Passive Hand Tremor Attenuator: Magnetic Spring

by

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Abstract

It is known that Parkinson's disease is a progressive disorder of the nervous system that has a significant impact on body movement. Symptoms of the disease begins with a barely noticeable tremor of the hands. Though Parkinson's disease is mostly recognizable by the tremors it causes on the patients, it generally leads to stiffness and reduction of movement as the time progresses. In this thesis, a novel approach is taken to reduce vibration through designing a passive wearable device with the use of magnetic actuators. In the proposed device, magnets are arranged in a particular alignment, so as to attenuate the hand tremors of the patients. The device has shown to be effective while weighing approximately 120 grams, which is a relatively lightweight device for the desired purpose.

Lay Summary

Movement disorders due to various neurological disorders are rife, and many patients with neurological disorders are suffering from hand tremors. Their daily activities and routines can be significantly affected. Despite all pharmaceutical attempts, only a few gadgets with very specific tasks are able to provide some assistance to the patients. For instance, weighted eating utensils, some exoskeletons which restrict the hand movements. In this study, a research is conducted to address the hand tremor by designing a wearable gadget to mitigate tremors using magnetic actuator. A prototype was built. The prototype was light and functional. It is the first wearable gadget that has been developed by magnetic springs without the need of any power source, but is able to function as well as those that do. The objectives in in the wearable gadget were satisfied:

- The device must be a passive mechanism;
- The device must have a universal application;
- The device must not restrict the fingers and wrist;
- The device must be lightweight;
- The device must be affordable.

Preface

All of the presented research henceforth was conducted in the University of British Columbia (UBC), in the School of Engineering under supervision of Prof. Hadi Mohammadi. All aspects of this thesis, including literature review, method, data collection and identification of the prototype was performed by the author of this thesis.

- *Mohammadi H., **Masoumi MM.** (2018). Human tremor attenuator, Potential IP (in the process of discussion with UILO)*
- ***Masoumi MM.** Han H, Mohammadi H., (2018). Human tremor attenuator, Journal of Applied Biomechanics, In preparation*

Table of Contents

List of Tables

List of Figures

List of Abbreviations

EMG: Electromyography

MMG: Mechanomyography

TLD: Tuned Liquid Dampers

DOF: Degree of freedom

SDOF: Single degree of freedom

TVA: Tuned vibration absorber

DVA: Dynamic vibration absorber

ATVA: Adjustable tuned vibration absorber

SMA: Shape memory alloy

Glossary

ζ: Damping ratio

ω_n: Natural frequency

ω: Angular velocity

E: Modulus of elasticity

I: Moment of inertia

M_1: Mass of the original system

M_2: Mass of the vibration absorber

K_2: Magnetic spring stiffness

K_1: Stiffness of the base

X_1: Amplitude of the original system

X_2: Amplitude of the vibration absorber

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I would like to express my profound gratitude to my supervisor, Prof. Hadi Mohammadi for his guidance and support before and after coming to UBC, which has led the fulfillment of this research possible. Special thanks to my committee members, Dr. Ray Taheri, and Dr. Bahman Naser, for their comments and compliments on my thesis, and for being present in my defense meeting despite their busy schedule. I am deeply grateful for the assistance provided by my family, Jalil Masoumi, Zahra Bahrololoomi, and Narjes Masoumi, for their warm encouragement and support, both spiritually and financially. It is with their support that allows me to be able to pursue my education in a vibrant environment. I would also like to extend my heartfelt thanks to Professor Mohammad Ebrahim Bahrololoom at Shiraz University. I would offer my special thanks to my friends, Wang HanChuan, Seyyed Saied Shojaeddin, Sedigheh Hosseinipanah, Seyyed Kazem Hosseini, Pouya Pejmanian, Mahdi Torabi Asr, and Erfan Taadizadeh, all of whom have provided assistance in this project.

Dedication

I dedicate this thesis to my beloved parents, Jalil Masoumi and Zahra Bahrololoomi, whose love and unselfish support laid the foundation to complete and fare well this study.

Chapter 1: Introduction

1.1 Introduction

Movement disorders are types of clinical syndromes defined by either a scarcity of involuntary and voluntary muscle movements, or by an excess of muscle movement such as seen with Parkinson's disease and the Essential Tremor disorder (Stanley, Joseph, & Mark, 2011). Both Parkinson's disease and the Essential Tremor disorder are considered the most rampant movement disorders as they include rhythmic and oscillatory involuntary movements. Tremors are the sole symptom of the Essential Tremor disorder, opposed to Parkinson's disease, which has many symptoms (Yiwen, et al., 2013). However, the symptoms of the Essential Tremor disorder can be identified in a person who is diagnosed with Parkinson's disease too which is why it is difficult to determine if the Essential Tremor disorder is present in an individual (Paula, Miguel, Adriana, & Francisco, 2014). Yet, there are some definite characteristics of both movement disorders which assist in differentiating among various tremors such as the age at onset [1] that affected body parts (Buijink, Contarino, Koelman, Speelman, & Rootselaar, 2012).

1.2 Tremor and its Classifications

The musculoskeletal system[2] is afflicted by movement disorders, which are usually classified into two general groups. Firstly, hyperkinetic movement disorders, which refer to dyskinesia (or

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[1] It is a medical term indicate the age when person develops first experience of disorder or initial symptoms of disease.
[2] providing framework, stability, and movement to the human body.

excessive), regularly repetitive, and involuntary movements. Secondly, hypokinetic movement disorders which relate to rigidity (resistance and stiffness during limb movement caused by a continuous intemperate contraction of muscles), bradykinesia (slow movement), hypokinesia (reduced amplitude of movements), and akinesia (lack of movement) (Kelly D & Lyell K, 2015). Grouped, they can be defined as a rhythmical shaking and trembling of a body part as a non-linear and non-stationary occurrence. Frequently, the movement is described as an involuntary and relatively a sinusoidal oscillatory motion (Mark S., 2005) (Giuliana & Mario, 2013) (Giuliana & Mario, 2013). Tremors are classified into two groups: resting tremors which occur when the body part is completely supported against gravity and muscles are not voluntarily active, and action tremors, which occur during voluntary muscle contraction. Both type of tremors have varying frequency and amplitude, based on the location of the occurrence in the various parts of the body. The tremor of Parkinson's disease is mostly recognized as a rest tremor[3] or pill-rolling tremor, with a frequency domain of 4 Hz to 7 Hz. On the other hand, the tremors noted in the Essential Tremor disorder are considered, to be action tremors, which have a large frequency range producing values from 4 to 12 Hz (Paula, Miguel, Adriana, & Francisco, 2014). Tremors can be classified by frequency, as frequencies of tremors lower than 4Hz, between 4 and 7 Hz, and above 7 Hz are considered as low, middle and high respectively. Type of tremors are further summarized in **Table 1-1** (Buijink, Contarino, Koelman, Speelman, & Rootselaar, 2012):

[3] Rest tremor is a reiterative back-and-forth movement of any part of body and limb, or head, jaw. Flexion–extension of the fingers are common type of tremor (Pietro, Britne, & Juan, 2012)

Table 1-1 Various Types of Tremors

Type of Tremor	**Subtype**	**Occurrence**	**Physical examination**
Rest Tremor	Rest/resting tremor	In a body part that is not voluntarily activated and completely supported against gravity.	Letting forearms rest on legs or armrest, flexed elbows, with palms in a supinated position.
Action Tremor	Postural tremor	During voluntary motion maintaining a position against gravity.	Keep arms and fingers in stretched and flexed positions.
	Simple kinetic tremor	During non-target-directed movements	E.g., finger tapping.
	Intention tremor	During visually guided movements aiming towards a target at the endpoint of a movement.	E.g., finger-to-nose test.
	Task-specific kinetic tremor	During a specific skilled task.	Specific and no-specific tasks.
	Isometric tremor[4]	During isometric muscle contraction[5].	E.g., contraction against a static object, making a fist.
	Isometric orthostatic tremor	During stance or stance phase of walking.	Standing on the feet, walking.

[4] as involuntary oscillations of one or more body parts happening in situations of isometric muscle contraction against a firm resistance, e.g. pushing the hand and arm against a hefty things. (Dennis A., Hans-Jürgen, & Jan, 2013)

[5] generating force without changing the length of the muscle

As declared in the aforementioned paragraph, the Essential Tremor disorder is a serious pandemic that affects the entirety of the world due to its presence in different societies. The rough estimated prevalence is 0.4 to 0.9% of the population which is six times higher than the prevalence of Parkinson’s disease. Moreover the tremor can emulate rhythmic myoclonus such as observed in dystonic or depressed patients who have been over-treated with plurality medications (Giuliana & Mario, 2013). The median age at onset of the Essential Tremor disorder is approximately 45 years, nevertheless there have been cases for which onset occurs during early adulthood was well as during childhood. The older an individual becomes the more visual symptoms become. Succinct information about most diseases that engender to the hand tremor are described with their respective tremor types, frequency ranges, and so forth, in **Table 1-2** (Buijink, Contarino, Koelman, Speelman, & Rootselaar, 2012)

Table 1-2 Tremor classification of Essential Tremor and Parkinson's disease

Diagnosis	Tremor type(s)	Frequency range	Accompanying features	Pathophysiology
Essential tremor	Posture intention rest	**4–12 Hz**	Additional or isolated head tremor tandem gait abnormality.	Involvement of parts of the cerebello-thalamo-cortical network.
Parkinsonian tremor	Rest posture intention	**4–9 Hz**	Bradykinesia, rigidity, postural problems.	Degeneration of dopaminergic pathways.
Enhanced physiologic tremor	Posture	**5–12 Hz**	Increases after caffeine intake, and upon stress and anxiety.	Consists of two distinct oscillations, a mechanical-reflex oscillation and a central-neurogenic oscillation.
Psychogenic tremor	Rest posture intention	**4–12 Hz**	Entrainment, increase in tremor amplitude with loading, inconsistent over time.	Unknown.
Cortical myoclonic tremor	Posture intention	**6–20 Hz**	(Family) history of epileptic seizures.	GABAA-ergic dysfunction within the cerebral cortex.
Toxic and drug-induced tremor	Posture intention rest	**3–12 Hz**	Medication/drug use, exposure to heavy metals, symptoms of metabolic disorders.	Various mechanisms.
Cerebellar tremor	Intention	**2–5 Hz**	Occurs during specific task (i.e., writing).	May be related to essential tremor or dystonia (writer's cramp).

Another classification of tremors has been done by Grimaldi G. and Manto M. in which the prominence of daily activities that are accompanied by tremors are summarized in **Table 1-3** below, following, their brief definitions.

Physiologic tremor is an involuntary rhythmical oscillation of upper limb segments, commonly in the frequency range of 8-12 Hz. This type of tremor often occurs with small amplitudes in healthy people, and is hardly noticeable with the naked eye.

Enhanced Physiologic Tremor is a distinct high frequency postural tremor affiliated with caffeine intake, drug administration, and muscle fatigue.

Rest tremor occurs while the limb is at rest and vanishes upon limb action. It typically begins asymmetrically at a distal location in the arm, between the frequency range of 3-6 Hz. Rest tremors in the upper body segments appear as though there is a "pill-rolling" motion in the hands.

Postural tremors are defined by tremors that occur in postural positions for which a frequency range of 4-12 Hz is standard. This type of tremor emerges immediately and is followed by an amplitude increase that occurs after only a few moments, situated in the line of gravity. Postural tremors are a form of tremors particular to Cerebellar[6] diseases, described as follows:

(1) Precision tremors have a frequency range of 2-5 Hz and occur during the execution of precision activities associated with the extremities and distal musculature.

(2) Asthenic (suffering from asthenia[7]) tremors are triggered by fatigue.

(3) Axial postural tremors.

(4) Midbrain tremors.

Kinetic tremors are induced during the execution of a body motion. The motion is typically maximum at the tip of limbs and possesses a standard frequency domain of 2-7 Hz. Kinetic tremors are intended to principally involve the proximal musculature and in general it is noticed that

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[6] The cerebellum is one of the areas in the brain controlling coordination and balance. Disease and problems are emanate from the cerebellum include: cancers, genetic disorders, failure of muscle control in the arms and legs that result in movement disorders- ataxias.

[7] abnormal physical weakness or lack of energy

oscillations are, in general, perpendicular to the intended motion. This type of tremor is brought more severe due to the addition of inertia.

Cerebellar tremors stem from cerebellar disorders. They are predominately composed of a combination of low frequency oscillations and are often paired with a kinetic component, usually connected to an attendant postural tremor. Specifically action tremors are commonly seen in cerebellar disorders.

Isometric tremors transpire when a voluntary muscle contraction occurs against a stationary object.

Orthostatic tremors are a high frequency tremors (with a standard frequency range of 13-18 Hz) often occurring in the legs and trunk that appears when standing or during isometric contraction of the limb muscles.

Dystonic tremors are primarily a postural, however at instances, kinetic tremors which occur in a body part that is affected by dystonia[8]. The frequency of dystonic tremors is usually irregular, however fluctuates between 4 to 9 Hz with an unsteady amplitude. The affects are generally localized and asymmetrical, though trembling can spread to other body and potentially the entire body. *Dystonic tremors* appreciate by goal-directed movements and after a couple of years may develop into genuine dystonia, becoming a source of diagnostic difficulty. The most abundant form of task-specific tremor is the primary writing tremor, which occurs while writing. Many authors ponder that the primary writing tremor is a type of dystonic tremor.

Midbrain tremors (also referred to Holmes tremor) are distinguished by a combination of rest, postural, and kinetic tremors with a frequency range of 2-5 Hz.

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[8] A neurological movement disorder in which a person's muscles contract uncontrollably, repetitive movement and twisting motion.

Thalamic[9] *tremors* are postural and the kinetic tremors (with potential additional, dystonic features) developing more than a month after a thalamic lesion involving posterior nuclei.

Rhythmic cortical myoclonus (also known as cortical tremors) are defined as action tremors that are likely with myoclonus and seizures.

Palatal tremors (also called palatal myoclonus) are categorized into symptomatic or essential tremors. Symptomatic palatal tremors are attributed with a rhythmic contraction of the Levator Veli Palatini muscle and are typically unilateral. In addition, this form of palatal tremor likely remains active while asleep. Comparatively, essential palatal tremors are bilateral and are due to contractions of the tensor Veli Palatine muscle (which is close to Eustachian tube). Due to the location of the contraction, patients will likely discern an ear click.

Psychogenic tremors have a frequency between 4 to 11 Hz and are characterized by a sudden onset with frequent remissions.

