SIMULATION STUDY OF TREMOR SUPPRESSION AND EXPERIMENT OF ENERGY HARVESTING WITH PIEZOELECTRIC MATERIALS

Jianqiang Ou

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APPROVED:

Xun Yu, Major Professor
Jiangtao Cheng, Committee Member
Yan Wan, Committee Member
Yong Tao, Chair of the Department of
 Mechanical and Energy Engineering
Costas Tsatsoulis, Dean of the College of
 Engineering
Mark Wardell, Dean of the Toulouse
 Graduate School

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The objective of this research is to develop a wearable device that could harvest waste mechanical energy of the human hand movement and utilize this energy to suppress wrist tremors.

Piezoelectric material is used to measure the hand movement signals, and the signal of wrist tremor is filtered to be utilized to suppress the tremor. In order to conduct the experiment of energy harvesting and tremor suppression, an experimental rig was fabricated. Two types of piezoelectric materials, PVDF (polyvinylidene fluoride) films and MFC (macro fiber composite) films, are used to harvest mechanical energy and used as actuators to suppress hand tremors. However, due to some shortages of the materials, these two types of materials are not used as actuators to suppress the wrist tremors. Thus, we use Matlab Simulink to simulate the tremor suppression with AVC (active vibration control) algorithm.

ACKNOWLEDGMENTS

I would like to thank my parents, my sisters and my friends for their support and encouragement mentally.

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CHAPTER 1

INTRODUCTION

The objective of this research is to develop a wearable device that could harvest waste mechanical energy of the human hand movement and utilize this energy to suppress wrist tremors. Since the frequency spectra of wrist tremors is different from the one of voluntary hand movements, piezoelectric material is used to measure the hand movement signals, and the signal of wrist tremor is filtered to be utilized to suppress the tremor. In order to conduct the experiment of energy harvesting and tremor suppression, I fabricate an experimental rig, which is driven by a linear stepper motor. Two types of piezoelectric materials, PVDF (polyvinylidene fluoride) films and MFC (macro fiber composite) films, are used to harvest mechanical energy and used as actuators to suppress hand tremors. However, due to some shortages of the materials, these two types of materials were not used as actuators to suppress the wrist tremors. I analyze the reason in Chapter 5.

1.1 Motivation of the Thesis

Most of the people having Parkinsonism suffer from tremor or involuntary disorder movement. They have to face difficulties in their daily life because of the hand tremor.

There are different methods to alleviate the symptoms of human hand tremor. However, most treatment methods accompany with different negative side effects. For instance, surgical therapy may comes with a high risk to a patient life because it has to operate on the brain, and drug therapy may have a negative long term side effect. Thus, this research is attempted to develop a non-invasive system that could suppress the human hand tremors.

1.2 Objective

The key objectives of this thesis are:

- To simulate the tremor suppression algorithm by using the Matlab Simuliink.
- To fabricate the experimental rig to mimic the human hand movement and the involuntary tremor.
- To conduct the energy harvesting experiment, and to evaluate the energy harvesting performance of different piezoelectric materials.
- To analyze the reasons why the current materials are not good enough to apply in the final device.
- To discuss some possible work in the future.

1.3 Thesis Outline

Chapter 2 begins with a brief review of selected literature pertaining to energy harvesting and active vibration control.

Chapter 3 talks about the design and manufacture of the experimental rig.

Chapter 4 describes the experiment results of the energy harvesting with the experimental rig.

Chapter 5 describes the modeling and simulation of tremors suppression with adaptive control and discusses the reason why MFC could not be used as actuators for the tremor suppression glove.

Finally, the main conclusions and some recommendations for possible future extension of this work are presented in chapter 6.

CHAPTER 2

LITERATURE REVIEW

This chapter gives a brief overview of useful literature in hand tremor, energy harvesting using piezoelectric materials, and active noise/vibration control technology.

2.1 Hand Tremor

2.3.1 Overview of Hand Tremor

Tremor is defined as an involuntary, approximately rhythmic, and roughly sinusoidal movement [1]. It occurs in many neurological disorders including essential tremor (ET) and Parkinson's disease (PD) [2].

A lot of research on hand tremor has been done mainly to discover its movement pattern by analyzing its amplitude and spectra. In fact, every person has his/her own tremor [3] but with different level of amplitude and spectra. Thus, even healthy people have a slight tremor, but people with Parkinson's disease suffer from a more serious tremor, so that they could not even control their movements [4]. As a result, it is hard for those patients to deal with their daily life. Since the frequency between human tremor and voluntary movement are different, it is essential to discover the frequency range of the human tremor and voluntary movement.

There are two types of tremor happens on the PD patients: (1) resting tremor, and (2) postural tremor. Resting tremor is such kind of tremor which happens when the patient stays relaxed and the limbs are fully supported [5]. Postural tremor happens while the patient is voluntarily maintaining a position against gravity [6]. For these two kinds of tremor, the displacement amplitude is in the range of $\pm$5mm [7], [8], [9]. In addition, the frequency tends to vary inversely with the amplitude of tremor. In other word, the frequency will increase while the amplitude of tremor decreases [10]. From the literature review, it is found that the frequency range of these two kinds of tremor is from 3 to 12 Hz [5] [11], [12].

2.3.2 Treatment for Hand Tremor

Nowadays, there are still no effective ways to totally cure human tremor, but there are different treatments that can alleviate the symptoms of the patients. Drug therapies and surgery are the two mainstream of current medical treatment.

Prescribed drug such as Alprazolam and Levodopa are typically used for alleviate the symptoms of PD patients, however they all have different kinds of serious side effects and have to be used carefully [13].

On the other hand, surgery is the alternative method for PD patient. Since all of these surgeries have to operate on human brain, it is very risky.

2.2 Piezoelectric Energy Harvesting

Energy harvested from wasted or unused mechanical power has become a more and more popular topic. One of these kinds of wasted power is generated from human activity.

The field of energy harvesting by utilizing piezoelectric materials has been researched greatly over past decades. Most research on this subject tried to maximize the energy harvesting ability of these piezoelectric materials. Usually, a monolithic piezoelectric material with a traditional electrode pattern and poled through its thickness is used for power harvesting [14]. However, a lot of research has been conducted on developing a broad range of piezoelectric composite sensor/actuators, some products derived from this research have their own operational advantages and characteristics. The majority of these products are applied in the field of control and vibration suppression applications [14], and they also have great potential for use in power-harvesting systems.

There are three kinds of piezoelectric materials, which are most frequently used. The first one are polymers (polyvinylidene fluoride, PVDF), and the second one are ceramics (lead zirconate titanate, PZT). The polymer materials are soft and flexible; however have lower dielectric and piezoelectric properties than ceramics. Conventional piezoelectric ceramic materials are rigid, heavy and tend to be in block form [15]. For the rigid property and the fragile nature of the ceramic materials, it is not suitable to apply ceramic material in many products, such as wearable devices. The third piezoelectric material is MFC (micro fiber composite). The MFC consists of rectangular piezo ceramic rods sandwiched between layers of adhesive, electrodes and polyimide film. The electrodes are attached to the film in an interdigitated pattern which transfers the applied voltage directly to and from the ribbon shaped rods. The MFC allows the fiber to withstand impacts and harsh environments far better than monolithic piezoelectric ceramic materials. Also it has better dielectric and piezoelectric properties than PVDF.

2.3 Active Vibration Control

Active vibration control (AVC) is similar to active noise control (ANC) as noise is generated by vibration. AVC is achieved by introducing a canceling “antivibration” wave through an appropriate array of secondary sources [16]. These secondary sources are interconnected through an electronic system using a specific signal processing algorithm for the particular cancellation scheme [16]. ANC/AVC can effectively attenuate noises/vibrations that are very difficult and expensive to control using traditional passive methods [16].

One of the advantages of the active vibration control method is that it can be utilized to attenuate low frequency vibration. Also, AVC devices can be much less bulky than passive treatments and materials and would be able to be made into compact embedded devices, which can be used in a much wider area of application [17]. In addition, AVC could effectively attenuate the vibration while the useful signal can be still not affected much. In other words, AVC can selectively suppress vibration. I discuss the two types of active vibration control strategy below.

