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Adaptive sliding bandlimited multiple fourier linear combiner for estimation of pathological tremor

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ABSTRACT

Pathological tremor is a roughly sinusoidal movement and impacts individuals' daily living activities. Biomechanical loading is employed as a potential method for tremor suppression with the accurate estimation of amplitude and frequency of tremor signals. In this paper, a study on tremor is conducted and the characteristics of tremor signals are analyzed. An adaptive sliding Bandlimited multiple Fourier linear combiner (ASBMFLC) algorithm is proposed to estimate the different desired signals with sliding frequency band and zero-phase lag. This method incorporates digital filter, Weighted-Frequency Fourier Linear Combiner (WFLC) and Bandlimited Multiple Fourier Linear Combiner (BMFLC) with modification of fundamental frequency and limitation of frequency range. Based on the experimental tremor signals, WFLC, BMFLC and the proposed algorithm are evaluated, respectively. The experimental results show that the developed algorithm could adapt to the unknown dominant frequency for determining the interesting frequency band without prior information. Furthermore, the improved method could provide higher accurate estimation of tremor and extract the voluntary components from measured signals, compared with WFLC and BMFLC, respectively.

1. Introduction

Tremor, a roughly sinusoidal and involuntary alternating movement, is caused by the rhythmic contraction of muscles [1] and usually occurs in the wrist joint and elbow joint. In general, tremor can be classified into the physiological tremor and the pathological tremor. The physiological tremor occurs with low amplitude and high frequency, and impacts individuals' precise actions [2]. Instead, the pathological tremor is associated with the disorder of neural systems and presents higher amplitude and broader frequency range with 3–14 Hz. The pathological tremor is not life-threatening, however, it corrupts human daily life with an oscillatory disturbance [3].

With the research of the tremor etiology, pharmacology and surgery were prevalently employed, but its negative effects were inevitable [4]. For developing other treatment methods of tremors, deep brain stimulation (DBS) of the globus pallidus or subthalamic nucleus of tremor patients [5], functional electrical stimulation (FES) of antagonistic muscles of joints to resist tremor [6–9] and biomechanical loading passively or actively acting in-parallel to the upper limb by external devices [10–13] were proposed. However, the high cost and potential danger impacted the application of DBS due to the limitations of technology. In FES, sEMG or EEG was introduced to predict and identify tremor movement, but the application of FES was also obstructed by the unstable biological signals [7]. When the clinical and functional test indicated that increasing the damping or inertia of limb could suppress tremor, biomechanical loading was developed [10]. Recently, wearable rehabilitation systems with constrained-layer damping [10,13] or with DC motors upper limb [11,12] were designed to suppress the tremor on wrist or elbow joint.

The external assistive devices like the biomechanical loading or FES were controlled by tremor signals to compensate tremor. FES activates motoneurons or reflex pathways by stimulating sensory nerve fibers and employs muscles as actuators to resist tremor. The characteristical parameters are derived to generate adequate stimulation patterns and counteract tremor [6–9]. For example, the total number of stimulation bursts for flexors and extensors per second is determined by the tremor fundamental frequency. In the tremor suppression by biomedical loading, the value and frequency of damping or inertia are real-time modulated by the amplitude and frequency of tremor signals, respectively [10–13]. In this regard, the real-time estimation of instantaneous tremor parameters by algorithms is important to develop robust orthotic for tremor suppression without affecting the voluntary motion. Digital low-pass or band-pass linear filters were successful in attenuating tremor, but the inherent phase lag and amplitude attenuation degraded the performance in human–machine interaction system. Later, an adaptive band-pass filter (ABPF) was designed to extract tremor without phase lag by updating the center frequency of the filter

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Table 1
Frequency band and clinical features of patients.

Medical History	Type of tremor	Body segments	Frequency band
Parkinsonian	Rest/Postural	Hand, Wrist or forearm	3–6 Hz
Cerebellar disorders	Kinetic/Postural	Limbs or trunk	2–7 Hz
Essential Tremor	Kinetic/Postural	Upper limbs	6–12 Hz
Extrapyramidal Syndrome	Rest/Postural	Upper limbs	3–4 Hz

according to the input signals [14], but the interesting band with zero-phase lag was limited to the center frequency and rather small which was not suitable to the multi-frequency tremor signals. A Hilbert–Huang transformation (HHT)-based filtering method was proposed to process the tremor recordings and to remove the nonlinear, non-stationary interference without priori-knowledge [15–17], but the characteristic of online computation had to be improved.