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[9] pertaining to the thalamus

Table 1-3 Definition of Tremor

Tremor type	*Amplitude*	*Frequency (Hz)*	*Distribution*	*Precipitants*
Physiologic tremor	Small, barely seen with the naked eye	**8-12**	Proximal and distal	–
Enhanced physiologic tremor	Visible – mild	**8-12**	Proximal and distal	Any posture
Rest tremor	Mild to severe	**3-6**	Distal/asymmetrical	Rest Mental Activities
Postural tremor	Mild to severe	**4-12**	Proximal and distal	Any posture
Kinetic Tremor	Mild to severe	**2-7**	Proximal≥ Distal	Execution of a movement
Isometric Tremor	Mild to severe	**Variable**	Body region in isometric contraction	Isometric muscle contraction
Asthenic cerebellar tremor *	Mild to severe	**Irregular**	Proximal and distal	Fatigue and weakness
Precision cerebellar tremor*	Mild to severe	**2-5**	Distal	Accurate placements
Cerebellar axial postural tremor*	Mild to severe	**2-10**	Proximal≥ Distal	Any posture
Cerebellar proximal exertional tremor*	Mild to severe	**3-4**	Proximal≥ Distal	Prolonged exercise
Rest postural and kinetic**	Mild to severe	**2-5**	Proximal≥ Distal	Any posture
Isometric Tremor***	Mild to severe	**13-18**	Legs and trunk	Isometric contraction of the limb muscles
Postural and Kinetic****	Unsteady	**4-9**	Asymmetrical	May increase with movement

*Postural tremor in cerebellar diseases, **Midbrain tremor, *** Orthostatic tremor, ****Dystonic tremor

1.3 Muscular Compartment of Upper Limb, Flexor and Extensor Muscles

Two groups of muscles aid in arm movement: flexors and extensors. The cross sections below in **Figure 1.1** distinctly illustrate these two groups of muscles in the arm.

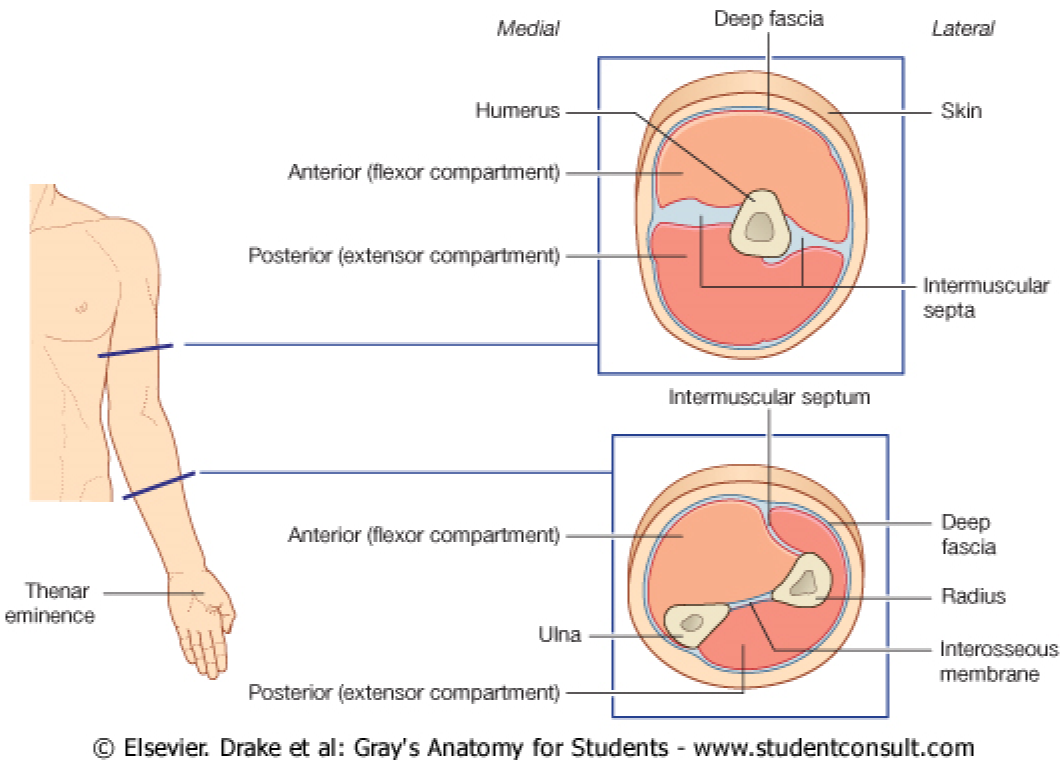

Figure 1.1 Cross Section of Upper Limb (Loukas, R. Shane, Peter, & Stephen, 2015)

The muscles in the arm are primarily used for the motions of the forearm at the elbow joint, whereas the muscles in the forearm are mainly used to move the human hand at the wrist joint in addition to the fingers and the thumb (Loukas, R. Shane, Peter, & Stephen, 2015). The muscles of the anterior (flexor) component of the arm are: the biceps brachii[10], the brachialis, and the coracobrachialis. The muscles of the anterior (flexor) component of the forearm are organized in three layers: (Gerard & Bryan, 2013)

A) The superficial layer composed of the flexor carpi radialis, the palmaris longus, the pronator teres and the flexor carpi ulnaris;

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[10] biceps two heads of origin; brachii arm)

B) The middle layer composed of the flexor digitorum superficialis muscle (which is deeper than the other three layers and is the largest superficial muscle in the forearm);
C) And the deep layer composed of the flexor pollicis (thumb) longus, the flexor digitorum profundus and the pronator quadratus.

Additionally, the contents of the Extensor component of the arm is the Triceps brachii (Gerard & Bryan, 2013) and the the posterior (extensor) component of the forearm is separated into two layers:

A) The superficial layer which is composed of the brachioradialis, the extensor carpi radialis longus, the extensor carpi radialis brevis, the extensor digitorum, the extensor digiti minimi, the extensor carpi ulnaris and the anconeus muscle;
B) And deep layer which is composed of the supinator, the abductor pollicis longus, the extensor pollicis brevis, the extensor pollicis longus and the extensor indicis muscle (Susan, 2015).

The intrinsic muscles of the hand are:

A) The palmaris brevis;
B) The palmar interosseous;
C) The dorsal interosseous;
D) The adductor pollicis;
E) The thenar muscles which consist of the opponens pollicis, the abductor pollicis brevis and the flexor pollicis brevis. These muscles act on the thumb and the thenar eminence [act on

the first Mcp joint] and provides free movement of the thumb in comparison with other fingers;

F) The hypothenar muscles (the medial aspect of the palm) which include the abductor digiti minimi, the flexor digiti minim brevis, and the opponens digiti minimi;

G) And the lumbrical muscles.

Neurologists' findings lend growing support for the claim that the flexor muscles are naturally stronger than the extensor muscles, aiding in the reasoning why nuances of the medial (inward) movement of arms among patients' causes hand tremors. However, most tremors are generated by larger muscles in the upper arm and forearm, with only negligible tremors developed in thenar. This implicit assumption is taken as the premise of this study.

1.4 Source of Tremor and Its Propagation in Hand

There is the possibility that tremors are generated due to elaborate interactions between the central and the peripheral nervous system. A multitude of structures are involved in tremorogenesis such as spinal cord, certain components at the supra-spinal level, including, the basal ganglia, the brainstem, the cerebral cortex, and additionally the cerebellum. All of the previous are contemplated as a foremost site of tremorogenesis due to the fact that rest tremors originates from the basal ganglia loop, whereas muscles and joints are obeying the laws of physics.

There are three general points in this case worth highlighting, the first of which being that tremors can be the result of the impaired function throughout all parts of the nervous system, including the basal ganglia (Parkinson's disease rest tremor), the brain stem, the spinal cord and so on. The second stating that sundry groups of neurons including tremors transpire to assorted rhythmic oscillations in the brain. Lastly, rarely has the unique center of a tremor been observed to describe the speed, rhythm, and amplitude of a tremor, which also rely on the tension of the involved muscles. (Giuliana & Mario, 2013) Simply, the origin of tremors has been studied for a long time from a pathological viewpoint, providing confirmatory evidence that the origin of tremors is staggeringly unknown (Dingguo, Philippe, Ferdinan, & Wei, 2011). As a result, by taking a neutral position, it is very hard to understand the contribution hand muscles provide during a hand tremor as many researchers' views are grounded on the overwhelming evidence that all involuntary muscle are involved.

1.5 Measurement Means of Arm Muscles Behaviors

Voluntary muscles, are also referred as skeletal muscles, are muscles fastened to bone that possess the major function of contracting (i.e. flexion or extension) to ease the movement and locomotion of bones. Voluntary muscles in the arm that embrace the upper and lower arm such as the biceps and triceps are afflicted by hand tremor. Two methods are often implemented to recognize tremors, electromyography (EMG), and mechanomyography (MMG).

1.5.1 Electromyography

First, electromyography (EMG) which reveals the electrical activities of skeletal muscles is useful to measure the electrical potential of muscle cells, however is unable to provide information relating to the mechanical behavior of muscle contraction.

1.5.2 Mechnomyopraphy

Second, mechanomyography (MMG) usefully accesses the activities of skeletal muscles by measuring the vibrations of the contracting muscles, however is in less demand among professionals. MMG functions by recognizing a correlation between the surface spatial propagation and the acceleration of the motor unit which is deduced from the theory of wave propagation and muscle anatomy. Additionally, has the ability to determine mechanical properties of skeletal muscles (i.e. assessment of vibration, stiffness, and contractile properties), muscle force, the types of muscle fibers present the muscle fibers that are active during contraction, muscle fatigue, degenerative changes in skeletal muscles, and with the assistance of a microphone and stethoscope the sound of muscle contraction which has been corroborated to be inherent feature of muscle contraction. The majority of prior studies are centralized on human's biceps brachii and triceps brachii with the approximate frequency spectrum of 2 to 120 Hz (Jaroslaw, Anna, Katarzyna, Guang H., & Artur, 2014) (Morufu, Nur, Jorge M., & Ahmad Khairi, 2014) The amplitude and average of the frequency contingent on muscle active stiffness change under different conditions. A study demonstrated that MMG clarifies the recognition of the age of onset of Parkinson's as the MMG of skeletal muscles of people with Parkinson's disease are likely subject to a lower average frequency and a greater amplitude in comparison with the healthy (Jarosław, et al., 2009).

Chapter 2: Mechanical View on Hand Tremor

2.1 Introduction:

The soft and hard tissues of the human body have the ability to withstand a certain degree of vibration, however exceedingly high vibrational frequencies and prolonged vibration at resonant frequencies are detrimental to the body. Excessive vibration can lead to organ failure, tissue malfunction, tissue degenerations, and considerable amount of discomfort (Sarah & Mohamad, Parkinson's Disease Treatment as Seen from a Mechanical Point of View, 2016). Due to the lack of diagnostic tools (hindering the medical process) and medicine processing an efficiency of only roughly 50%, it is difficult to accurately identify patients with hand tremors.

In fact, these factors end up yielding a tremor identification accuracy of only between 50 to 70%. In the case of a severe tremor, it may be erroneously diagnosed as other disorders as its large amplitude can appear similar to the observed repetitive movements of other disorders, such as seen in Parkinson's disease patients that are prescribed with levodopa[11] (Giuliana & Mario, 2013). Very few effective treatments for tremors have been recorded, especially in patients who are diagnosed with amplitude the Essential Tremor disorder in which the amplitude of the tremors interfere with most of the basic gestures of daily life, leading to social inconvenience. (Giuliana & Mario, 2013) (Buijink, Contarino, Koelman, Speelman, & Rootselaar, 2012). Despite all of the attempts to reduce tremors through medical treatments and surgical intervention, negative side-effects occur in most cases. This leads to the conclusion that, biomechanical engineering is a discipline that has potential to limit tremors with the implementation of non-invasive techniques. The simplest means

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[11] one of the major drugs which is used to treat Parkinson's disease.

to dampen tremors is by adding a particular mass on the limb as a form of inertial load; this is a technique known as biomechanical loading. Biomechanical loading consists of studying the external forces and voluntary muscle contraction in the tremored hand. The results of inertial loads on a hand tremor was first recorded in 1974 and since then, more sophisticated means to resolve tremors have been designed, such as exoskeleton orthosis and various wearable gadgets. (Eduardo, Juan A´, Juan Manuel, Julia´n, & Jose´, 2012). All prior research and studies have led to further progress in the study of musculoskeletal models, which not only play a critical role in learning the behavioral characteristic of the skeletal system, muscle coordination, and movement, but also in the field of tremor disorders.

2.2 Musculoskeletal Models and Dynamics of Human Arm

Musculoskeletal models are a form of simulating hard and soft tissues that are used to estimate the amount of force a mechanism undergoes during body movement (Daniel & Anthony, 2015). Modelling is split into two categories which are determined by the scale of the structure. The first category consists of structures that are microscopic in scale for which the focus is placed on comprehensive physiological details. One of the typical microscopic models is the Huxley-type model. The second category consists of structures that are macroscopic in scale which focuses on more generalized features that are increasingly tractable and far simpler than those seen in the microscopic scale. The most commonly used macroscopic model is the Hill-type muscle model which has the appealing feature of “scaling”. The Hill-type muscular model, which was further improved into the Zajac muscle model, is able to achieve behavior similar to that of various muscles. Though precision is sacrificed, the benefit of having such simplicity for the representation of complex muscle mechanics is deemed worthy. (Giuliana & Mario, 2013) As tremors are notably more associated with the upper limbs, wrist-joint skeletal models of the wrist joint and elbow are focused on heavily by many of the latest studies.

Human upper limbs are part of a complicated dynamic system, and the understanding of their kinesiology (also referred to as dynamics) is necessary before a functional control strategy can be executed. In terms of the dynamic viewpoints of the upper extremities, every degree of freedom (DOF) is actuated by more than two driving elements (muscles). For instance, five muscles take part in elbow flexion: the biceps brachii, the brachialis, the brachioradialis, the pronator teres and the extensor carpi radialis longus. (Hashemi & Golnaraghi, 2004). A study has been done by P. Yao et al, 2012, in which the wrist joint is studied as one of the most involved joints in upper limb tremors (Peng, Dingguo, & Mitsuhiro, 2012). The reason that such intensive studies are conducted for the wrist joint is because it is one of the most both flexible and tremulous joints in the human body (suggesting that flexion-extension and abduction-adduction actions are easy), and wrist motion is pivotal for upper limb function (Sarah & Mohamad, Parkinson's Disease Treatment as Seen from a Mechanical Point of View, 2016) (Peng, Dingguo, & Mitsuhiro, 2012).