2.3.3 Feedback Control

The scheme of feedback control is depicted in Figure 1. As shown in the figure, r(s) is the reference input, and y(s) is the final output. Error signal e=r-y is passed into a compensator h(s) and applied to system g(s) [20]. The key factor of designing the controller is to choose an appropriate compensator h(s) to minimize the error and guarantee the stability at the same time. However, there are two disadvantages for this configuration: (1) it only provides limited broadband noise attenuation over a limited frequency range (2) it possibly become unstable for the positive feedback at high frequencies where the phase response is not easily controlled [16].

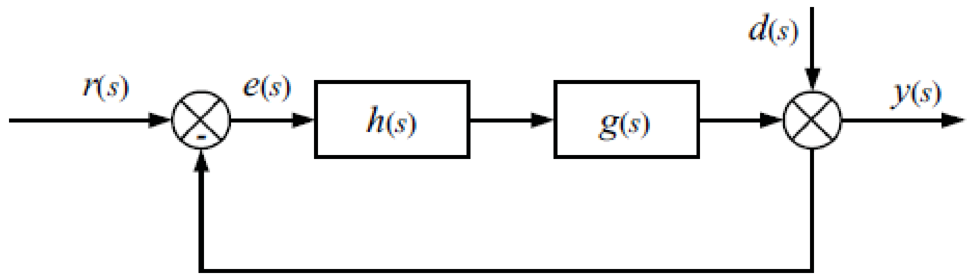


Figure 1 Principle of feedback control. [20]

2.3.4 Feedforward Control

Feedforward control methods can significantly improve performance over simple feedback control whenever a signal correlated to the disturbance is available [20]. The scheme of feedforward control is shown in Figure 2. A reference signal, which is correlated to the primary disturbance, is applied in this control system [20]. An adaptive filter utilizes both this reference signal and the error signal to generate the “antivibration” signal that is applied to the system by the actuator. This strategy is to generate such a secondary disturbance to minimize the effect of the primary disturbance at the location of the error sensor [20]. Due to the stability of this configuration, it is considered for the AVC system in this research.

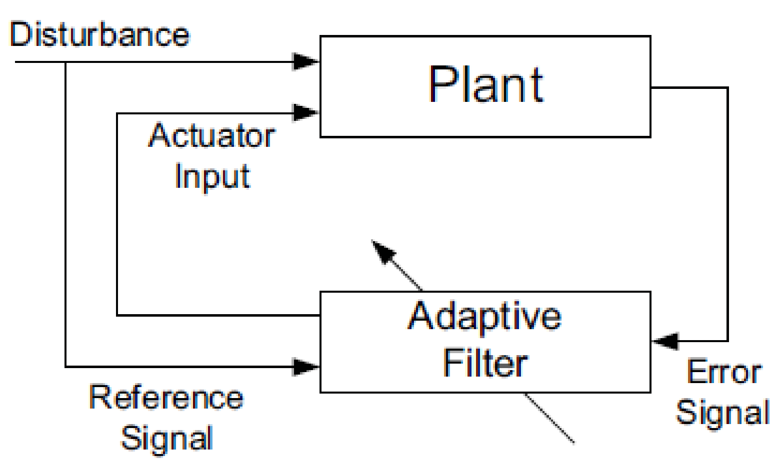


Figure 2 Principle of feedforward control. [20]

CHAPTER 3

DESIGN AND MANUFACTURE OF THE EXPERIMENTAL RIG

This chapter outlines the description of the complete design and the equipment used for the experimental rig.

3.1 Problem Identification

To design the experimental rig to mimic human hand tremor, we first need to determine the vibration frequency of the human hand. As mentioned in the literature review, the displacement in the range between $\pm$5mm and the frequency of actual human hand tremor is observed between 5 and 12 Hz.

3.2 Selection of Linear Motor

Because I attempt to use a linear stepper motor to drive the artificial arm to move, I first need to choose an appropriate motor.

Here is the analysis of the parameters of the motor below:

Assuming a sinusoidal type of motion with the amplitude of X, in meter, and frequency of f in Hz,

$$x(t) = X \, Sin(\omega * t) \qquad (4\text{-}1)$$

where, the angular velocity $\omega = 2 * \pi * f$.

The equation for velocity is;

$$v(t) = X * \omega \, Cos(\omega * t) \qquad (4\text{-}2)$$

The equation for acceleration is;

$$a(t) = - X * \omega^2 * Sin(\omega * t) \qquad (4\text{-}3)$$

Then, the force is

$$F = - X^* m^* \omega^2 *Sin(\omega *t) \tag{4-4}$$

where m is the weight of the artificial arm, which we assume it is 0.5Kg.

The peak force, Fpeak = $m^* X^* \omega^2$.

And it runs at 5 Hz with magnitude of 5mm

$$v(t)peak = X^*\omega = X^*2\pi^*f = 5^*2^*3.14^*5 = 157mm/sec \approx 6 \text{ inch/sec.} \tag{4-5}$$

$$Fpeak= m^*X^* (2 ^*\pi^* f)^2 \approx 2.5 \text{ N} \tag{4-6}$$

As discussed above, the motor has to be able to provide 2.5 N force when it move in the speed of 6 inch/sec.

Finally, I chose the Haydon Kerk Linear Actuator 43M4Z and the DCS4020 Bipolar Chopper Drive. As shown in Figure 3, the performance of 43M4Z (the curve with characteristic “Z”) could totally satisfy the requirement.

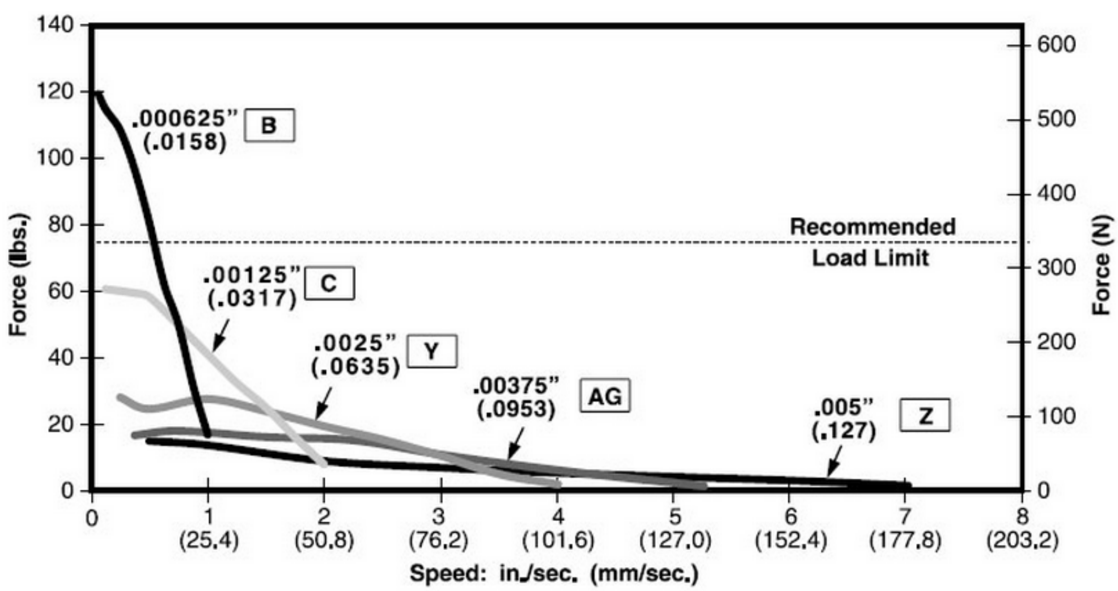


Figure 3 The performance of the linear actuator 43M4Z. [19]

3.3 The Detail Dimension of the Experimental Rig

This section shows details dimension of experimental rig. As shown in Figure 4, the experimental rig size does not take too much space. Overall, the size of experimental rig is 14inch × 7inch × 18inch (length × width × height).

Figure 5 shows the experimental rig after fabrication process. The experimental rig consists of one linear motor, two springs, one artificial palm, one aluminum pipe, one hinge and four pieces of wood. Since the experimental rig needs to emulate the wrist tremor, I connect the artificial palm with the aluminum arm by two springs, which allow the palm to move forward and backward while the arm is vibrating.