However, adaptive combined methods could adapt to the frequency and amplitude of tremor with zero-phase according to the gradient descent algorithm (the least mean square (LMS)) [18]. Fourier linear combiner (FLC) formed a dynamic truncated Fourier series of desired signals based on the sinusoidal components [19,20]. FLC adaptively estimated the Fourier coefficients of inputs with known frequency and constructed the desired signals canceling periodic interference. The weighted fourier linear combiner(WFLC) algorithm could model any quasiperiodic signal as a modulating sinusoid, and track its frequency,amplitude and phase by incorporating frequency adaptation procedure into FLC. However, WFLC algorithm could only adapt to a single dominant frequency in the input signals. For the case of tremor signals modulated by two frequencies close in frequency domain, the performance of WFLC would degrade [21,22]. For canceling the low frequency components which decreased the accuracy of tremor estimation, a Benedict–Bordner filter was introduced before WFLC [3,23], but this method introduced phase lag. To overcome the drawbacks of FLC and WFLC, Bandlimited multiple Fourier Linear Combiner (BMFLC) comprised of several Fourier Linear Combiner was derived [24,25]. In BMFLC, the frequency band was divided into equal portions and BMFLC could track the multiple frequency components in the input signals with corresponding fundamental frequency. Main drawback of BMFLC lied in tracking signals with a fixed frequency band with prior experience of tremor signals [24]. This increased the number of weights and increased the susceptibility to noise, which degraded the real-time implement. The recursive least squares (RLS) and Kalman Filter were also introduced into BMFLC replacing the LMS algorithm to raise the comuputing speed and accuracy [26], but it didn't improve the drawback of BMFLC with fixed frequency band. With the prior knowledge of the frequency band of the periodic motions, a combination of linear filtering and modified-WFLC or modified-BMFLC was employed to estimate the actual signals and the results were compensated without the phase-shifted and attenuation which was usually caused by filters [27]. However, this method didn't invlove the charachteristic that frequncy band slides with time and individual of tremor signals. In this paper, a method is proposed in which BMFLC is incorporated with WFLC and modification of frequency, so that the frequency band could slide in time or individual. The similer estimate of actual tremor signals could be achieved with fewer computation and time compared with existing algorithms, like BMFCL or WFLC.

The rest of the paper is organized as follows: Section 2 studies the characteristic of the tremor and design an algorithm for estimating the instantaneous tremor parameters. Section 3 describes the source of patholgical tremor signals and the mechanical platform for mimicking tremor incorporating with voluntary motion. Section 4 presents the results on tremor modeling and the extraction of voluntary motion by the proposed algorithm. Section 5 concludes the paper.

2. Theory/calculation

During the filtering and estimation of tremor, the accuracy of the tracking algorithms was directly determined by the frequency range of tremor signals [28]. In this section, the tremor profiles of various subjects were analyzed to evaluate the tremor frequency range.

2.1. Analysis on tremor frequency characteristic

In recent years, several studies indicate that physiological tremor might be caused by central nervous system with oscillatory activity, mechanical resonances or derangement of reflex loop [29]. Due to the multi-factors, the physiological tremor appears as a quasi-periodic component inherent in normal motions with a frequency range in 8–14 Hz and an amplitude (100 μm) in 3D direction [24]. In ref. [25], 6 healthy subjects and 10microsurgeons are selected. The mean frequency range for surgeons and novice subjects are [9.33 Hz, 11.6 Hz] and [7.6 Hz, 10.3 Hz], respectively. While the tremor bandwidth of novice subject is about 2 Hz (10–12 Hz) and surgeon is about 3 Hz (7–10 Hz) during stationary and tracking tests. This research indicates that the tremor frequency band changes in different physiological tremors.

Pathological tremor is defined as impair motor performance and is distinct from other involuntary movement disorders by its repetitive and stereotyped feature [30]. Significant insights of the oscillatory activity recorded in different parts of the nervous system are performed to explore the mechanism of pathological tremor. The study shows that the central neural oscillator is in charge of generating the abnormal rhythmic activation patterns of muscles [31]. Recently, analysis of tremor recordings on the pathological tremors is employed to conclude the general frequency band and the clinical features as depicted in Table 1.

According the Table 1, pathological tremors are classified into essential tremor, Parkinson's disease (PD) etc. according to the frequency and amplitude. It illustrates that pathological tremors occur on different body segments and in different task or position-dependence. The significant result is that the dominant frequency band with different bandwidth changes in pathological tremors or body segments.

To determine the dominant frequency and frequency band of pathological tremor, tremor signals downloaded from the website of Motus Bioengineering Inc [32] are analyzed. For example, essential tremor often occurs in hands, especially when you do simple tasks like drinking and writing. Essential tremor worsens with time and may be severe in some people. The signal of essential tremor accompanying voluntary movements of the wrist is illustrated in Fig. 1.

Parkinsonian usually occurs while the body segment is maintained in a rest position and may disappear with action. For this reason, the profile of Parkinsonian' extremities is more significant without the voluntary movements as shown in Fig. 2.

Based on the frequency characteristic of pathological tremor recordings, pathological tremor is likely to have dominant