Recent studies on passive wearable gadgets highlights the utmost importance of passive vibration absorbers. As a myriad of active vibration absorbers have been developed to address a specific issue caused by tremors, they are usually not applicable for uses other than their intended design. A research paper by Hashemi et al. detailed the two DOF dynamic model of the upper limb with mass concentrated at the centroid, intarsia and planar. Currently, most studies rely on sinusoidal motion in order to estimate tremor and mechanical smoothing (Mark S., 2005) (Hashemi & Golnaraghi, 2004); however, real tremors are more complex than the implemented harmonic motion (excluding tremors at the wrist joint) as the hand is assumed to be a uniform rod. The tuned vibration absorber design by Hashemi et al consists of one passive DOF pendulum that is able to mitigate rest tremors in the elbow and shoulder. (Hashemi & Golnaraghi, 2004). In another study, they considered the possibility of two and three DOF systems and H_2 optimization criterion. (Mostafa, Mojtaba, Farzam, & Ahmad F., 2014). Therefore, all prior studies carried out on planar three DOF systems with hard tissues (such as bones) and soft tissues are modelled as rigid bodies are also modelled with frictionless joints with either centers of rotation or fixed axes. Since hand tremors have a range of driving frequencies, multi vibration absorbers are needed (Sarah & Mohamad, Parkinson’s Disease Treatment as Seen from a Mechanical Point of View, 2016). By some means, all discussed vibration absorbers are able to recognize and suppress the hand’s tremor.

2.3 Comparison of Wearable Gadgets and Devices

In this section, selected analogous devices, with respect to the aims and scope of this study (i.e. passive devices), will be compared to the bracelet developed under the supervision of Prof. Hadi Mohammadi. All listed devices will have the appearance of a wearable gadget, excluding bulky exoskeleton orthoses on either the hand or wrist, and also any devices designed to facilitate factors other than motion or damping in order to constrain the motion of the tremor. Certain gadgets using recent technological advances have been developed, such as the Lifeware Spoon, which was bought and commercialized by Google (BBC, 2014) and Microsoft’s smart wristband, a watch-like device claiming to withstand tremor in Parkinsonian hands (McGoogan, 2017).

2.3.1 Method for Treating Tremors-Patent (US 6361549 B1)

The concept behind this cuff-like design is to suppress the tremor by applying pressure on the extremities. It is claimed that it is effective for all people with both Parkinson's disease and the

Essential Tremor disorder. The amount and duration of pressure is to be determined through experience, experiment and observation. Specific locations have not been defined, but it is suggested to place one of the cuffs above or below the elbow, and the other on the wrist. Other locations may be effective, however, are not stated.

Problems with this invention include, the empirical-based procedure, and that applying large amount of pressure on the extremities would not be viable for the enfeebled or the elderly. The schematic is illustrated in the **Figure 2.1** (US Patent No. US 6361549 B1, 2002).

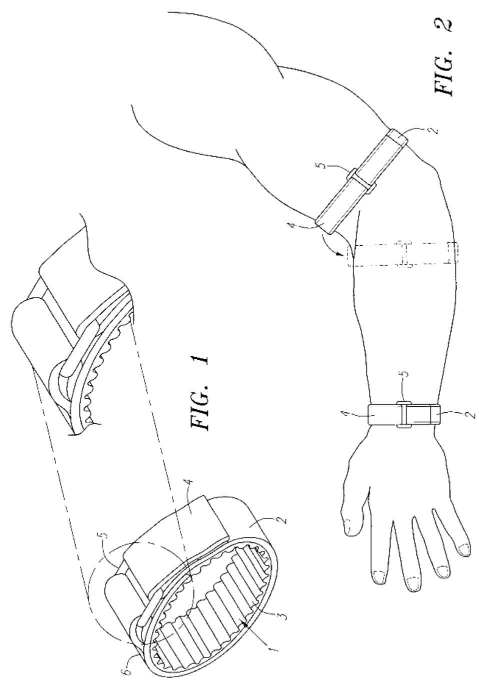

Figure 2.1 Patent, 2002, US 6361549 B1

2.3.2 Readi-Steadi® Anti-Tremor Orthotic Glove System and KSA Childrens Weighted Hand Splint

These are gloves equipped with weights that are worn by the patients. Unlike other commercialized weighted eating utensils, they are not task specific. Though both revolve around the concept of adding weight to the patients' hands, the gloves are designed in a way that the amount of weight can be modified to the desire amount determined through trial and error. These are claimed to be convenient and low-maintenance.

Figure 2.2 KSA Children Weighted Hand Splint

Figure 2.3 Readi-Steadi

2.3.3 Weighted Bracelet For Fine-Motor Activity (US 20080072622 A1)

Promoting fine-motor[12] functions, this fairly heavy bracelet has magnetic beads embedded among embroideries which fasten around the hand (see **Figure 2.4**). The concept of this invention is to

[12] It is the coordination of muscles, especially small muscles, in movements.

disguise weights as a bracelet while appearing aesthetically pleasing (US Patent No. US20080072622 A1, 2008).

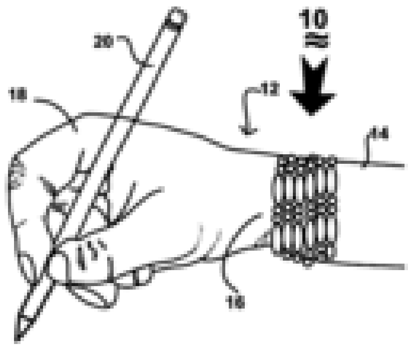

Figure 2.4 Patent, 2008, US 20080072622 A1

2.4 Research Motivation

The question of the feasibility of implementation other means and materials to mitigate hand tremors in a passive manner rather than using inertial mass is raised in all previous studies, research, and attempts. Various types of materials that are non-toxic or are regarded as rare materials will be considered. Among all available materials inertial mass, liquid and magnets were chosen for this design, as these materials are able to reduce tremors by possessing damping properties. Designs based on the selected materials were then developed; however, designs must be proven through scientific means and characterized by their mechanical damping properties. To accommodate the previous, these designs went through multiple experiments as a "Proof of Concept", before the design with the best damping capability was selected. Without adequate experiments, it would be impossible for the design to be developed into a passive wearable gadget.

2.5 Research Objectives

In this study, data is collected in order to design a high efficiency, innovative, passive and wearable gadget that dampens vibration. In order for the gadget to be wearable on the wrist, some limitations must be addressed. The dimensions and the weight of the gadget must be within a reasonable range for the elderly and it must also be able to function in all orientation, during rotation, and during movement of the hand.

2.6 Thesis Outline

This thesis is organized into 6 chapters:

A. In chapter one, general information and the classifications of tremors is provided, including the definition of tremor from a medical viewpoint.

B. In chapter two, previous studies and research from a mechanical viewpoint, and previous inventions are discussed.

C. In chapter three, the proof of concept and the damping effect of selected materials are studied. The design with the highest performance is selected and further analyzed.

D. In chapter four, the damping and mechanical behavior of the magnetic spring system is further studied and the importance of the magnetic field is also further elaborated.

E. In chapter five, the final prototype is designed and its application is portrayed. Additionally, a simulator is developed for prototyping.

F. In the last chapter, conclusions and possible future work are discussed.

Chapter 3: Proof of Concept for Damping Efficiency

3.1 Introduction

As noted previously, Parkinson's disease (PD) is considered to be a neurodegenerative disorder with potential to cause significant tremors in certain bodily components of patients. Tremors are clinically categorized by instinctive, regular and/or discontinuous involuntary movements of one or more body parts, such as the hands and feet. PD may be associated with multiple different types of tremors which may take place both at rest as well as during specific postural stances or voluntary movements. The frequency of these involuntary movements varies from 4–5 Hz to 8–10 Hz (Giuliana & Mario, 2013). However, the rest tremor, the most identifiable indication of PD, typically develops in the upper limbs with a vibrational frequency in the range of 3–7 Hz (Buijink, Contarino, Koelman, Speelman, & Rootselaar, 2012).

In the following, all currently available vibration absorbers are discussed as a means of define their effectiveness in attenuating tremor in PD patients and the advantages and disadvantages of the concepts behind each vibration absorber are outlined.

The history of the vibration absorber begins in 1911 when Frahm patented a device based on the theory of both undamped and damped dynamics, known as the dynamic vibration absorber (DVA), in addition to the tuned vibration absorber (TVA), which could be used to dampen vibrations of structures, it was useful for narrow frequencies The concept of the TVA includes a mass, a spring, and a damper which allows for a wide range of frequencies to be damped within the system (Philip, Michael J, Stephen, Julian, & George, 2005). All of previous are fixed to the location of maximum vibration in the system to allow for the TVA to perform most effectively.

In 1928, Den Hartog and Ormondroyd broadened the frequency range even further by incorporating a viscous damper in the TVA (Sarah, Mohammad, Ali, & Ali, Structural control and biomechanical tremor suppression: Comparison between different types of passive absorber, 2017) (Sarah, Mohammad, Ali, & Hassan, Tremor Reduction at the Palm of a Parkinson's Patient Using Dynamic Vibration Absorber, 2016). In addition to TVAs, there are more alternatives that are used to develop adjustable tuned vibration absorbers (ATVAs) by either widening the small operating range of the TVA or by adjusting the resonant frequency of the TVA. This is why multiple TVAs are made of multi DOF systems, allowing for the TVAs to dampen the system's vibration over several frequencies. The implementation of several passive controllers such as SDOF and multi DOF TVAs to reduce the tremor in patients' hands by Gebai et al. (Sarah, Mohammad, Ali, & Ali, Structural control and biomechanical tremor suppression: Comparison between different types of passive absorber, 2017). More studies suggest other alternatives to reduce tremors, such as active vibration controllers. In order to effectively implement an active vibration control system, it must apply counterforces to the hand with the same amplitude and frequency as that of the tremor which is incredibly challenging and in most cases requires energy sources and sensors. Another possible option is the use of various smart materials to adapt TVAs such as by means of shape-memory alloys, piezoelectric materials, and magnetorheological material, all of which are materials that go through a stiffness change during stimulating (Lari & Pekka, 2009) (Palomares, Nieto, A.L., Chicharro, & Pintado, 2017). The table below traditionally categorizes the applications of smart materials in the most common vibration absorbers with respect to classification of, passive, active, and hybrid vibration absorbers (Lari & Pekka, 2009).

Table 3-1 Traditional Classification of smart materials with respect to the design for the wearable gadget

	Passive	*Active*	*Hybrid*
piezoelectric materials	x	x	x
shape-memory alloys	x	x	x
magnetorheological material		x	

Piezoelectric materials are mainly used as base isolation materials which can transfer the energy of damping into heat in the resistors within RLC circuit[13]. As this circuit is designed for piezoelectric materials, the circuit includes inductors and resistances which are connected in series with the piezoelectric material to form a harmonic oscillator that can be designed for a particularly chosen frequency (Kozień & Kołtowski, 2011). This allows the piezoelectric material to be shunted in these circuit, working in a manner similar to TVAs.

The rationale for the concept of shape-memory alloys (SMA) to be used in passive vibration absorbers is their damping effect as they undergo reversible changes in their crystalline structure from austenite to martensite when their temperature is decreased. In low temperatures where the crystalline structure is martensitic, the crystalline structure is highly twinned, whereas in high temperatures yielding austenite, the crystalline structure represents a body-centered cubic structure. Martensite is comparatively flexible, in contrast to austenite (which is fairly stiff) and an increase of the elastic modulus (Young’s modulus) is about threefold from the low to the high temperature state. Additionally, the relationship between the elastic modulus and temperature is non-linear and the material experiences hysteresis. (Rustighi, Brennan, & Mace, 2004). The

[13] an electrical circuit including a resistor (R), an inductor (L), and a capacitor (C)

disadvantages of their transformations is the temperature hysteresis, the difference of temperature between the martensite phase and austenite phase (possibly yielding a 10 to 20°C difference) and also the fact that plastic deformation of the SMA occurs which transforms the crystalline structure (Lari & Pekka, 2009). The previously stated all pose issues regarding vibration control.

Smart materials are also considered a candidate as they have several applications such as those seen in magnetic actuators. Magnetic actuators are mostly kept active or semi-active by means of electromagnets, however even when they are used with permanent magnets they still require some source of energy (Qian, et al., 2017). Magnetic actuators have applications in many fields such as in cutting, and machining tools which are usually in the form of active damping devices (Fan, Xiaodong, & Yusuf, 2014). Consequently, they are out of the scope of this thesis, but when considering passive devices, there are passive vibration isolators such as magnetic bearings which can be considered (Qiang, et al., 2013) passive magnetic bearings (PMBs), produce non-contact levitation of an object by permanent magnetic attractive or repulsive forces, and are commercialized by many industries such as the Linz Center of Mechatronics GmbH (Linz Center of Mechatronics GmbH (LCM), 2018). Permanent magnets improve the dependability of the device, and increase behavior that resemblances viscous damping elements, specifically when there is friction. The main advantage of magnetic based actuators is that the stiffening and damping properties are tunable simply by changing the gap between the magnets (Bonisoli & Vigliani, 2007). Many technological applications such as vibrational isolation and energy harvesting that rely on the basis of magnetic suspension owe to the advancement of the magnets such as neodymium-a rare-earth metal.

Permanent magnets can easily be used in the structure of springs simply because two similar poles repel one another (Radu, Alexandru, Camelia, Marius, & Bogdan, 2017). From a terminological point of view, the terms "magnetic spring" and in particular "passive magnetic spring" have been well stablished in literatures. However, it is also a concept of design implemented in many devices, especially when substituting mechanical springs. A typical force-displacement behavior of a common magnetic spring is shown in **Figure 3.1** which showing completely nonlinear behavior (Matthew A. & Metin, 2018) (Radu, Alexandru, Camelia, Marius, & Bogdan, 2017) (Nicu-Bogdan & Radu, 2017) (Miroslav, Josef, & Miloslav, 2012).