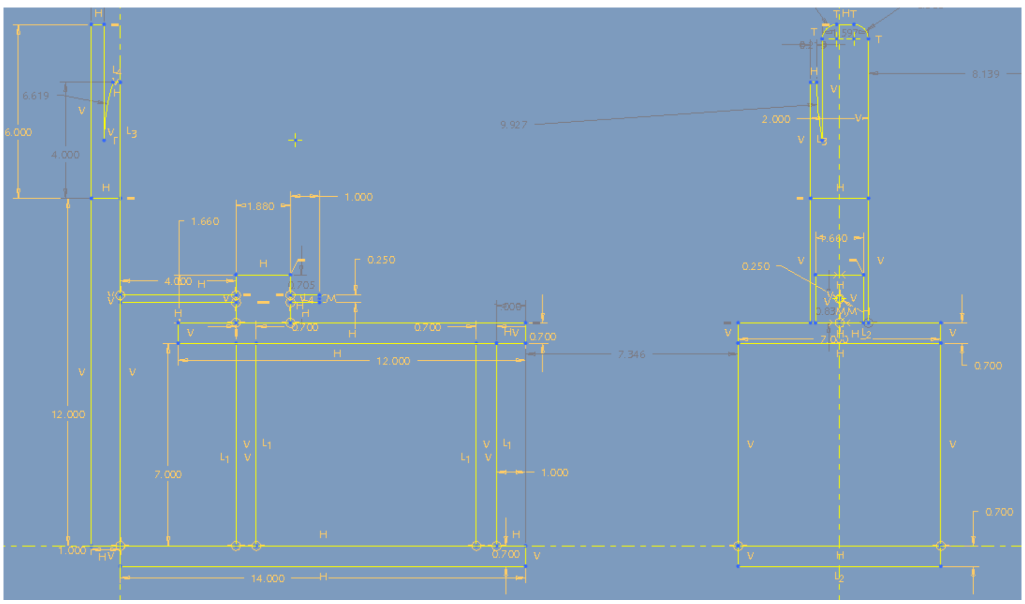


Figure 4 The dimension detail of the experimental rig.

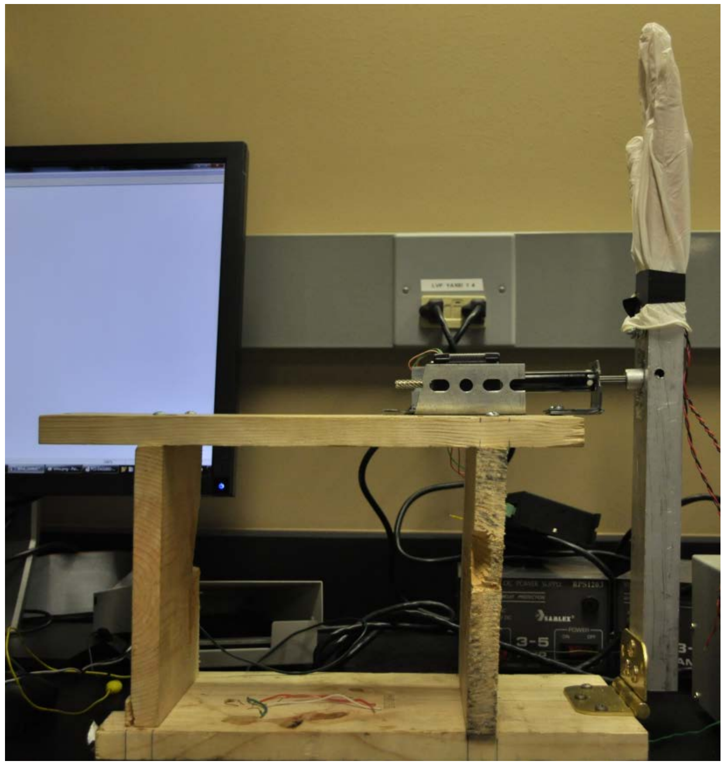


Figure 5 The experimental rig.

CHAPTER 4

THE EXPERIMENT SETUP AND RESULT ANALYSIS

This chapter describes the experiment setup and the result analysis of energy harvesting. I also discuss the reason why the MFC (macro fiber composite) films could not be utilized as the actuator of the human hand tremor suppression.

4.1 Experiment Setup for the Energy Harvesting

The complete set up of the experimental rig used in this study is shown in Figure 6. Figure 7 shows the detail of the energy harvesting glove with different kinds of piezoelectric materials (MFC (macro fiber composite) and PVDF (polyvinylidene fluoride).

As shown in the Figure 6, PC is responsible for converting the sinusoid wave signal to the form which the motor drive could recognize, and this form of electrical signal is transmitted by a data acquisition board. The motor drive and power supply are used to drive the linear motor, and the motor moves forward and backward in a certain frequency, which is determined by the signal from the I/O board. The artificial palm wears an energy harvesting glove, which is covered by a piece of piezoelectric material. Since the artificial palm is connected with two springs, it will stretch the glove when it is vibrating, and therefore a force will strain the piezoelectric material. As a result, the material will generate a voltage, which will be transferred to the rectifier circuit, and measured by the oscilloscope.

As shown in the Figure 7, the energy harvesting glove is made of an elastic rubber glove, which is with one piece of piezoelectric material at the back. Its flexibility allows the artificial palm to freely move forward and backward.

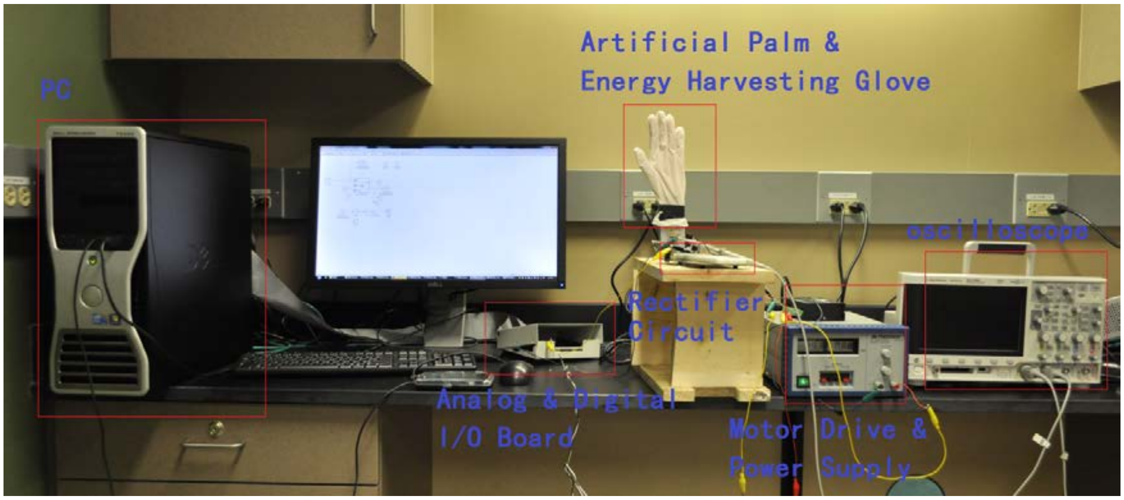
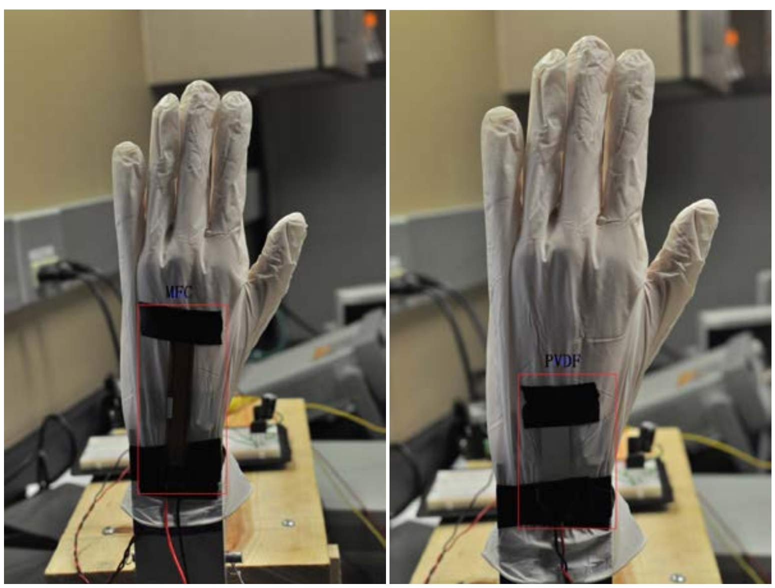


Figure 6 The experimental setup of energy harvesting



(a)MFC (b)PVDF

Figure 7 The energy harvesting glove with MFC and PVDF

4.2 Result and Analysis

As shown in Table 1, the energy harvested by MFC and FVDF is very low, it may be due to two reasons: (1) the piezoelectric materials are not tightly enough attached to the energy harvesting glove, so that not enough waste mechanical energy could be harvested. (2) Just one piece of material is not enough, we need to cover the glove with more piezoelectric materials.

