sum_{k=1}^{p} a(k) \cdot x(n-k) + e(n) \,, \tag{2}$$

where p is the model order, $a(i)$ are the unknown coefficients, and $e(n)$ is the prediction error.

The optimal model order for each segment of the analyzed signal is selected by Akaike's information-theoretic criterion. Next, the unknown AR parameters, $a(i)$ are calculated from the data.

Finally, the PSD is estimated for each segment as shown below:

$$PSD_{AR}(f) = \frac{\sigma_e^2}{\left| 1 + \sum_{k=1}^{p} a(k) \exp(-j2\pi fk) \right|^2} \,, \tag{3}$$

where σ_e^2 is variance of white noise.

The PSD obtained for each segment was examined in the 1–20 Hz frequency range because the frequency corresponding to a tremor is usually between 3–12 Hz.

Detection of the dominant frequency for each time window is based on an algorithm that finds the amplitude and location of the peak in the PSD by fitting a quadratic polynomial to sequential samples. The values of these samples must exceed the declared threshold level.

For example, Fig. 5–6 show the results of applying the described method for assessing simulated Parkinson's hand tremor. As expected, both tremor frequency as well as tremor amplitude change in time. During the period that Parkinson's tremor is present (e.g. in Fig. 5 the period between the 23rd and 33rd second), slight variations of tremor frequency are observed.

We concluded that the frequency which occurs most often during a specific task (see Fig. 6) should be considered as the representative tremor frequency for this task.

We compared the results obtained by the proposed method to other methods which are based on Fourier transform [9,16]. As shown in Fig. 8, the dominant frequency detected as the peak in the power spectrum (determined by Fourier transform) corresponds to the highest amplitude of the signal $a_d(n)$ (see Fig. 5 – in the 7th second). It is worth noting that this value of tremor frequency is different from the frequency value occurring most often.

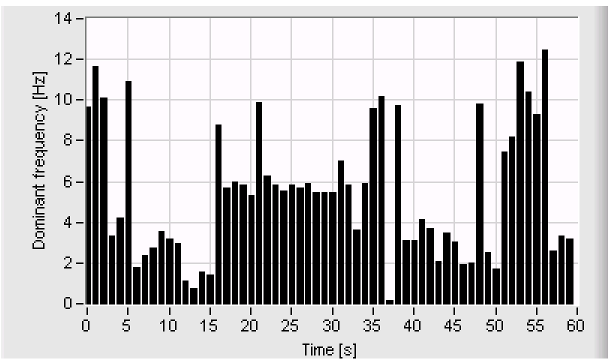

Fig.5. The dominant frequency determined for each 1 s segment of the signal $a_d(n)$ representing hand tremor during simulation of Parkinson's disease

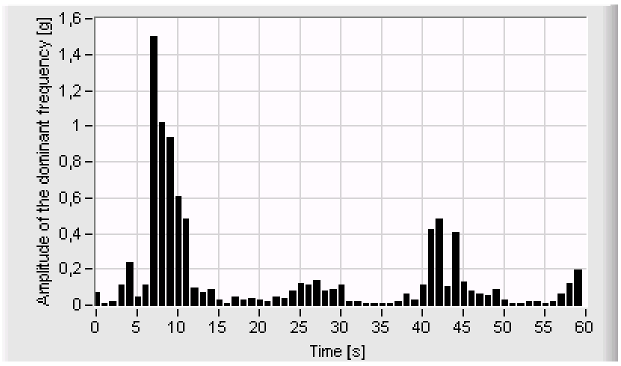

Fig.6. The amplitude of the dominant frequency determined for each 1 s segment of the signal $a_d(n)$ for simulated Parkinson's hand tremor

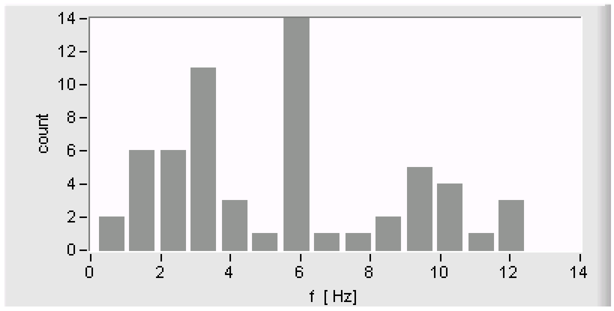

Fig.7. The histogram of the frequency determined by the proposed method for simulated Parkinson's hand tremor