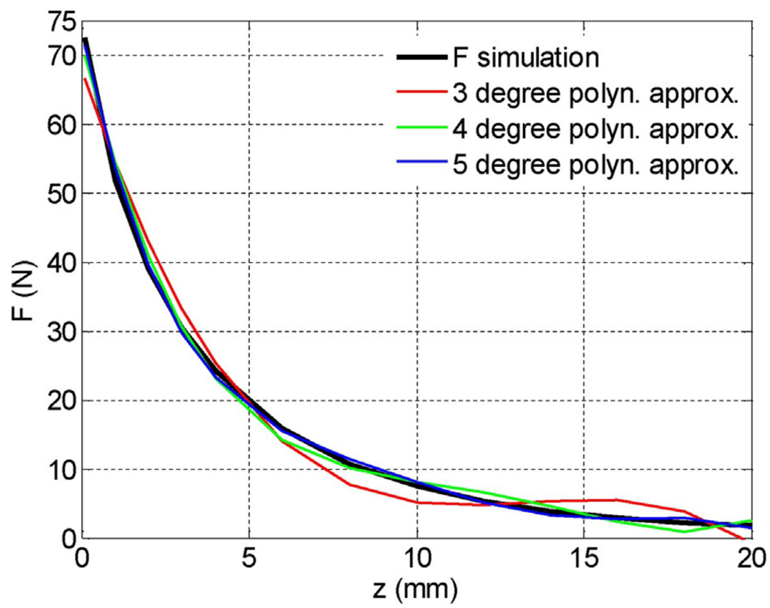

Figure 3.1 The force-displacement curve of a simple magnetic spring and its polynomial approximation[14] to demonstrate the nonlinear relationship (Radu, Alexandru, Camelia, Marius, & Bogdan, 2017) (Nicu-Bogdan & Radu, 2017)

Designed for an energy harvesting application, a hallow tube enclosed with magnets at both ends was fabricated with a magnetic stack positioned inside the tube with the ability to move axially in

[14] It is a method of the numerical method of approximation

which axial movement caused the stack to be repelled by the magnets at the ends. This apparatus was surrounded by coils in order to harvest energy from the motions of the human body. During motion, the magnetic stack inside the hollow tube starts to freely move axially along the length of the apparatus by means of magnetic springs (nonlinear repulsive force of the magnets) at both ends of the apparatus, hence changing the magnetic field of the magnetic stack, causing an electrical current to be generated in the coils covering the outside of the apparatus (Wei, Junyi, Nan, Jing, & Wei-Hsin, 2017) (Abu Riduan, Chinsuk, & Gwiy-Sang, 2012) (Saha, O'Donnell, Wang, & McCloskey, 2008). The concept is shown below:

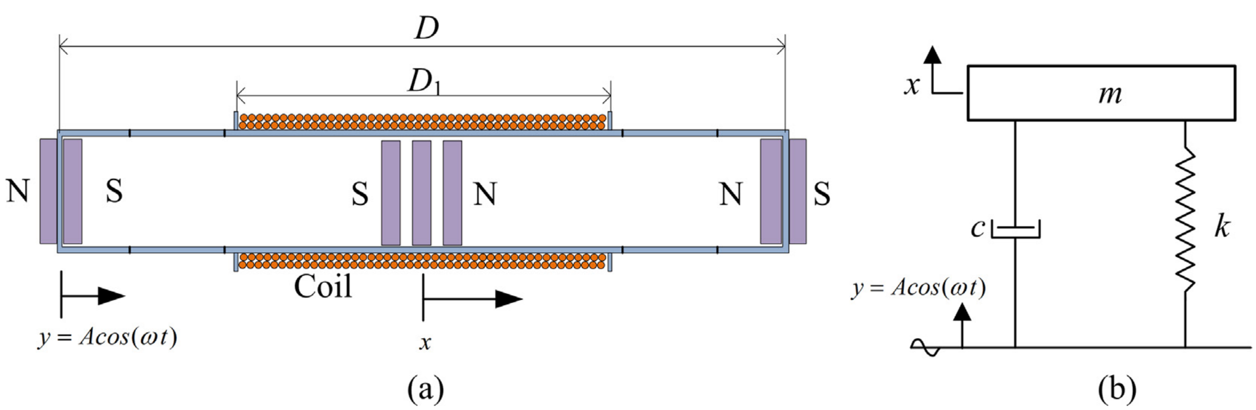

Figure 3.2 the concept of energy harvester shown the design on the left side(D is the length of the container, D_1 is the length of coils around the tube, and x is the displacement of the magnetic stack inside the container), and the right side shows the base excitation because of human motion which is applies to the energy harvester (Wei, Junyi, Nan, Jing, & Wei-Hsin, 2017)

The concept in **Figure 3.2** goes through a harmonic based-excitation. It means that the magnetic stack movies inside the apparatus by the harmonic based-excitation which resemblance of human motion. The question if there is any possibility for this devices to work as a vibration absorber is raised, leading to the idea of using the same concept, a magnetic spring system passively working with magnetic springs, is drawn in order to control hand tremors.

In this study, three engineering concepts were chosen in order to attenuate the hand tremors present in PD patients: (1) using inertial mass, (2) using floating liquid, and (3) using magnetic springs.

3.2 Design of Experiment

The objective of this section is to select the most favorable results with respect to damping efficacy comparing the spring and mass based system, the liquid based system, and the magnetic spring based system. In order to attain the results, a simple experiment was designed with a cantilever.

This experiment was conducted using an aluminum cantilever with a length of 32 cm, a width of 2.5 cm, and a thickness of 0.2 cm. A vibration recorder with an accuracy of ±0.5g, and a weight just above 30 grams, was firmly fastened under the tip of the cantilever. The experiment was first conducted with a 48 grams weight attached at the tip of the cantilever, as shown in **Figure 3.3**. Next, the inertial mass was replaced by a half-filled bottle of water measuring 10 cm in height, 2.5 cm in diameter and 48 grams in weight, as shown in **Figure 3.4**. The second experiment, using water, expected to have a higher damping effect than the first experiment, in regard to the principle of Tuned Liquid Dampers (TLD)[15] a principle that is applied to buildings where water tanks are located on the roof (Jitaditya, Harsha, Shameel, & Reza, 2014). The tip of the cantilever was lowered by roughly 0.5 cm from rest position [16] when either mass was applied and was pushed down by another 3cm before releasing. Oscillation was measured until the cantilever experienced

[15] A Tuned liquid damper is a container filled half full with water that uses the sloshing energy of the water to reduce the dynamic response of the system when it is excited with vibration.

[16] The rest position of the cantilever is assumed to be inclusive of the beam and the vibration recorder

relatively halted motion during which vibrations were recorded every 0.05 seconds (f=20 Hz). The experiment was then repeated several times as to minimize possible errors. The focus of this section is to apply the data collected in designing a practical attenuator using permanent magnets.

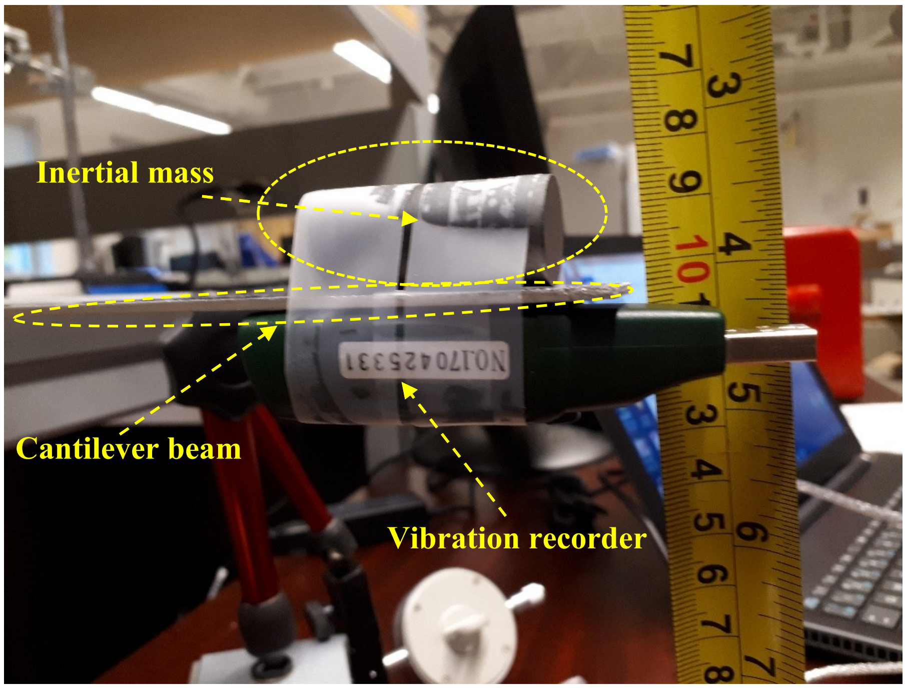

Figure 3.3 The tip of beam is shown for the experiment involving free vibration of the inertial mass, where all oscillations were recorded less than 50 milliseconds apart. The inertial mass was located on the tip of the beam and vibration recorder was positioned under the beam (as shown above).

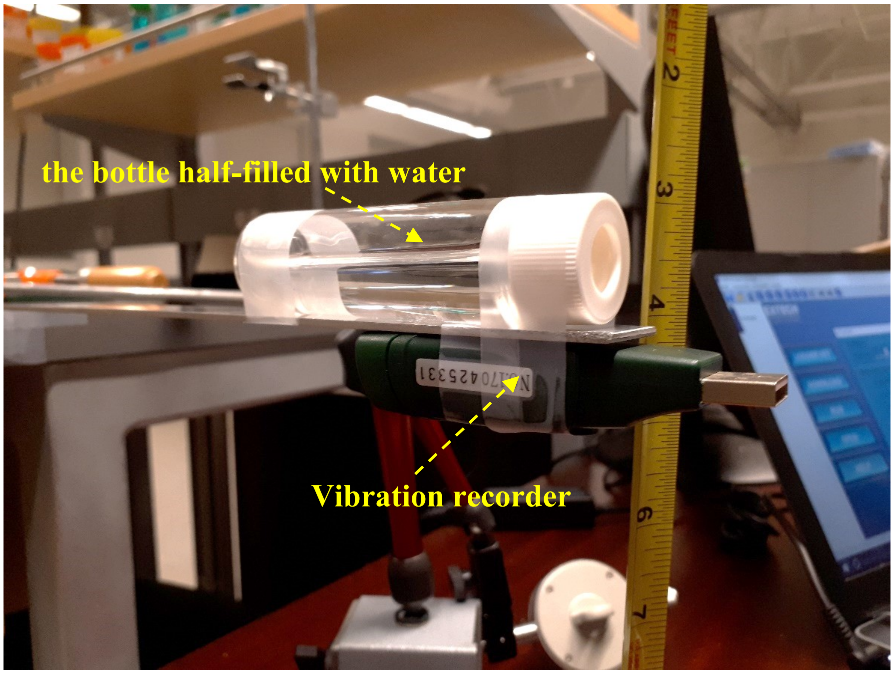

Figure 3.4 The experiment involving of the bottle half-filled water bottle positioned on the tip of the beam with the vibration recorder positioned under the beam.

3.3 Magnetic Spring System

Permanent magnets were used in this simple design of a magnetic spring system. The design consisted of a cylindrical container where free moving magnets were positioned inside the hollow chamber and the chamber was enclosed with magnets positioned at both ends. The arrangement of the polarity of the magnets affected the functionality of the attenuator, so it was ensured that the magnets were arranged in such a way that the magnet inside the container repelled the magnets at the ends of the container. A schematic of the magnetic attenuator is shown in **Figure 3.5**, following the same concept of the energy harvester which was introduced in the beginning of this section (**Figure 3.2**) however, without the coil positioned around it. The samples were made for the experiment, as illustrated in **Figure 3.6**. The height of levitation is determined by the strength of the magnets clarifying why the sample on right of **Figure 3.6** levitated a greater distance as it was located on the top of neodymium magnet. The samples used in this experiment were made from simple ceramic magnets, with a diameter of 1.7 cm and a thickness of 0.4 cm, that were stored inside the container processing a height of 13 cm and diameter of 3 cm. As mentioned previously, the magnetic spring system was designed for two different cases the first sample with a weight of approximately 80 grams (as shown in the right of **Figure 3.6)** and the second sample with a weight of approximately 38 grams (as shown in the left of **Figure 3.6**). Both samples underwent the same procedure as stated in the previous section and both were placed vertically on the tip of the beam as the levitation effect was desired. The first sample lowered the cantilever by 0.7 cm from the rest position and the second sample lowered the cantilever by 0.4 cm from the rest position.

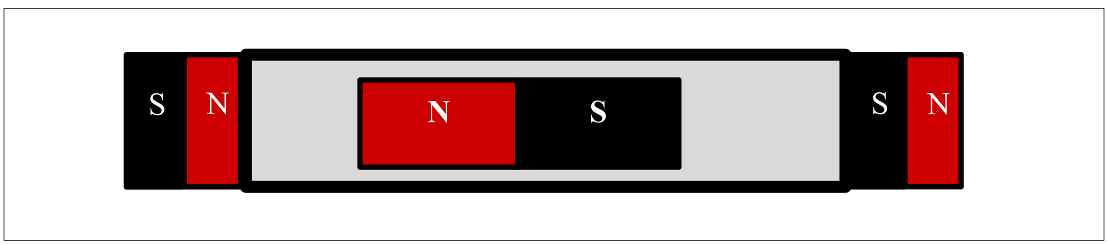

Figure 3.5 Schematic view of the magnetic spring system concept, which is similar to the energy harvester

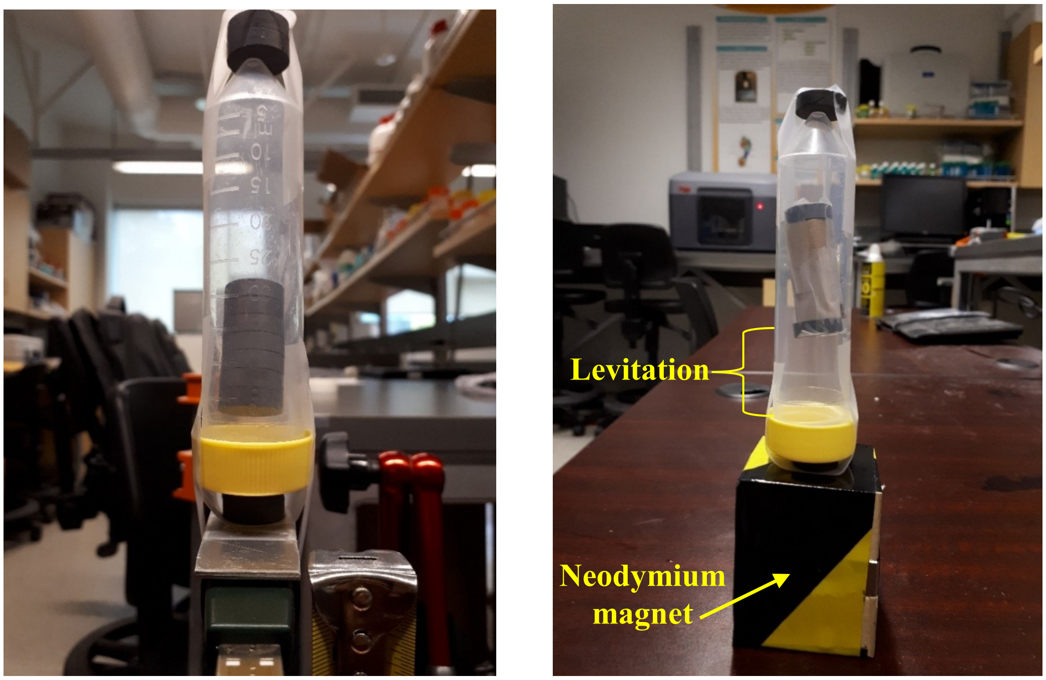

Figure 3.6 The samples of magnetic spring system with the first sample on the left vertically located on the tip of the beam, demonstrating the experiment. The second sample, on the right, located on the neodymium magnet, illustrating the levitation.