Load	Voltage (mV)	Power (mW)
Open Circuit	230	N/A
3.3 KΩ	23	0.00016
14.8 KΩ	41	0.00011
38.5 KΩ	89	0.00021

(a) MFC

Load	Voltage (mV)	Power (mW)
Open Circuit	105	N/A
3.3 KΩ	10	$3*10^{-7}$
14.8 KΩ	25	0.00004
38.5 KΩ	49	0.00006

(b)PVDF

Table 1 Energy harvesting result

CHAPTER 5

SIMULATION OF TREMOR SUPPRESSION

This chapter describes the simulation of tremor suppression with adaptive control technology by using Matlab Simulink. In this simulation, we apply the active vibration control technology to suppress the tremor. The tremor signal will be considered as the “unwanted vibration”, and will be processed by the AVC system to generate a “anti-tremor” signal to suppress the tremor. In addition, since the frequency range of the tremor is different from the one of voluntary movement, the “anti-tremor” signal will not affect the voluntary signal much.

Moreover, in this paper we only conduct the simulation for the tremor suppression, instead of the real tremor suppression experiment. The reason is that the MFC actuator needs a very high operating voltage (up to 1500 V), so it is not safe, economic and convenient.

5.1 Active Vibration Algorithm

Filtered-X least-mean-square (FXLMS) is one of the most popular ANC/AVC algorithms [16]. The block program of a ANC/AVC system with FXLMS algorithm is as shown in Figure 5-1. P(z) is the primary path transfer function, S(z) is the secondary path transfer function, e(n) is the residual vibration (tremor), and the x(n) is the reference signal of the noise.

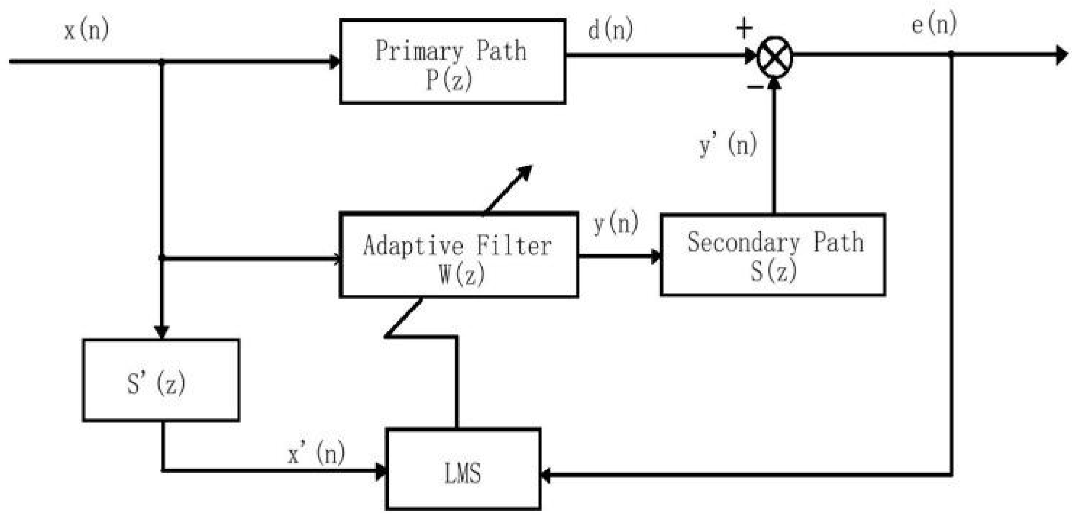


Figure 8 Block diagram of ANC/AVC system with FXLMS algorithm. [16]

The primary vibration is given as,

$$d(n) = P(n) * x(n) \tag{5-1}$$

Where, P(n) is the impulse response of the primary path, and x(n) is the reference signal vector of the vibration source, and $*$ denotes linear convolution.

The antivibration is given as,

$$y'(n) = s(n) * [w^T(n)x(n)] \tag{5-2}$$

Where, w(n) is the weight coefficient vector of adaptive filter, respectively, s(n) is the impulse response of the secondary path.

The residual vibration is given as,

$$e(n) = d(n) - s(n) * [w^T(n)x(n)] \tag{5-3}$$

And the objective function is based on the mean-square error (MSE):

$$\xi(n) = E[e^2(n)] \tag{5-4}$$

In order to minimize the mean-square error, the weight update equation should be:

$$w(n+1) = w(n) + ux'(n)e(n) \quad (5\text{-}5)$$

Where u is the step size, $x'(n)$ is the reference signal vector x(n) filtered by the estimated secondary path transfer function $s'(n)$.

5.2 Computer Simulation

The computer simulation is conducted by using Matlab Simulink with a sample frequency of 1000 Hz, a voluntary hand movement signal source is of combinations of 1Hz and 2Hz sinusoidal waves, in which the 1Hz component had amplitude of 3 and the 2Hz one had amplitude of 2. Three different sets of data are used as the tremor signal source. The diagram of the simulation model in Simulink is shown in Figure 9.

As shown in Figure 9, a high pass filter is used to distinguish the tremor signal from the voluntary movement signal, and the filtered tremor signal is used as the reference input for the adaptive control system. The movement after tremor suppression is used as the error signal for the adaptive control system in order to minimize the involuntary movement, and since the frequency of tremor signal is different from the one of voluntary movement, it will not affect the voluntary movement.

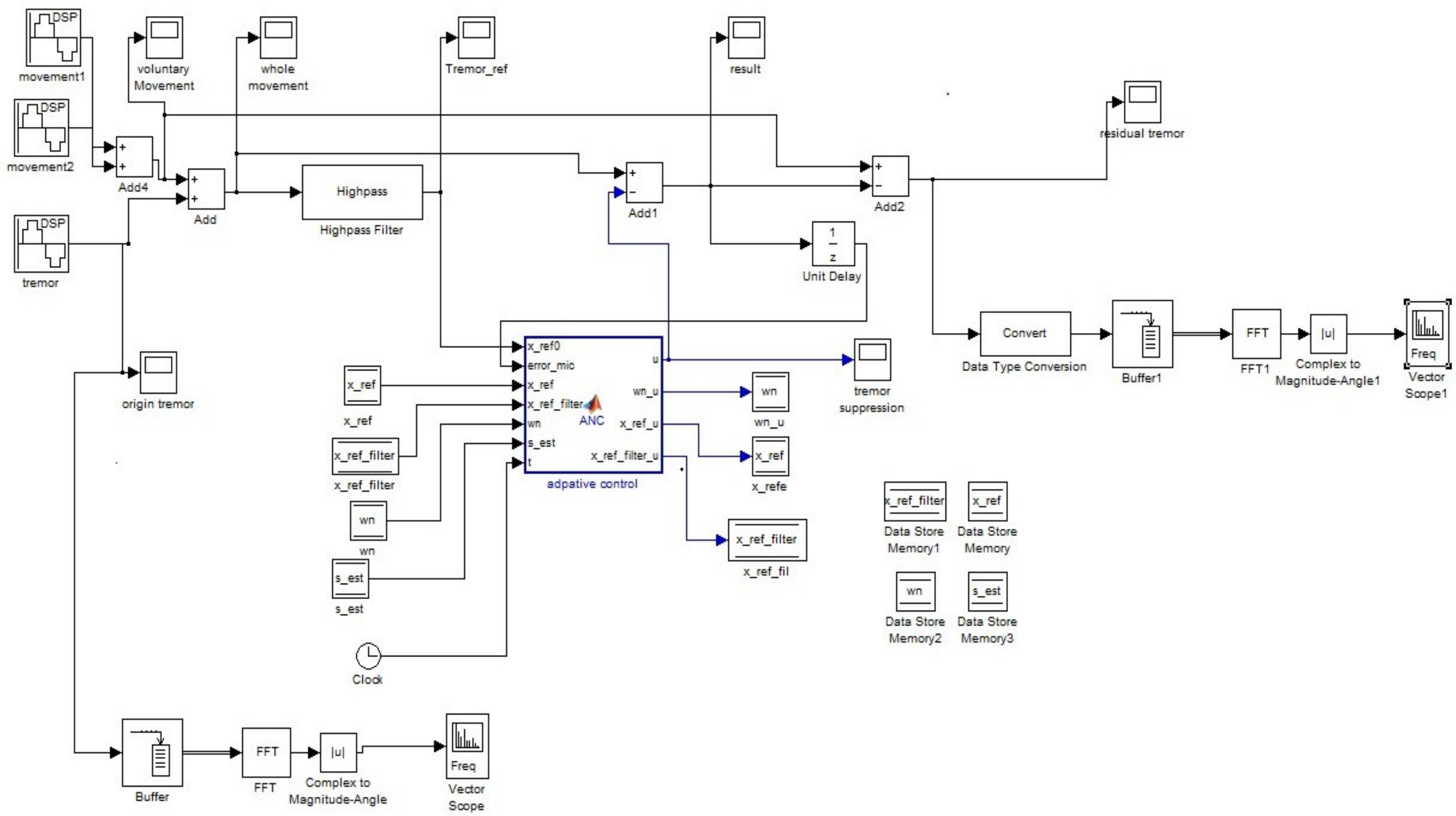
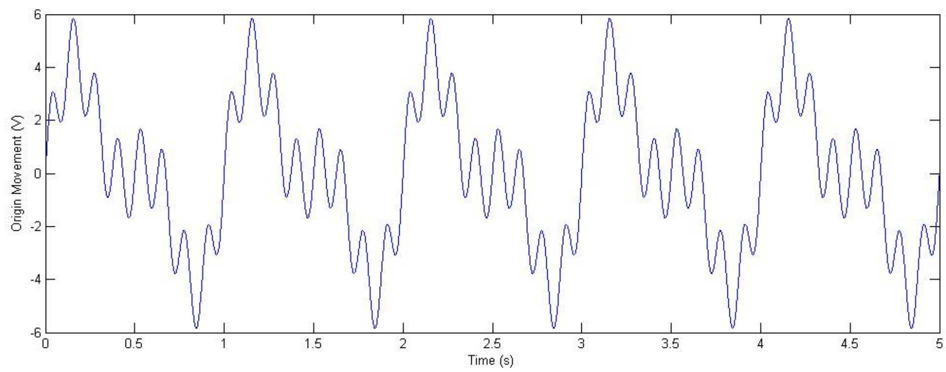