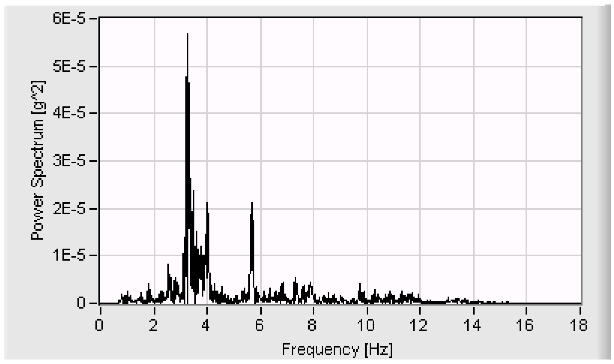

Fig.8. The power spectrum based on the Fourier transform of the signal $a_d(n)$ for simulated Parkinson's hand tremor

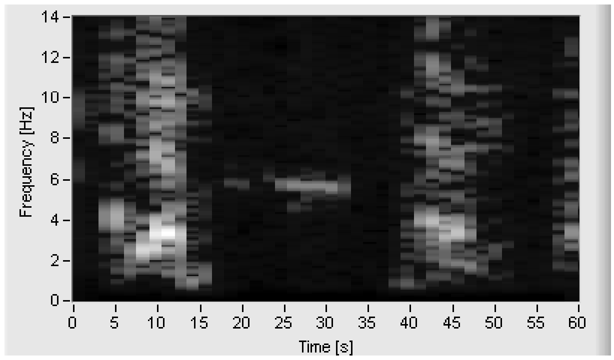

Fig.9. The spectrogram obtained by the STFT method for hand tremor during simulation of Parkinson's disease

However, the spectrogram obtained by the STFT method (see Fig. 9) illustrates the changes of tremor frequency in the time-frequency domain but the frequency resolution is poor. The frequency resolution of spectrum estimated on AR model is equal to 0.24 Hz for 1s time windows which were used for the analyzed signal segmentation.

Results

Hand tremor was recorded for 60 s during typical neurological tests from several healthy subjects sitting in an armchair as well as standing. The subjects were asked to perform the following tasks:

Task A – Hands rest on the table (i.e. supported against gravity) while sitting

Task B – Arms and hands are stretched out forward when sitting

Task C – Arms and hands are stretched out forward when standing

Task D – Drawing the spiral of Archimedes

Task E – Simulation of Parkinson's tremor ("pills rolling").

The results obtained for two healthy subjects at different age are presented in the Table 1 and Table 2, respectively. In order to assess the variability of tremor frequency and amplitude during each task, statistical parameters were calculated. The frequency f_{task} represents the most often occurring tremor frequency during a specific task.

As expected, hand tremor amplitude (A_{mean}) reaches the highest value during simulation of Parkinson's tremor. In this case, the standard deviation (SD) of tremor amplitude is significantly greater compared to the values of the SD obtained for other tasks.

Physiological tremor can be examined while performing task A, B, C. As expected, it is usually characterized by high frequency (8-12 Hz) and very low amplitude. When pathological tremor was absent, the lower frequencies (< 3.5 Hz) dominated. Even under resting conditions a low frequency component became prominent.

Table 1. Hand tremor frequency and amplitude – the young subject

Task	f_{task} [Hz]	$f_{mean} \pm SD$ [Hz]	$(A_{mean} \pm SD) \times 9.81$ [m/s^2]
A	2.4	5.2 ± 3.5	0.02 ± 0.01
B	1.7	5.9 ± 3.2	0.04 ± 0.03
C	7.6	7.1 ± 1.7	0.04 ± 0.03
D	7.7	6.3 ± 3.1	0.02 ± 0.01
E	5.8	5.4 ± 3.2	0.15 ± 0.27

Table 2. Hand tremor frequency and amplitude – the middle-aged subject

Task	f_{task} [Hz]	$f_{mean} \pm SD$ [Hz]	$(A_{mean} \pm SD) \times 9.81$ [m/s^2]
A	9.8	6.9 ± 3.2	0.01 ± 0.01
B	2.3	7.2 ± 4.0	0.02 ± 0.01
C	8.6	6.6 ± 3.1	0.03 ± 0.05
D	2.1	6.8 ± 3.5	0.02 ± 0.01
E	9.9	6.6 ± 3.6	0.19 ± 0.26

The preliminary results obtained from several healthy subjects show that the developed method can be employed to discriminate pathological tremor from physiological tremor.

Finally, it should be noted that to detect pathological tremor a subject should perform several various tasks.

Conclusion

In this paper we presented the method for assessing hand tremor recorded by a 3-axis accelerometer placed on the index finger. This method allows us to determine tremor frequency for short time windows, and assess variability of tremor frequency while performing typical neurological tests.

It is based on off-line analysis of the signal representing only fluctuations of acceleration caused by unintentional hand movement. In order to eliminate the influence of gravity and voluntary hand movement, we applied the DWT to the analyzed signal. The proposed method provides better accuracy of determining tremor frequency compared to the STFT method. The preliminary results obtained from healthy subjects demonstrated that this method can be used in diagnostics, namely to recognize a kind of human tremor and assess its severity.

This method is planned to be further validated by testing it on a database including a wide range of pathological tremors.

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