3.4 Results and Discussion

All data recorded were compiled and analyzed, such that significant data showed the differences in the three groups of experiments (mass, liquid, and magnets). The first experiment was conducted with the 48-gram solid mass which was subjected to damping and vibration control by applying a counterforce to the beam. This was possible as the excitation frequency was higher value than the natural frequency and as a result, two opposing forces cancelled one another and the beam stopped vibrating. The oscillation obtained from the solid mass is shown in **Figure 3.7**, demonstrating that the time intervals increase, effects from the damping become more prominent. It can be seen in **Figure 3.7** that there is relatively asymmetric vibration over time, this is because the vibration recorder could not sample vibration signals with periods less than 50 milliseconds. The average error in the data collected was 0.2492 cm.

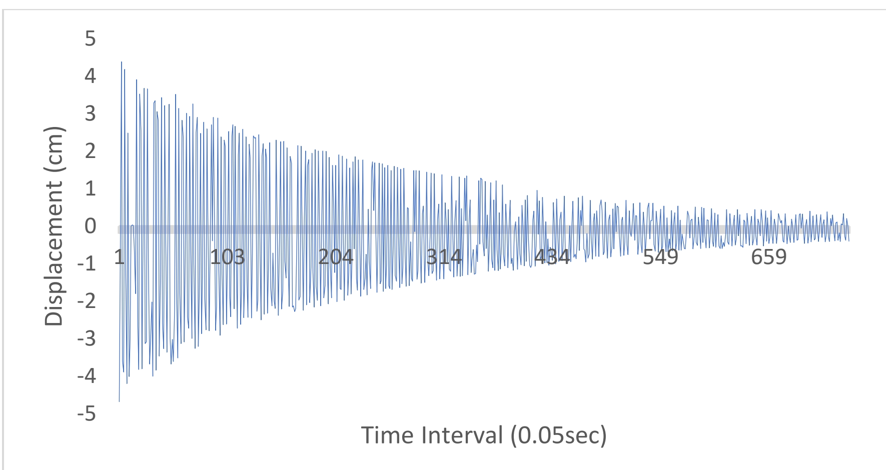

Figure 3.7 The recorded oscillation of the solid mass

Secondly, the vibrational response of the half-filled water bottle is shown in **Figure 3.8**. Damping in this experiment occurred due to a counterforce developed from the movement of water. This concept, as mentioned prior, is used on the top of skyscrapers to mitigate external structural vibration, such as earthquakes. This passive damper (actuator) is ideal for damping planar motions. In this study, the water was more responsive to the counterforce in comparison to the inertial mass. Irrespective of certain resonances, the water can obviously dampen much more than the inertial mass, as shown in **Figure 3.8**.

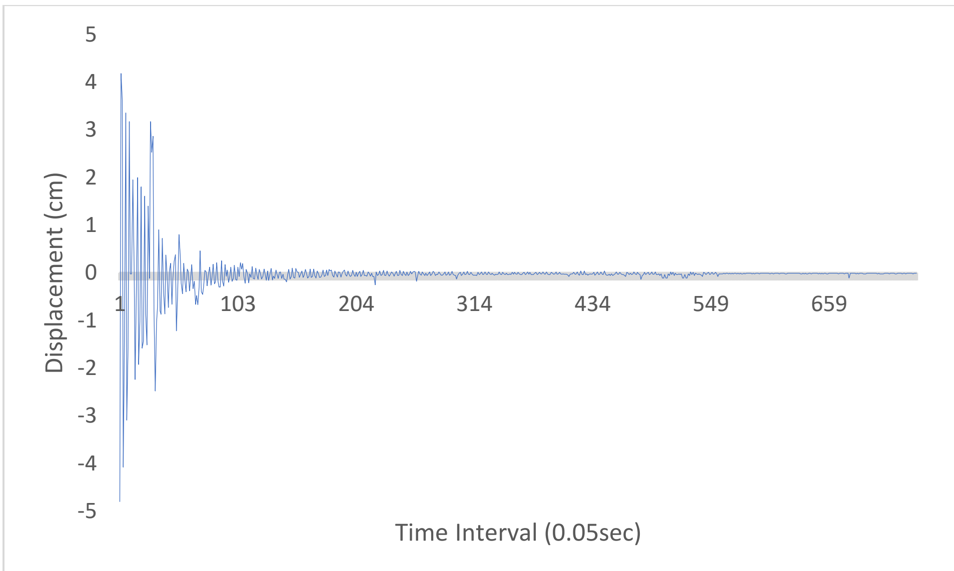

Figure 3.8 The vibrational response of the water half-filled water bottle, outlining the major oscillation which occurs in the first one-sixth of an interval.

Lastly, the magnetic spring system was designed to allow for the magnets to levitate, when positioned on the tip of the beam. The system was able to neutralize most of the vibration very quickly, as shown in **Figure 3.9**. Both samples of the magnetic spring system listed in the previous section were tested, but with different weights. To certain extent they experience the same behavior over the oscillation period. However, experienced significant differences during oscillation when compared to the tests using the half-filled water bottle and the inertial mass suggesting that levitation plays a crucial role in damping. The repelling forces between the magnets induces levitation even when there is no excitation which contributes substantially to the ability to dampen the vibration at the beginning of the oscillation, as shown by the drastic decrement of oscillation at the start of **Figure 3.9**. The rest of the figure continues over low frequencies due to its mass. It was noted during the experiment that the levitating magnets inside the bottle had made contact with the magnets at the ends for the first and/or the second periods, leading to a few peaks. The mean error of the data collected was -0.0225 cm.

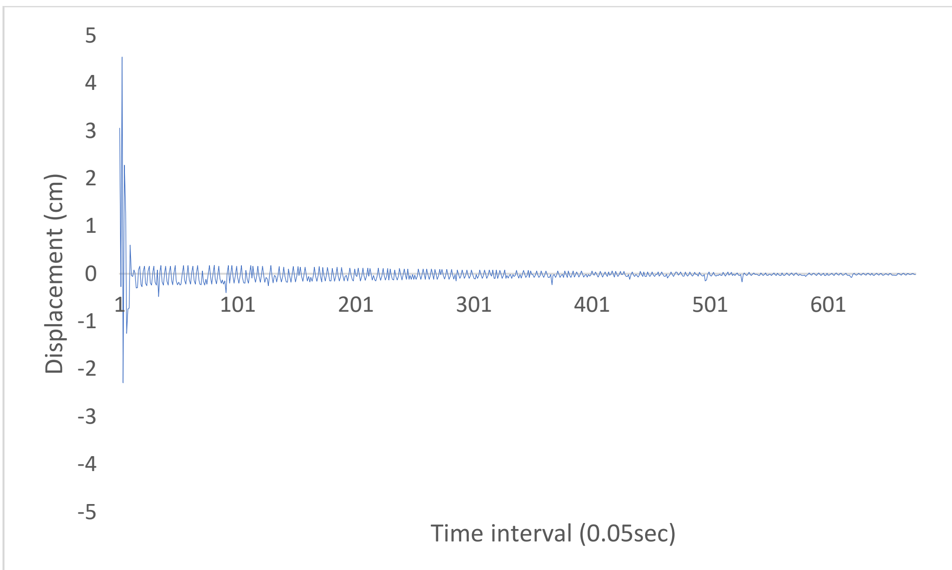

Figure 3.9 The vibration of the magnetic spring system is shown outlining that oscillation over only occurred over a few periods just after the beginning of the vibration.

The data from all experiments are consolidated into one figure, as shown in **Figure 3.10**, for easier comparison. With similar initial displacement and minimal margin for error, it can be perceived that the damping effect from the magnetic spring system was the most efficient at damping vibration, due to its ability to reduce the vibration in a very short period of time. It is worth mentioning once more, that the second magnetic spring system, having a lighter weight of 38 grams, was chosen for further experiments rather than the heavier first sample, which weighed about 80 grams. Therefore, the magnetic spring system should be integrated into the design of a wearable gadget for the mitigation of hand tremors further characterization and experimentation on its behaviors.

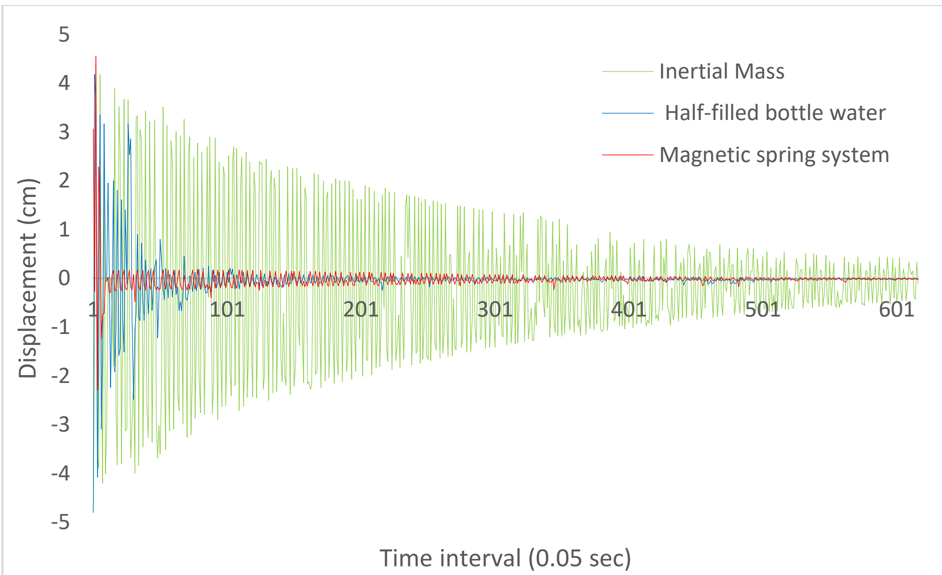

Figure 3.10 The results from all three tests illustrating the superior damping behavior of the magnetic spring system

The exponential trend-lines of all three experiments are illustrated in **Figure 3.11**. Appendix A and B contain information about how the exponential trend-lines are derived and how the damping ratios of the inertial mass, the half-filled water bottle with water and the magnetic spring system are calculated.

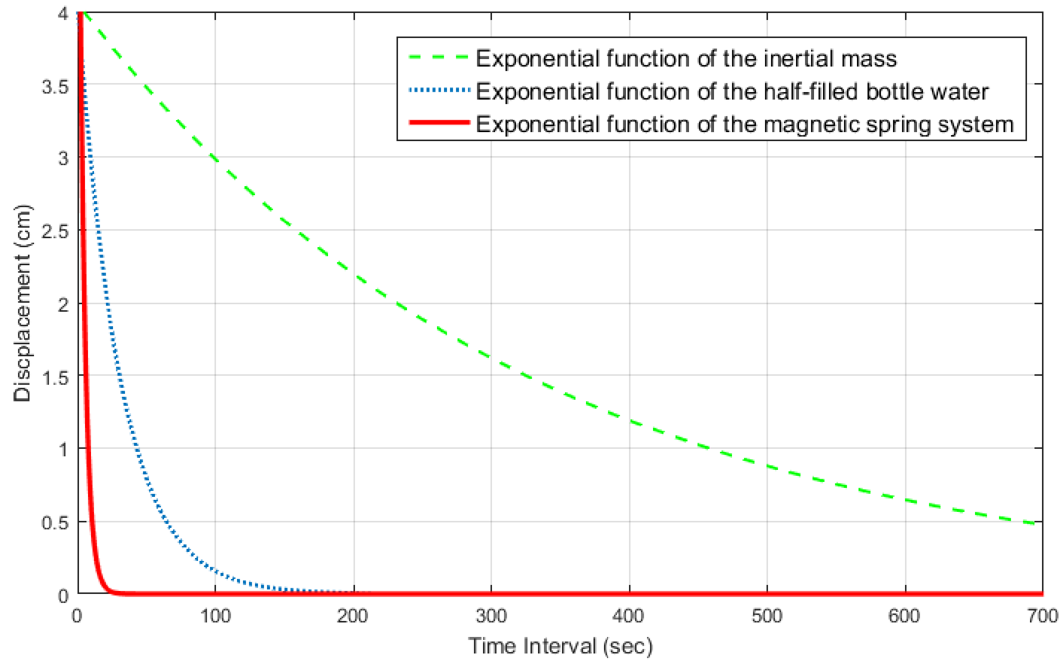

Figure 3.11 Exponential trend-lines of the inertial mass, the half-filled water bottle and the magnetic spring system

3.5 The Magnetic Spring System from Theoretical Viewpoint

This chapter mostly contains empirical studies, but in order to hypothetically understand the magnetic spring system, this chapter comes to the end by theoretical viewpoint of the magnetic spring system. The magnetic spring system was a passive vibration absorber with the configuration of an undamped system with two degree of freedom.

Consider the magnetic spring system as a passive vibration absorber, which can cancel the effect of the disturbance by virtue of an internal model of disturbance. This magnetic spring system has an equivalent stiffness of magnetic springs. When the system is excited, the cylindrical mass in the magnetic spring system is excited too, leading to create a new motion with almost inverse behavior. It can reduce amplitude response at a specific frequency, insofar as, the steady state vibration amplitude is zero as long as its natural frequency is consistent to the frequency of the external excitation.