Figure 9 Diagram of the simulation model in Simulink

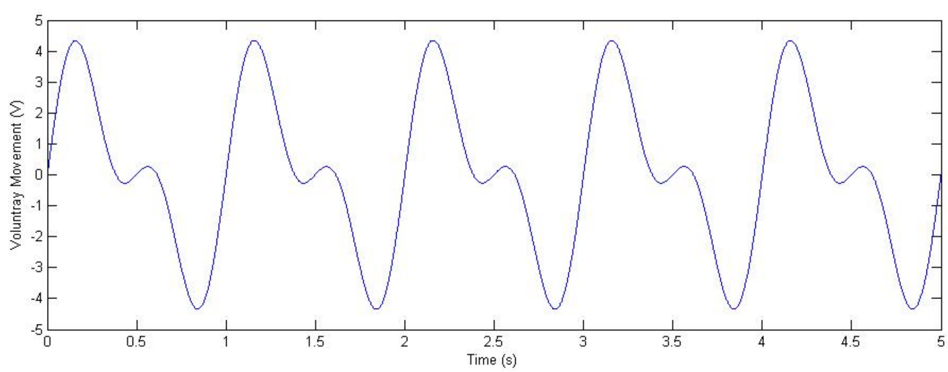
5.3 The Analysis of the Result

5.3.1 First Set of Tremor Signal

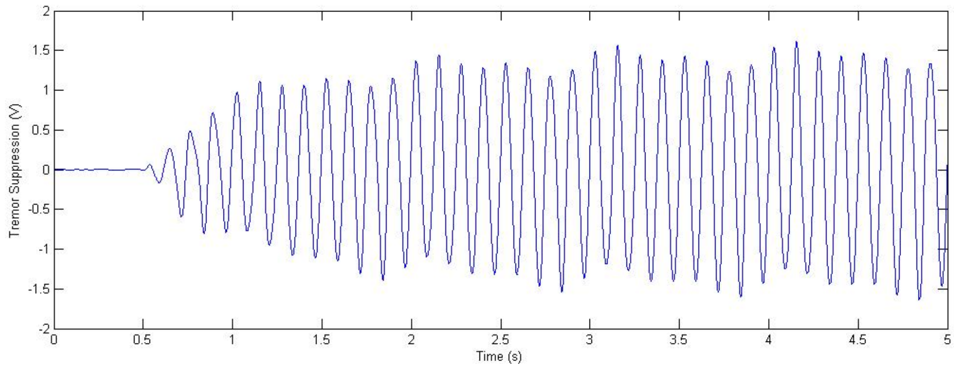
The first set of tremor signal is a 8Hz sinusoidal waves with amplitude of 1.5. As shown in Figure 10, the simulation result indicates that the adaptive control decrease the amplitude of tremor from 1.5 to less than 0.2.