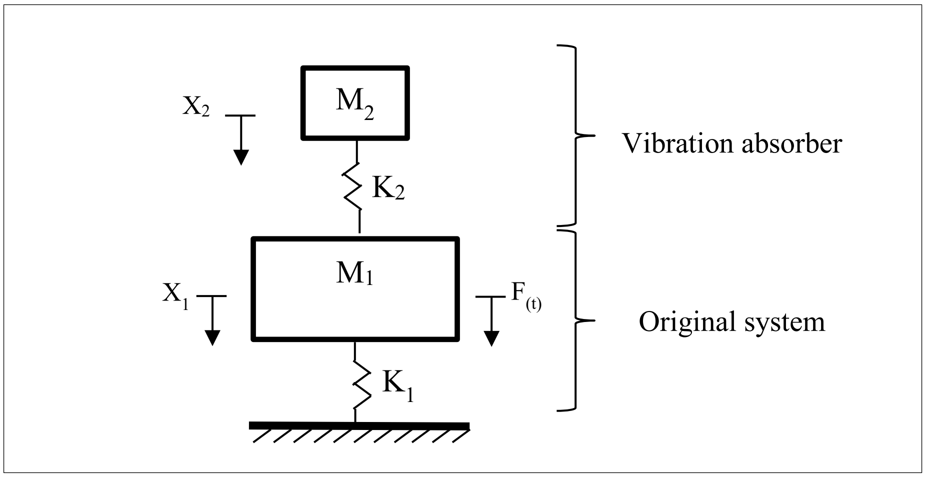

Figure 3.12 General configuration for undamped of 2 Degree-of-Freedom system of the base isolation is represented in the figure for the magnetic spring system, M_1 is the mass of the system body and M_2 is the mass of the cylindrical mass inside the magnetic spring system, K_2 is an equivalent magnetic spring, K_1 is the stiffness of the base of the body of the magnetic spring system.

With respect to FBD of M_2 and M_1 two equation can obtained respectively:

$$M_2\,\ddot{x}_2 + K_2 x_2 = K_2 x_1 \tag{1}$$

$$M_1\,\ddot{x}_2 + (K_1 + K_2)x_1 - K_2 x_2 = F_\circ \sin(\omega t) \tag{2}$$

The equation of motion of 2-DOF system is:

$$\begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix}\begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} + \begin{bmatrix} K_1 + K_2 & -K_2 \\ -K_2 & K_2 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} F_\circ \sin(\omega t) \\ 0 \end{bmatrix} \tag{3}$$

The input function is defined below due to the harmonic excitation.

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} X_1 \\ X_2 \end{bmatrix}\sin(\omega t) \tag{4}$$

$$X_1 = \frac{(K_2 - M_2\ \omega^2)F_\circ}{(K_1 + K_2 - M_1\ \omega^2)(K_2 - M_2\ \omega^2) - {K_2}^2} \tag{5}$$

$$X_2 = \frac{K_2\ F_\circ}{(K_1 + K_2 - M_1\ \omega^2)(K_2 - M_2\ \omega^2) - {K_2}^2} \tag{6}$$

The objective is to reduce the amplitude of X_1, so the numerator is equal to zero.

$$K_2 - M_2\ \omega^2 = 0 \tag{7}$$

$$\omega^2 = \frac{K_2}{M_2} \tag{8}$$

The natural frequency of the vibration absorber equals the frequency of excitation, in this case, it logically dampens the whole vibration.

The study in this section rationally approves the idea to engage the magnetic spring system on the wearable gadget, which is excited by the hand tremor. The hand tremor is a harmonic force which is assumed in most studies as a sinusoidal motion, as noted in Chapter 2.

Chapter 4: Parametric Study of the Characterization of the Magnetic Spring

4.1 Introduction

As previously noted in Chapter 3, the three engineering concepts that were chosen for the design of the proposed hand tremor attenuator include a system based on inertial mass, a system involving suspended liquid, and a system developed with magnetic springs. Upon testing, it became evident that the system that implemented magnetic springs worked more effectively than the other two tremor attenuator designs. In this chapter, further revisions that improve the functionality of the magnetic spring design regarding the solution of hand tremors in patients are thoroughly discussed. As the magnetic force between two magnets is inversely proportional to the distance squared between the magnets and that the spring constant of magnetic springs are proportional to the magnetic force developed, it becomes clear that the magnetic field and the distance between the two magnets are key factors in the spring constant of the magnetic springs involved. Two arrangements were considered for the construction of the proposed magnetic spring, a simple structure that consists of two supports at each end of the spring where the magnetic discs are positioned and an arrangement with an identical structure, however with a dummy mass positioned in between the supports (**Figure 4.1**). In order to control the final spring constant provided by the springs, three variables were custom-designed: the mass of the magnets, the magnetic field associated with the magnets, and the gap between the magnets. The previous factors are controlled by changing the amount of magnetic discs on either the supports or the dummy mass, depending on the particular design. In order to develop the most effective design regarding the specific configuration of the magnetic springs, the same experimental procedure that was applied previously (as discussed in Chapter 3) was also applied.

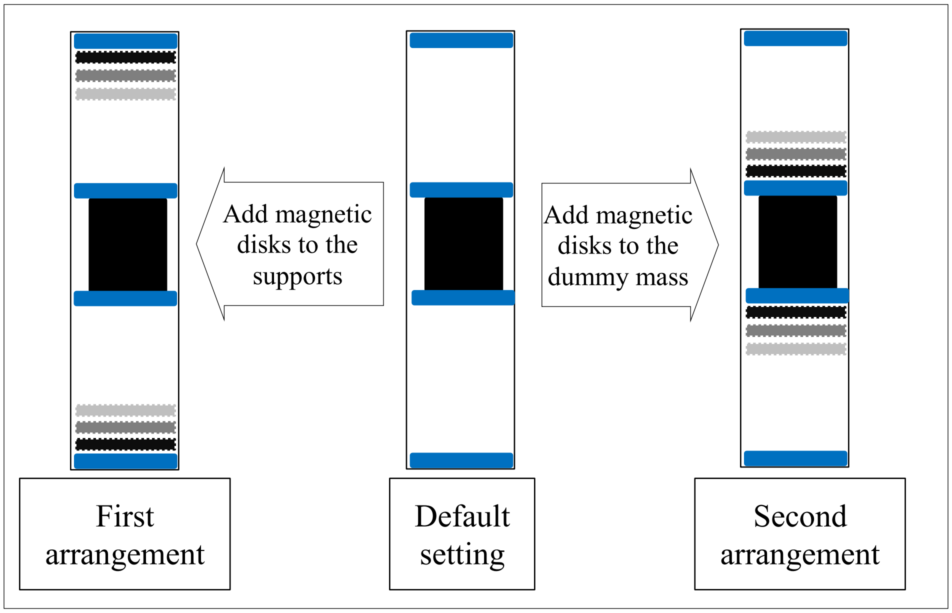

Figure 4.1 the two arrangements to characterize the magnetic spring

4.2 Magnetic Spring Design

The design of the magnetic spring model, as shown in **Figure 4.2**, consists of a shell that houses a cylindrical mass with magnets on both ends in addition to two cylindrical support. The shell was developed with a length of 4.5 cm in the axial direction, a wall thickness of 1 mm and a diameter of 13 mm to accommodate the 7.5 gram mass and 11.1 mm diameter, 0.79 mm thickness neodymium N40[17] magnets, allowing the cylindrical mass approximately 4 cm of freedom in the axial direction. The shell was designed to have an inner diameter exceedingly similar to that of the diameter of the cylindrical mass as a means of preventing the cylindrical mass from rotating and also has a 4 mm lengthwise slit for the attachment of the supports. This longitudinal slit allows for

[17] N40 is a grade for super-magnets with the magnetism of 1.26-1.29 Tesla.

the calibration of the magnetic spring by adjusting the distance between the supports and the cylindrical mass.

The disassembled individual 3D printed[18] components of the design based on the magnetic system in Chapter 3 are displayed in **Figure 4.3.** Additionally, this figure outlines the thin slits that were made in the supports which were used as a means of embedding magnetic disks into the components. Comparatively, three assembled prototypes outlining the position of the cylindrical masses are shown in **Figure 4.4.**

The cylindrical masses within the shells were levitated by repulsive forces developed against the magnets placed within the supports, as the sets of magnets were positioned to have similar poles facing each other. Due to this, the default setting of the device uses four magnetic disks: two on the cylindrical mass and one embedded in each support. As opposite magnetic poles attract each other, the magnets on the cylindrical mass were tilted as a result of the attraction between the opposite faces of the magnets placed within the supports. An example of this tilted result is shown in **Figure 4.5**.

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[18] 3D printed by MOJO Desktop 3D printer from Statasys which uses ABSplus to print models, in layers with a minimum in thickness of 0.17mm.

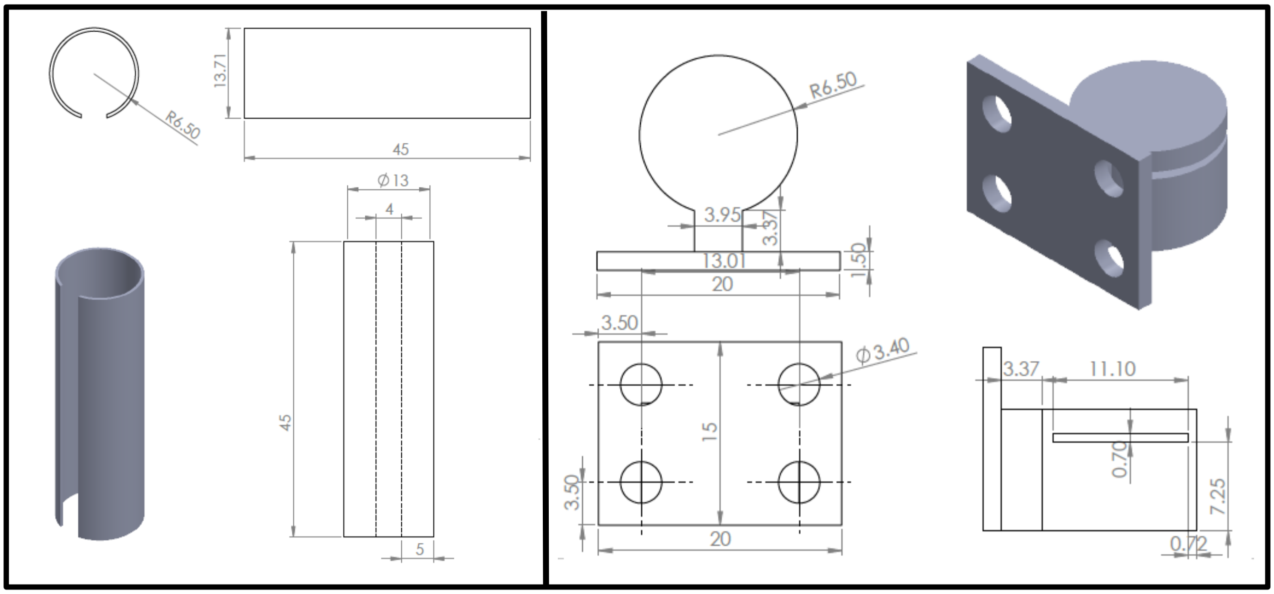

Figure 4.2 Component drawings of the magnetic spring model including the shell and support components, shown from left to right respectively.

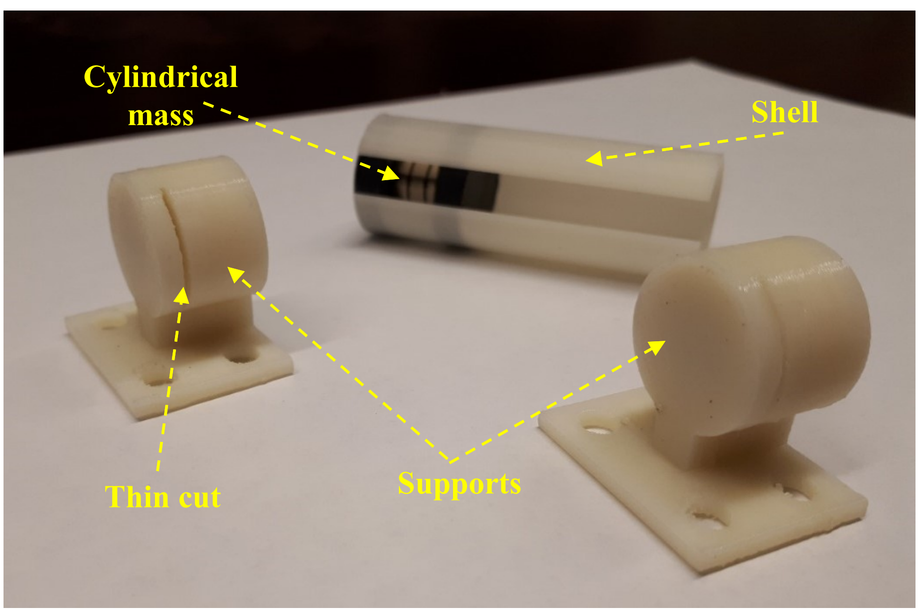

Figure 4.3 Exploded view of the model, outlining the two supports, the cylindrical mass and the shell.

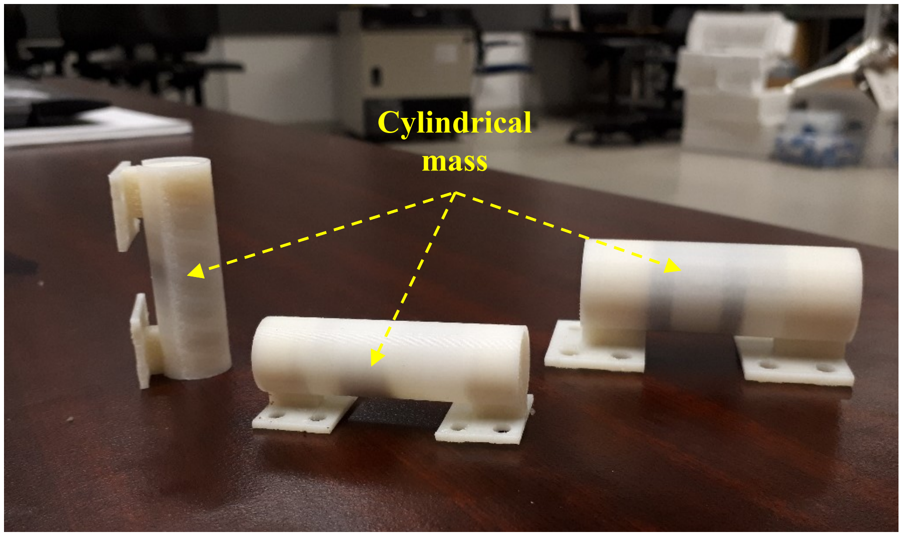

Figure 4.4 3D printed prototypes of the magnetic spring model, outlining the cylindrical mass within each.