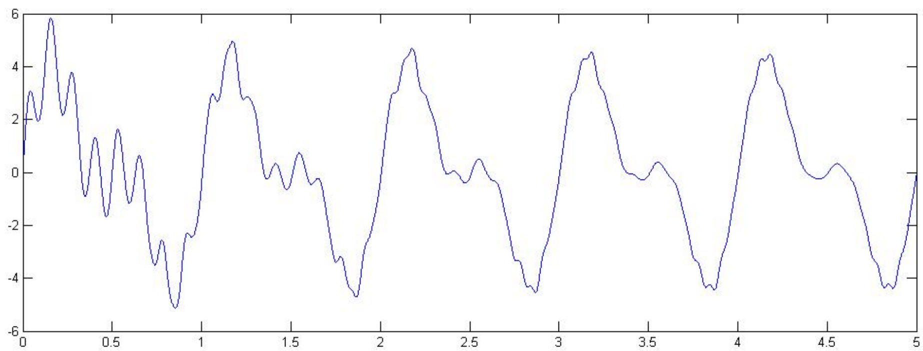
(a) The origin movement with tremor



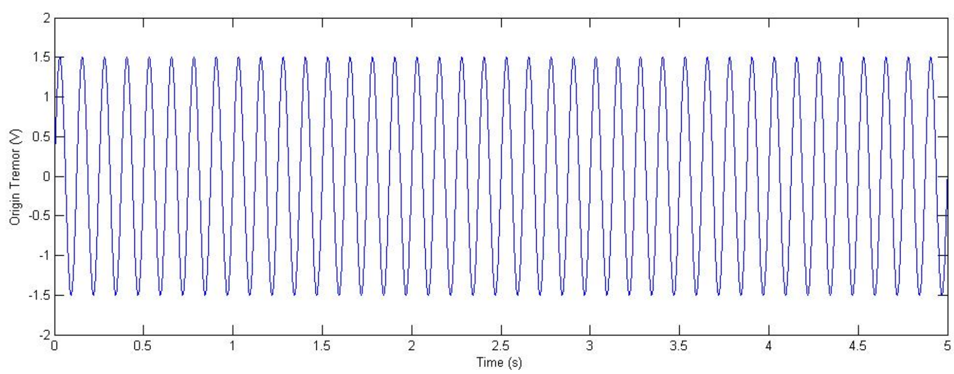
(b) The voluntary movement



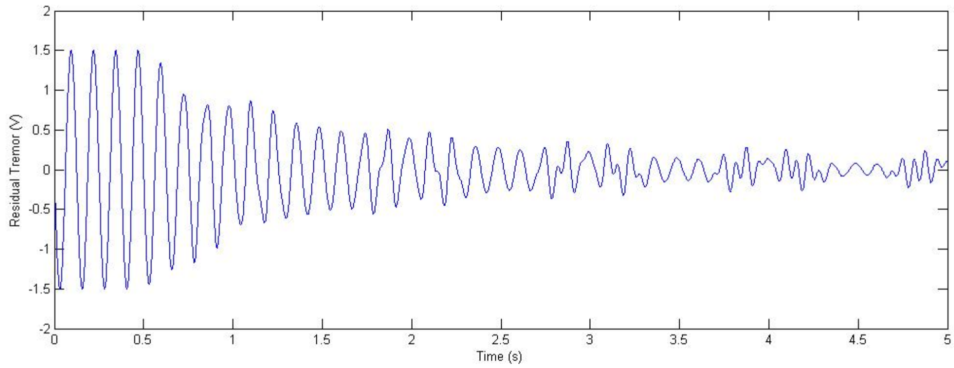
(c) The tremor suppression signal



(d) The residual movement with tremor suppression



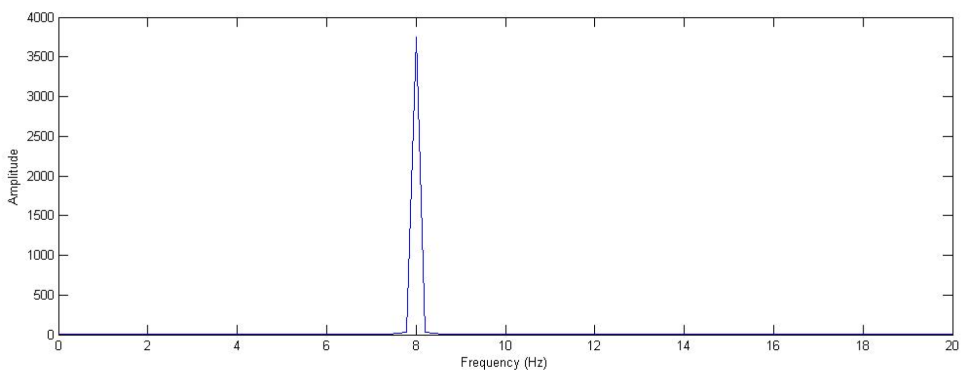
(e) The origin tremor



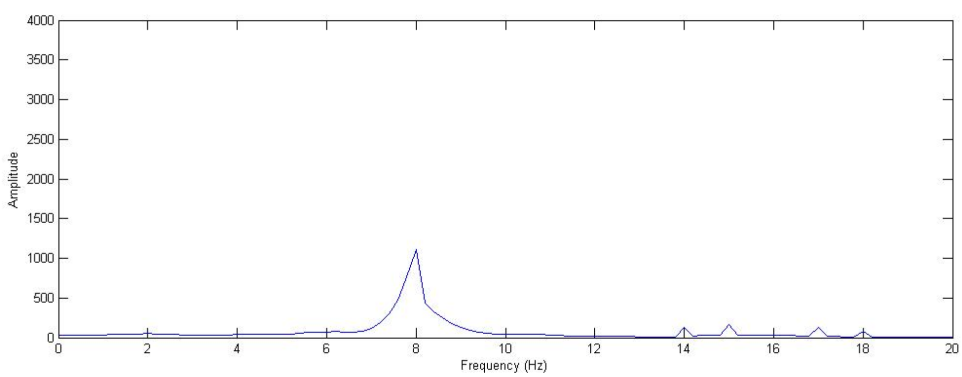
(f) The residual tremor after tremor suppression

Figure 10 The simulation result of the first set of tremor signal

The spectra of origin tremor and residual tremor are shown in Figure 11, and the 8Hz tremor is effectively depressed after the adaptive tremor suppression.



(a) The spectra of origin tremor

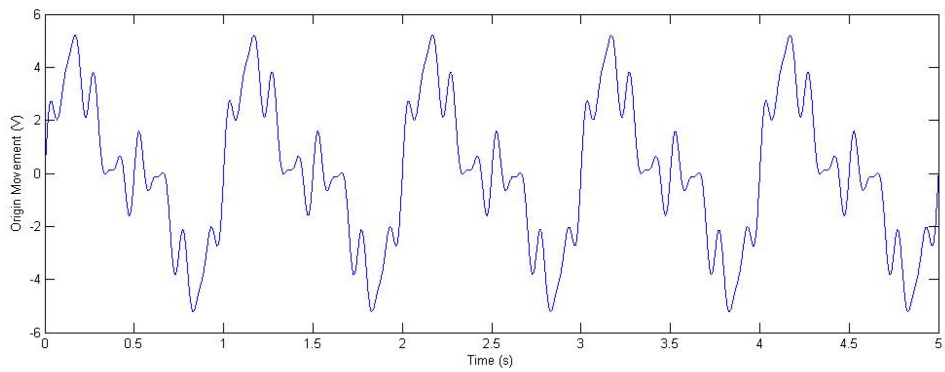


(b) The spectra of residual tremor

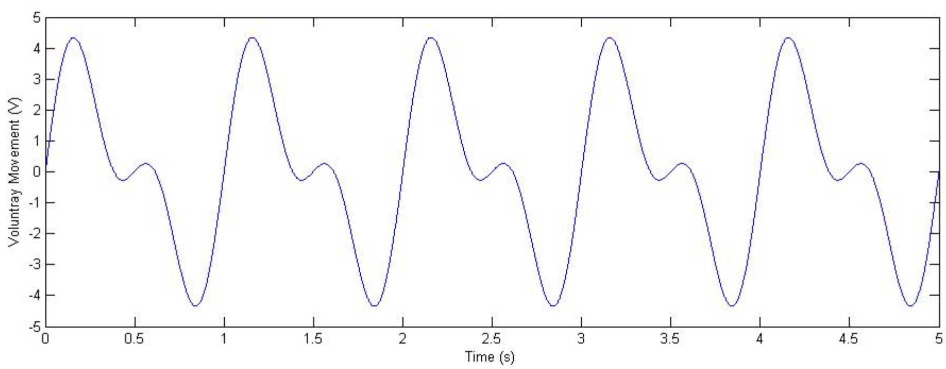
Figure 11 The comparison of the spectra in the first set

5.3.2 Second Set of Tremor Signal

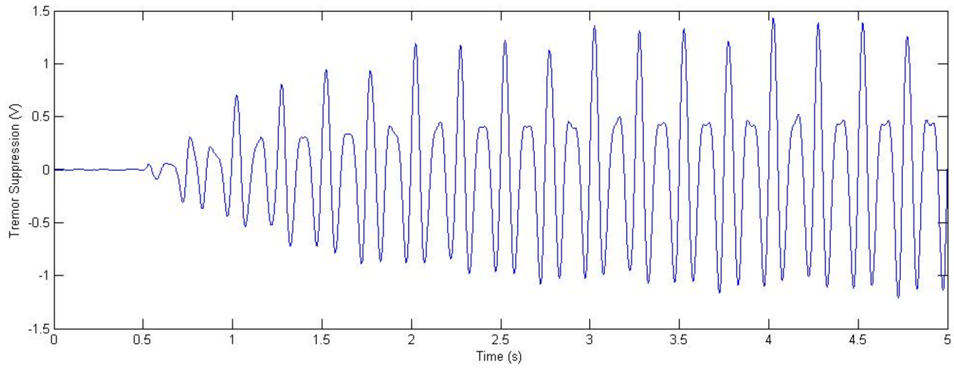
The second set of tremor signal of combinations of 8Hz and 12Hz sinusoidal waves, in which the 8Hz component had amplitude of 1 and the 12Hz one had amplitude of 0.5. As shown in Figure 12, the simulation result indicates that the adaptive control decrease the amplitude of tremor from 1.5 to less than 0.5.



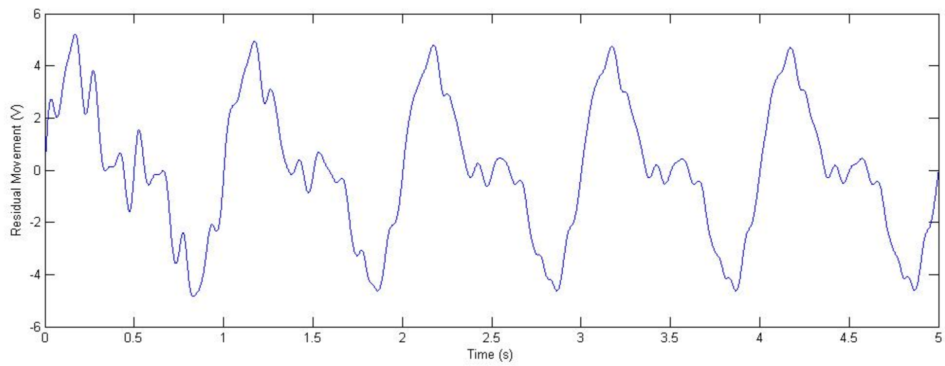
(a) The origin movement with tremor



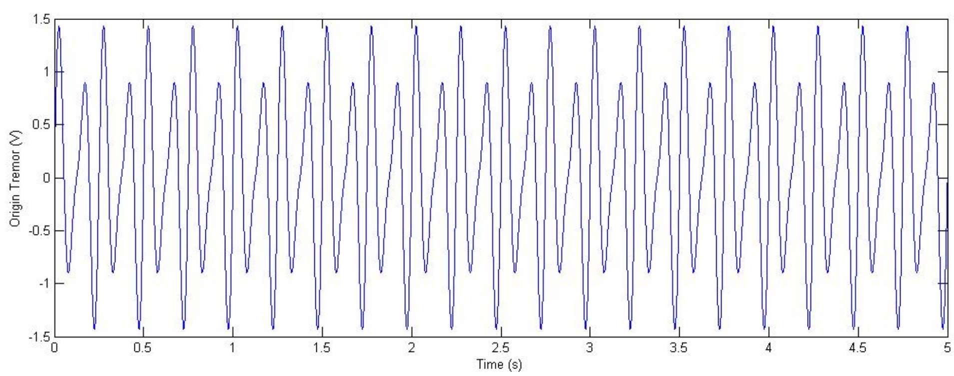
(b) The voluntary movement



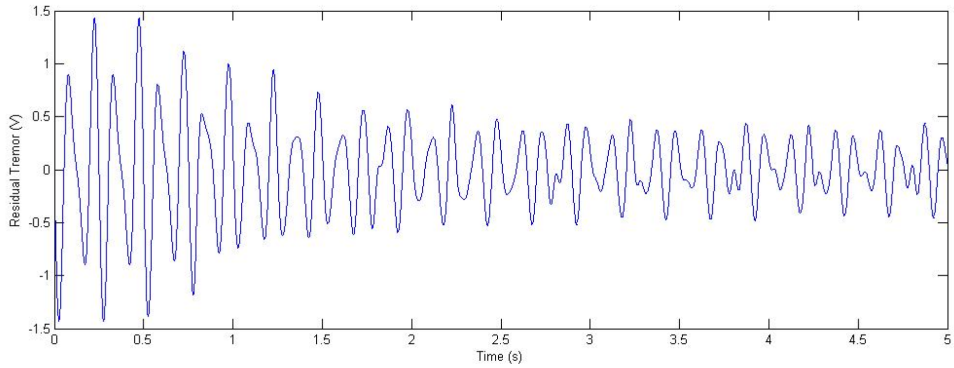
(c) The tremor suppression signal



(d)The residual movement with tremor suppression



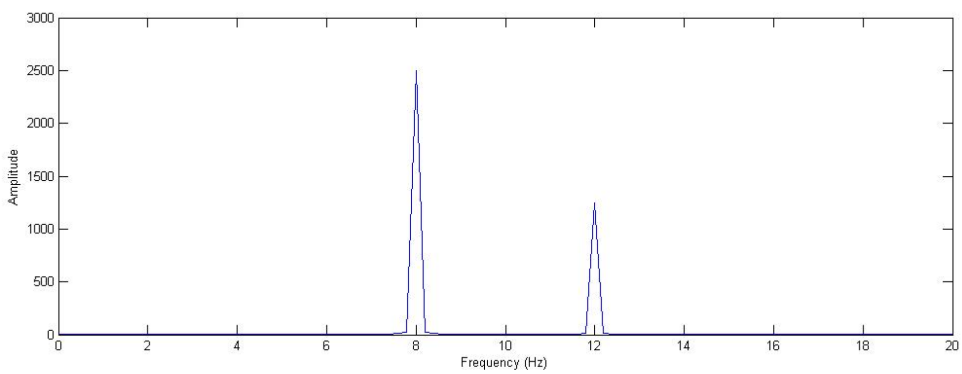
(e) The origin tremor



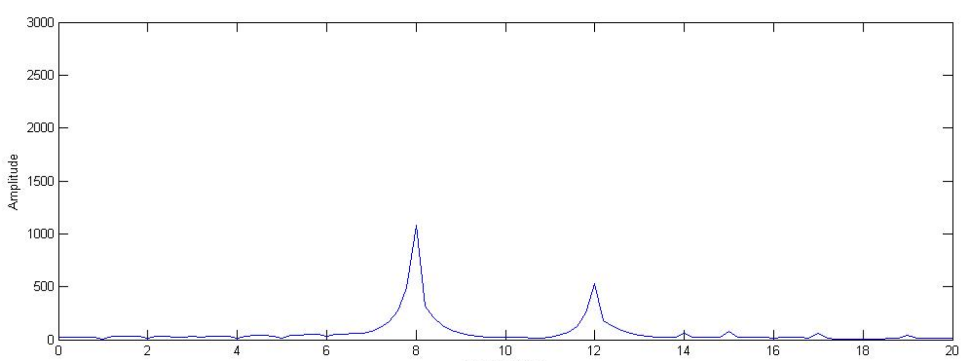
(f)The residual tremor after tremor suppression

Figure 12 The simulation result of the second set of tremor signal

The spectra of origin tremor and residual tremor are shown in Figure 13, and the 8Hz and 12 Hz tremor is effectively depressed after the adaptive tremor suppression.



(a) The spectra of origin tremor

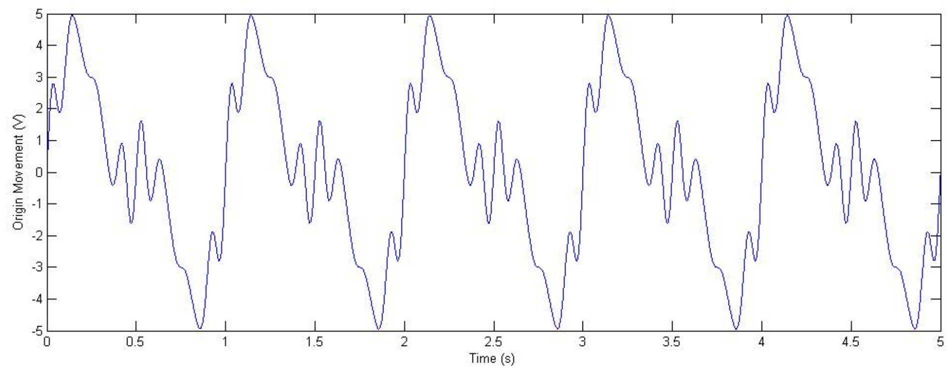


(b) The spectra of residual tremor

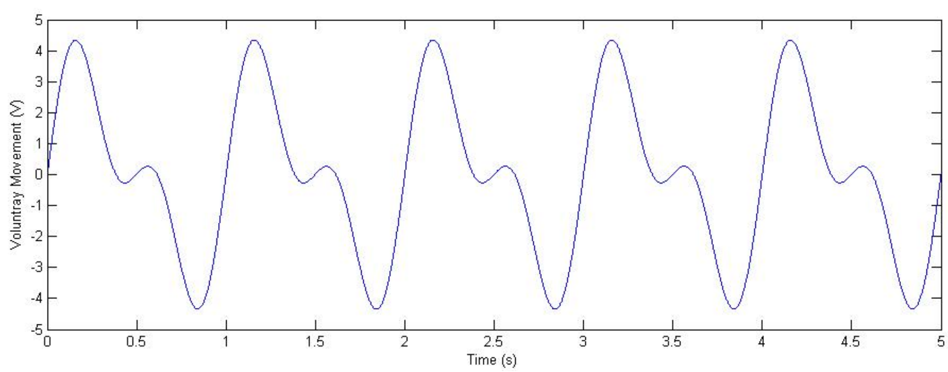
Figure 13 The comparison of the spectra in the second set

5.3.3 Third Set of Tremor Signal

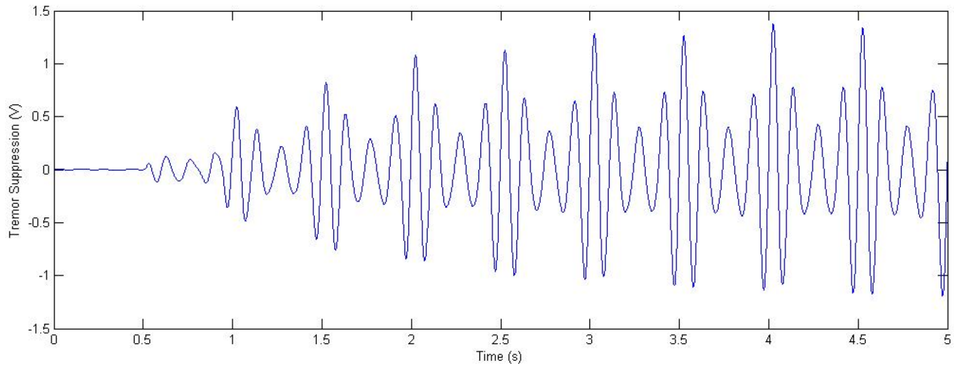
The third set of tremor signal is of combinations of 8Hz,10Hz and 12Hz sinusoidal waves, in which the 8Hz component had amplitude of 0.8, 10Hz component had amplitude of 0.5 and the 12Hz one had amplitude of 0.2. As shown in Figure 14, the simulation result indicates that the adaptive control decrease the amplitude of tremor from 1.5 to less than 0.5.