4.3 Design of Experiment

The experimental procedures in this chapter are identical to the experiments conducted in Chapter 3, however are inclusive of the magnetic spring model. At the default setting the entire model has a weight approximately 13.1 grams, however due to the tilted mass in the model, friction occurs between the mass and the shell during oscillation.

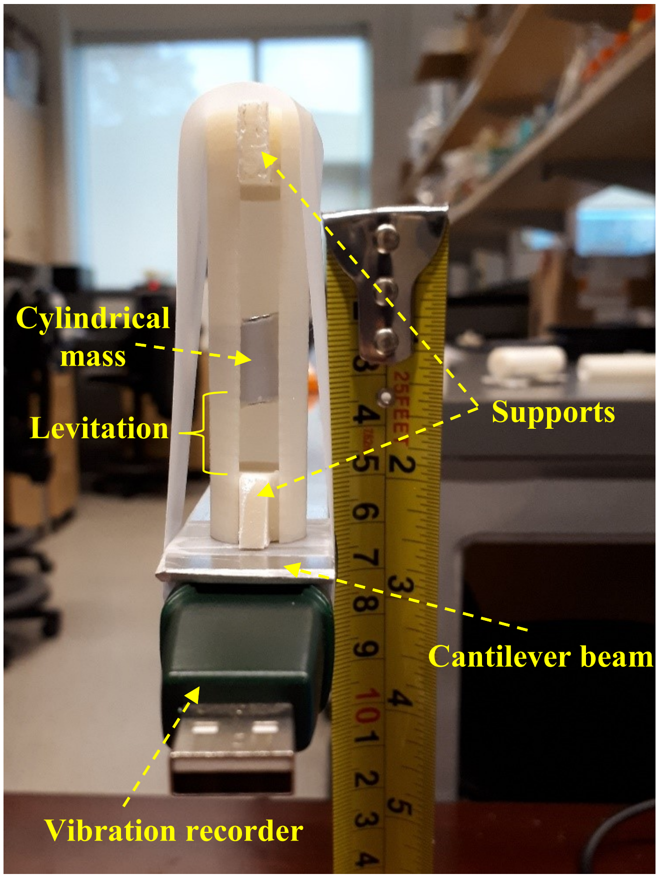

Figure 4.5 The location of the model on the tip of the beam, showing the tilted cylindrical mass during levitation.

4.4 The First Arrangement: Increased Magnetic Field in the Supports

In the first arrangement, the magnetic fields of the supports are amplified by adding magnetic disks to the supports. Four experiments were conducted in this arrangement where an additional magnetic disk was added to each support after every consecutive iteration with the first experiment being completed with the default settings. The weight of the additional magnetic disks adds 1.2 grams to the entire model each iteration. All experiments in this arrangement underwent the same procedures as detailed in Chapter 3 where the default was the first model and the second model had two extra magnets compared to the default, the third model had 4 extra magnets compared to the default and the fourth model had 6 extra magnets compare to the default.

The oscillation results of the four experiments are shown in **Figure 4.6**. As illustrated in the figure, the implementation of the default setting yielded the highest efficiency in regards to oscillation reduction.

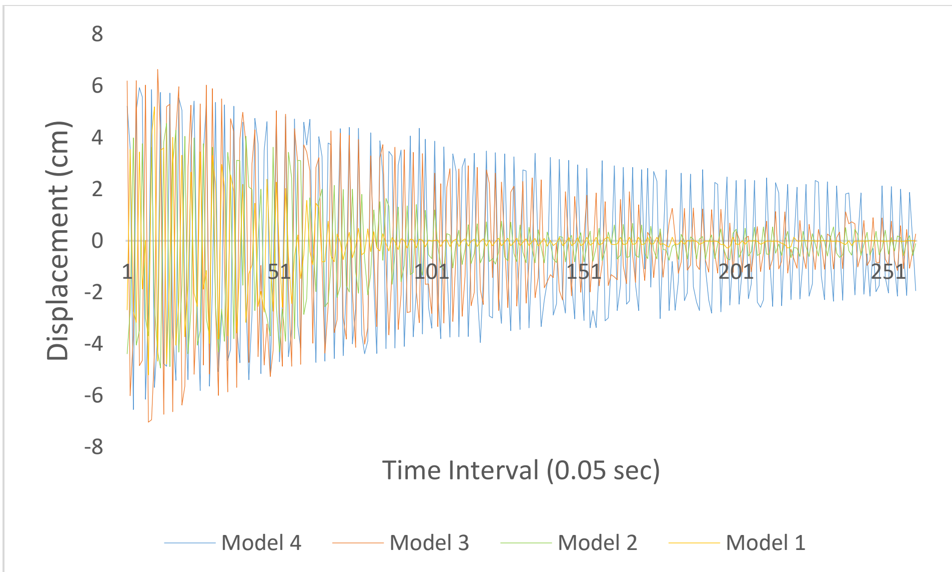

Figure 4.6 Vibrational results of the first arrangement, magnetic field was increased in the supports in each experiment. Model 1 (the first model) was the default setting, by adding two magnetic disks Model 2 was made, Model 3 and 4 had four and six magnetic disks respectively more than the default setting.

4.5 The Second Arrangement: Increased Magnetic Field in the Cylindrical Mass

In the second arrangement, similar procedure was applied, but with the magnetic disks added to the cylindrical mass instead of the supports. Similarly, four experiments were conducted, however the initial starting point possessed two additional magnets compared to that of the default. In this arrangement, The first model had and additional magnetic disk on each end of the cylindrical mass relative to the default setting. Respectively, the second model had two more magnetic disks than the first model, and similar relationship was yielded for the third and fourth models. The oscillations of the four experiments were recorded and the results are portrayed in **Figure 4.7**. As it is difficult to decipher which displacement versus time relationship was gained from each model, Further data processing is required to have a better understanding of each models damping behavior.

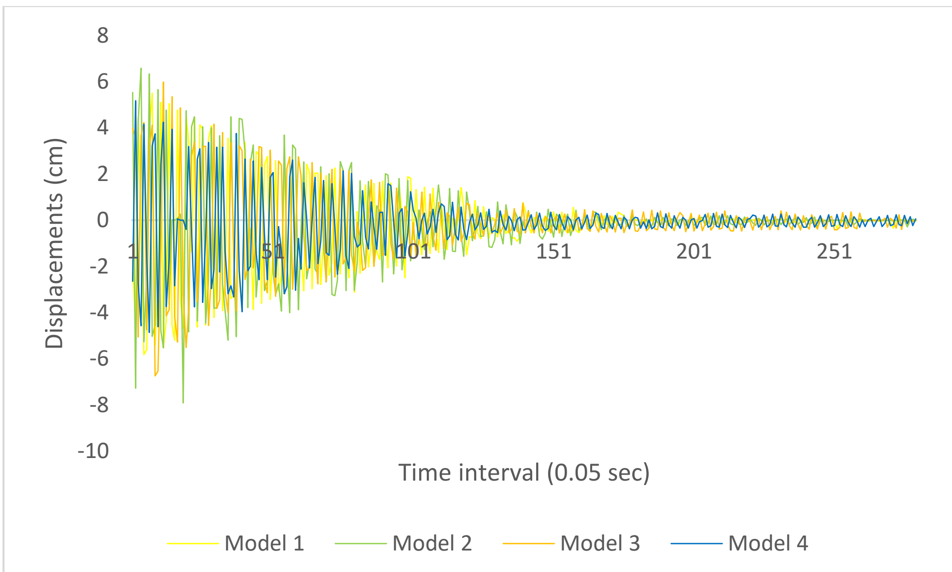

Figure 4.7 Vibrational results of the second arrangement, magnetic field was increased in the cylindrical mass in each experiment. Model 1, 2, 3 and 4 had two, four, six, eight magnetic disks respectively more than the default setting.

4.6 Results and Discussion

In order to visualize the damping efficacy of both arrangements, the oscillation results required further processing. As the vibration recorder used for this study had a maximum recording frequency of 20 Hz and the frequency of the beam was a value larger than 20 Hz, not all maximum points could be approximately recorded. Due to this, interpolation among the maximum points was required for calculation. A data sets were chosen that contained 8 data points yielded from the oscillation results in which the interpolation was calculated with respect to the maximum points in each set. In order to construct a curve that had the best fit regarding the maximum points obtained from the eight point data sets, curve fitting was needed after the interpolated values were determined. Using MATLAB, the curve fitting was achieved using single term exponential functions for each oscillation result in the two arrangements, the results of which are summarized in **Table 4-1** and **Table 4-2.** As the R-Squared value accounts for the total variation in data accounted for by the model and that all of the R-Squared values produced by the curve fitting are values relatively close to one, it is assumed that the curves developed account for a large amount of the data presented within the sets.

Table 4-1 Exponential functions and R-squared values of the first arrangement

	Model 1 (default setting)	Model 2	Model 3	Model 4
R-squared	0.944	0.914	0.964	0.972
Exponential function	$5.821e^{-0.0234x}$	$5.37e^{-0.01137x}$	$7.359e^{-0.00814x}$	$6.257e^{-0.00416x}$

Table 4-2 Exponential functions and R-squared values of the second arrangement

	Model 1	Model 2	Model 3	Model 4
R-squared	0.986	0.9743	0.950	0.95142
Exponential function	$6.25e^{-0.0139x}$	$6.879e^{-0.01367x}$	$6.128e^{-0.0136x}$	$5.097e^{-0.01402x}$

The exponential trend-lines developed from the functions were graphed a single plot, illustrating the damping effect of the four experiments in the first arrangement, as shown in **Figure 4.8**. From the graph, it can be determined that the first experiment had the best damping capability as the displacement reaches approximately 0 cm in the shortest time opposed to the fourth experiment in which the displacement experienced very little change over the relative period of time. Therefore, it can be speculated that the larger the magnetic field in the supports, the less the cylindrical mass moved. The exponential trend-line of the fourth experiment (as shown in blue) is similar to the exponential trend-line of the inertial mass in Chapter 3, so the experiments after the fourth experiment were ignored.

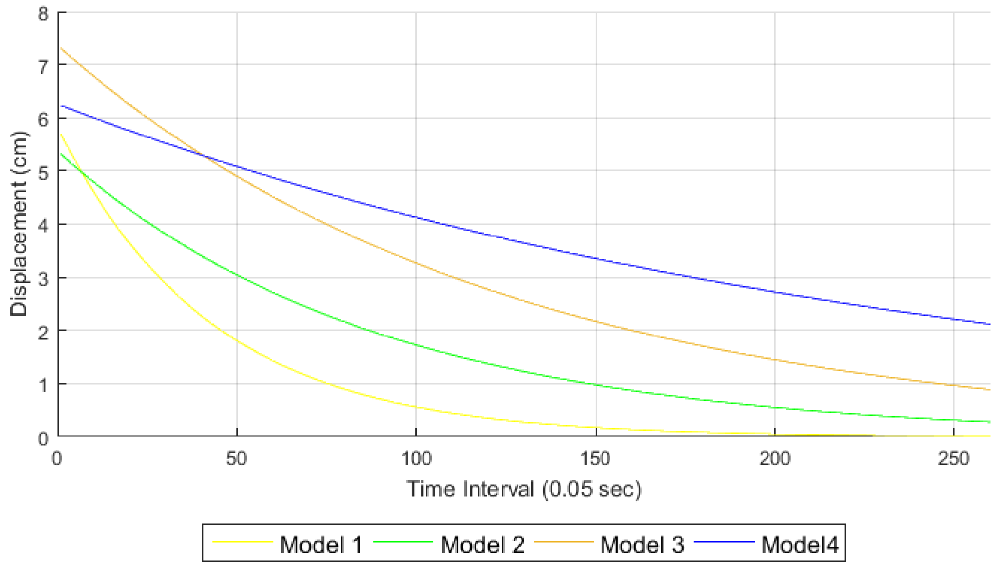

Figure 4.8 Exponential trend-lines of the first arrangement

For the second arrangement of experiments, in addition to the magnetic field increasing when magnets were added the mass of the cylindrical mass was increased as well. The exponential trend-lines of this arrangement are illustrated in **Figure 4.9**. From **Figure 4.9,** it can be determined that increasing both the magnetic field and the mass lead to the same damping efficiency, as all of the trend-lines converge over identical time intervals. This suggests that, there is a direct relationship between the magnetic field and the mass. No significant changes can be seen in damping efficacy when both the magnetic field and the mass are increased simultaneously, thus the lighter the mass, the smaller the magnetic field.

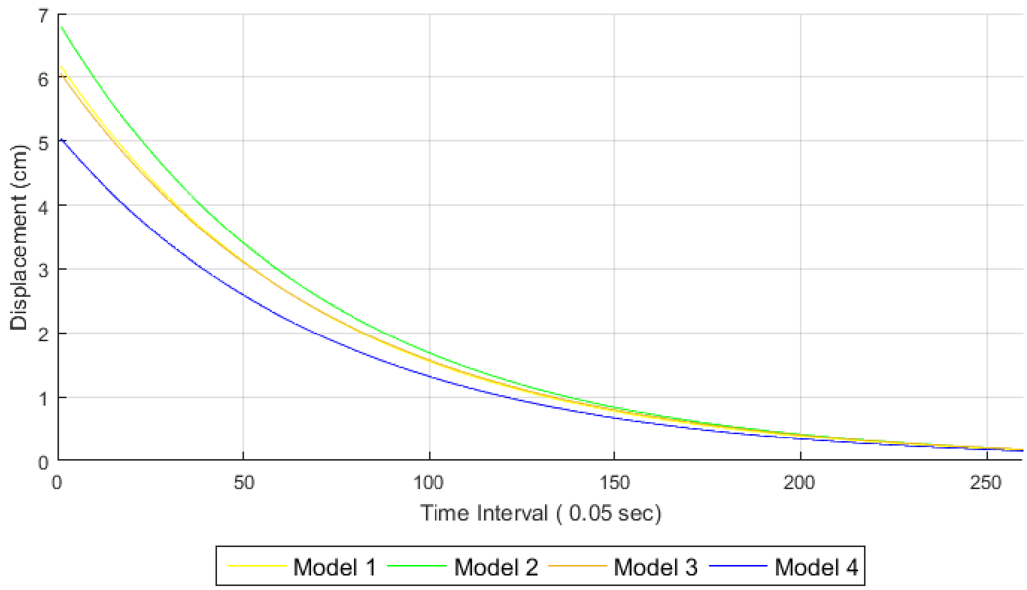

Figure 4.9 Exponential trend-lines of the second arrangement which the magnetic field was increased in the cylindrical mass. In each model two magnetic disks were added.