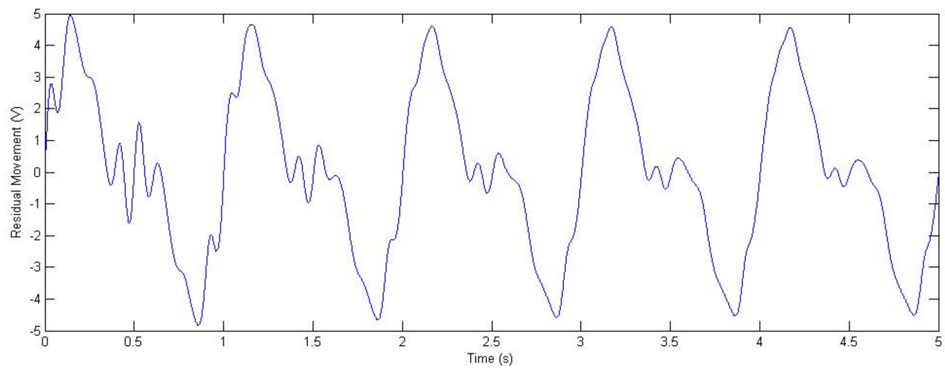
(a) The origin movement with tremor



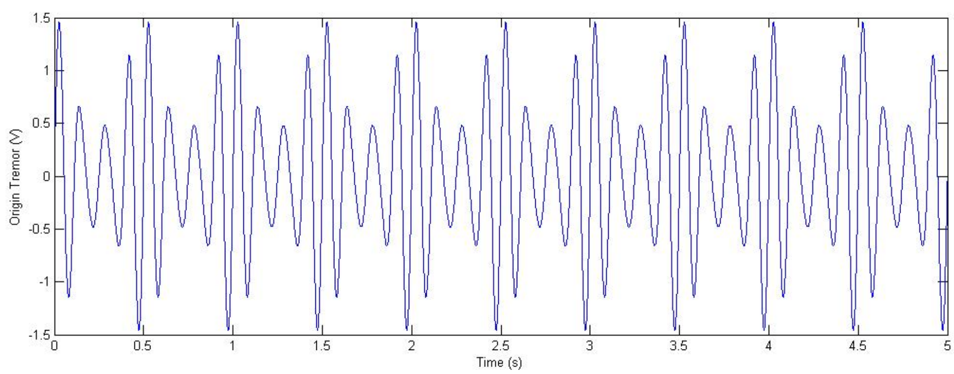
(b) The voluntary movement



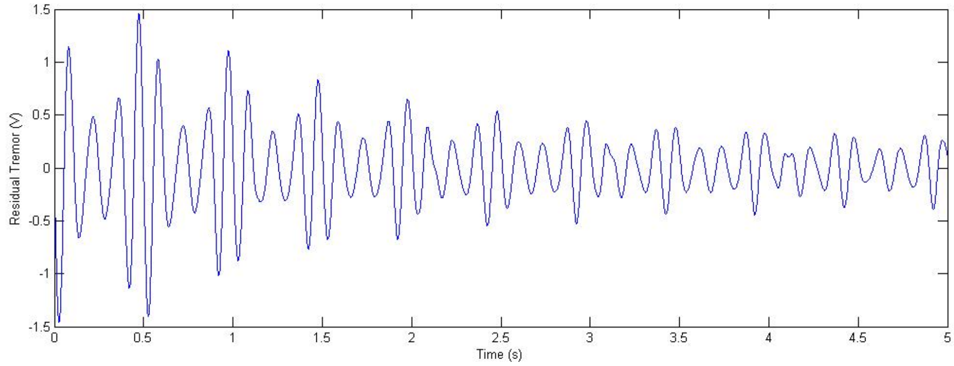
(c) The tremor suppression signal



(d)The residual movement with tremor suppression



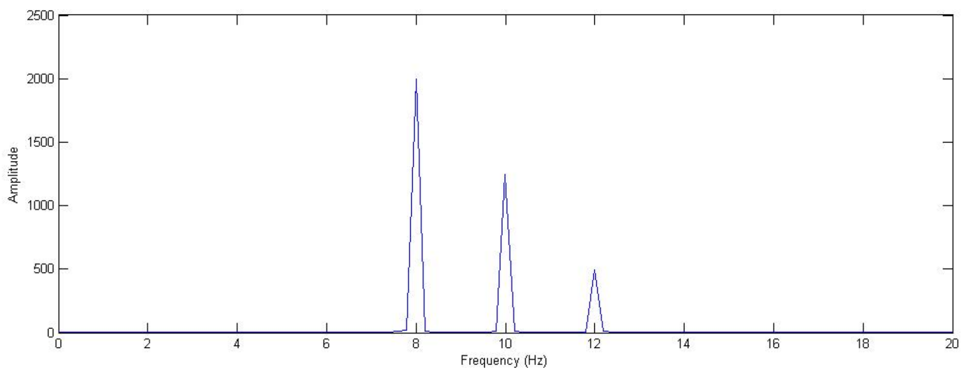
(e) The origin tremor



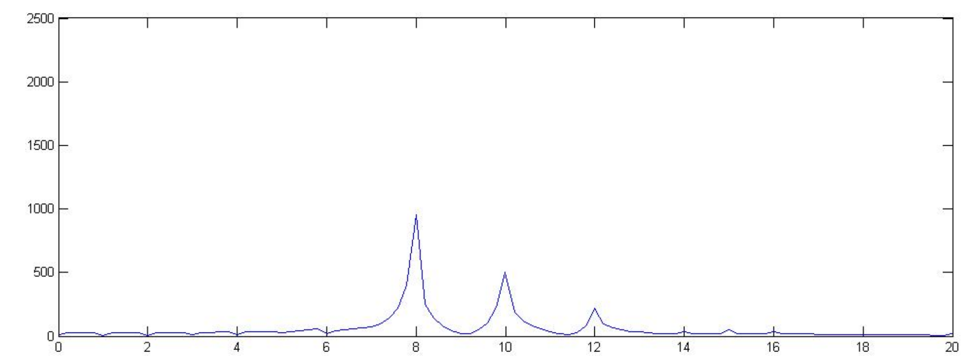
(f) The residual tremor after tremor suppression

Figure 14 The simulation result of the third set of tremor signal

The spectra of origin tremor and residual tremor are shown in Figure 15, and the tremor is effectively depressed after the adaptive tremor suppression.



(a) The spectra of origin tremor



(b) The spectra of residual tremor

Figure 15 The comparison of the spectra in the third set

According to the analysis and comparison of different kinds of tremor, we could find that the AVC algorithm works well in different condition, especially in the case of the tremor of single frequency.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

In this thesis, tremor suppression with adaptive control technology was simulated, and the result indicates that it can effectively decrease the amplitude of the tremor and does not affect much of the voluntary hand movement. The flexibility of the MFC material is useful for fabricating a tremor suppression glove, but its high operating voltage (up to 1500 V) makes it not suitable to be used as an actuator for this tremor suppression, because it is not safe, economic and convenient.

Also, we build an experimental rig to conduct the energy harvesting experiment, and it is also useful for the tremor suppression experiment in the future. The energy harvesting experiment result indicates that the voltage harvested from one piece of MFC could be up to 239mV. The harvested energy is not high enough for meaningful vibration control.

6.2 Future Work

The main reason that we fail to fabricate the tremor suppression glove is that the piezoelectric materials we use could not satisfy the requirement. If the operating voltage of the MFC decreases to an appropriate level, the glove could be manufactured with MFC. As mentioned previously, since the MFC could harvest a voltage up to 239 mV, if we cover the energy harvesting glove with more MFC materials, considerable energy might be harvested to power the vibration sensors and power for the micro controller unit.

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