Three parameters were selected for the study of the magnetic spring: an increase in the weight of cylindrical mass, an increase in stiffness, and an increase in both of the stiffness and mass simultaneously. The first parameter was not desirable because when the weight of the mass increased the cylindrical mass hit the supports as the magnetic force was not strong enough. The second parameter was accomplished in the first arrangement as the stiffness was increased and the weight of the cylindrical mass remained constant and the third parameter was achieved in the second arrangement as both of them were increased.

4.7 Comparison of the Two Arrangements

From the above experiments it can be seen that there are clear differences between adding additional magnetic disks to the cylindrical mass versus to the supports, though testing situations varied the weight of the model in its entirety in both the first and second arrangements remained constant as the number of magnetic disks that were added to the model was identical. The exponential trend-lines of the two arrangements when only two additional magnets were incorporated in the system are available in **Figure 4.10** the second comparison showing the exponential trend-lines of the two different arrangements with four additional magnets each is available in **Figure 4.11** and the exponential trend-lines of the two arrangements in which the model consisted six extra magnetic disks are shown in **Figure 4.12.**

In the figures, the blue dashed represent the exponential trend-line from lines the experiments in the first arrangement and the orange lines represent the exponential trend-line from the experiments in the second arrangement. The cylindrical mass often came in contact with the supports over the initial time intervals in both arrangements, in addition to having increased friction due to the contact between the shell.

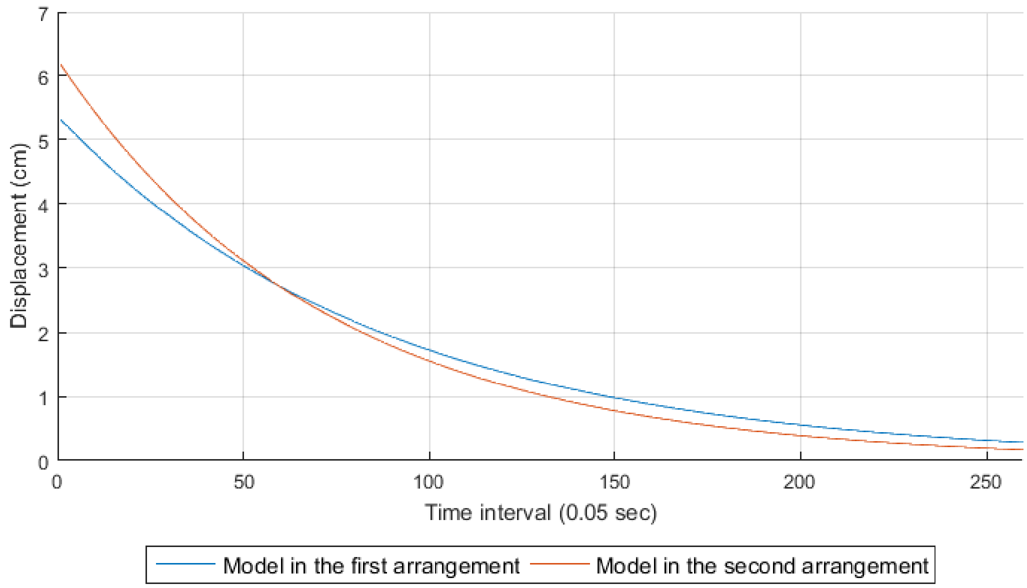

Figure 4.10 Exponential trend-lines of both arrangements with two additional magnets

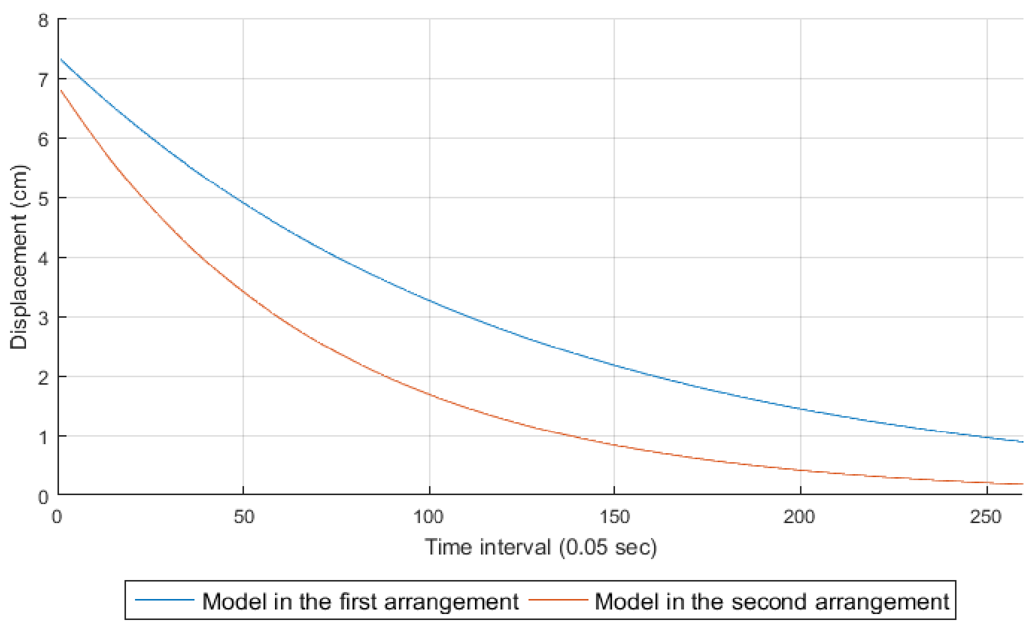

Figure 4.11 Exponential trend-lines of both arrangements with four additional magnet

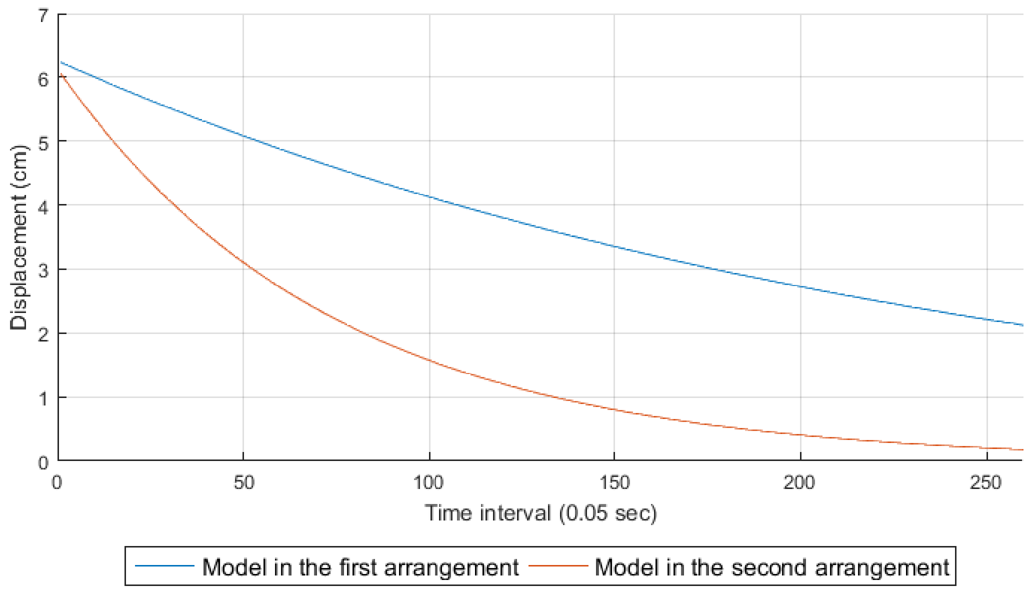

Figure 4.12 Exponential trend-lines of both arrangements with six additional magnets

From the results of these comparisons, it can be concluded that increasing the magnetic field on the cylindrical mass produced better effects than increasing magnetic field on the supports over the same time interval of oscillation.

4.8 Comparison of Base Isolations Systems: Mass-Spring Systems and the Magnetic Spring Systems

Conventional spring systems and magnetic spring systems are comparable when applied to base isolation systems. Conventional springs consist of a mass and a spring with a non-negligible mass and stiffness, whereas magnetic springs have at least two magnets levitated on each other where the levitating magnet can either be the mass or be attached to an object. These magnets are able to function similarly to a spring due to the repulsive force between identical poles. The repulsion between the magnets resembles a non-linear spring, as the repulsive forces becomes stronger as the distance between the magnets decreases. However, unlike the magnetic spring system, conventional spring system are able to function under both compression and extension circumstances. Furthermore, in a conventional spring system, the spring can be either linear or non-linear. Though the spring in a conventional spring system has a non-negligible mass for which the effective mass should include a third of the mass of the spring in some studies the spring mass is ignored for simplicity.

Therefore, the most effective fine-tuned magnetic spring, such as those that are required for a hand tremor attenuator, should be based on the second arrangement where both the mass and the magnetic field are increased simultaneously. This suggests that the higher the magnetic field, the heavier the mass, having increased potential to counteract hand tremors. Heavier masses will require higher magnetic fields otherwise the magnetic force will not be strong enough to levitate the magnets and they will come in contact with one. Another key point is that the magnetic springs have nonlinear behavior which should be linearized over the small domain consisting of the specific application of the actuator. This linearization should be in a small domain of high repulsive force where the distance between both magnets is minimal as to obtain more stiffness to allow for heavier masses to be used to counteract the hand tremors.

Chapter 5: Proposed wearable gadget for hand tremors

5.1 Introduction

The parameters of the magnetic spring system that were studied in the previous chapter are further discussed in regards to the desired damping requirements of the system. Additionally, a prototype of the designed magnetic actuator that has complete functionality over rotational excitations is introduced for effective implementation in a wearable gadget used to reduce the amplitude of hand tremors. The desired design criteria as well as the various testing methods used to assure satisfactory function of the prototype are thoroughly explained and the conclusion as to why the developed prototype has potential for real-life application is recognized.

5.2 Design Criteria of the Wearable Gadget

In order to develop the most efficient wearable gadget possible, specific criteria were chosen for the design as follows:

- The device must have universal application. The concept of this assisitve device is to aid those whose daily lives are affected by hand tremors. Though there are commercializd products currently available, many of these products have very specific applications of use and have limited function for day-to-day incorporation.
- The device must be afordable. The wearable gadget must be available to those all across the world regadless of finacial situation.
- The devices must minimize the restriction of movement. Hand, wrist and fingers movements are not to be restricted with ideal location for the device as shown in **Figure 5.1** outlining both the overall ideal gadget location as well as ideal actuator placement.

- The device must be a passive mechanism. The device should be passive as passive mechanisms require less maintainence and do not depend on external energy sources to funtion.
- And the device must be lightweight. The weight of the wearable gadget should be kept within the contraints disscussed in Chapter 2 while maintaining within the functioning range as demonstrated in Chapters 3 and 4.

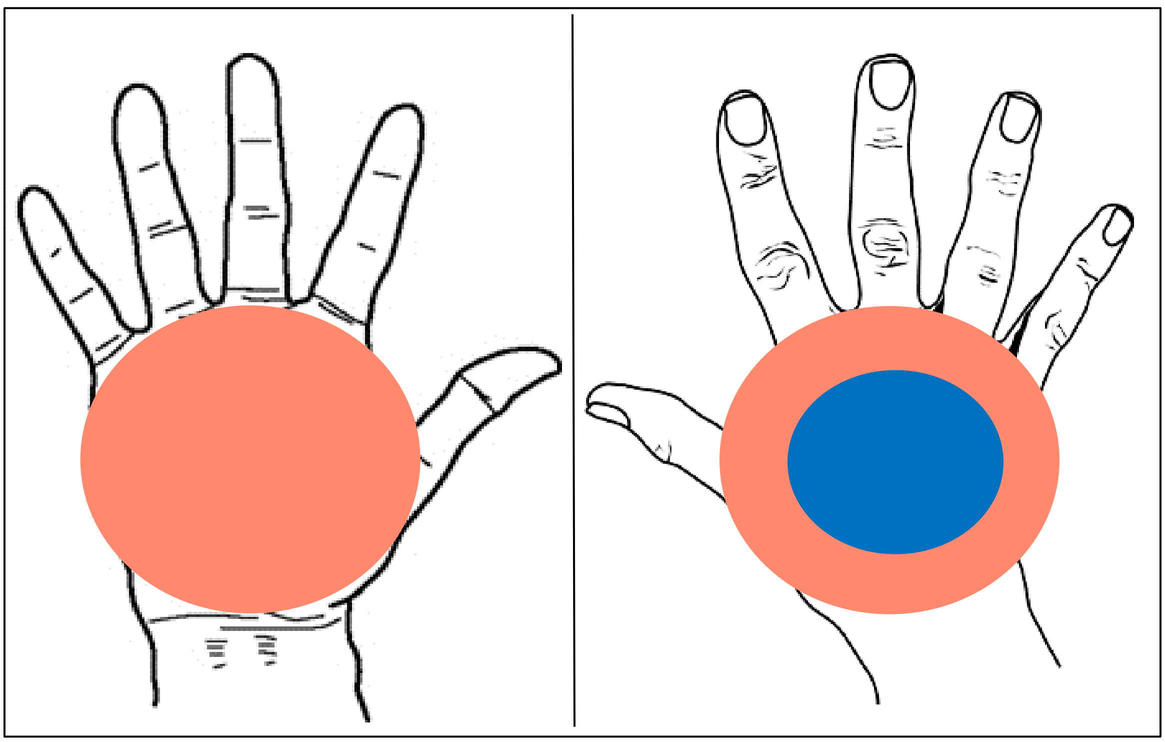

Figure 5.1 Ideal placement of the wearable gadget with red outlining the location of the body of wearable gadget and blue outlining the location of the gadget components.

5.3 Review of the Magnetic Spring System

The design and parameter designation of the magnetic spring system occurred in Chapters 3 and 4 respectively, however the main features and concepts are summarized as follows:

- The relation between the force applied and the decrease in distance between magnetic poles in a magnetic spring system in nonlinear;
- The magnetic spring system used has a single axial configuration;
- And though gravity plays an important role, the magnetic force of the system is mainly influenced by the mass that is integrated into the actuator suggesting that the heavier the masses are that are required for the actuator, the stronger the produced magnetic field must be.

5.4 Disadvantages of Integrating a Magnetic Spring System into the Wearable Gadget

As the magnetic spring system is uniaxial, a slight change in the position of hand has the potential to change the orientation of the magnetic spring system, thereby causing inability of adequate gadget function. These positions include the main movements of the forearm, the elbow, pronation[19], supination[20], and the movements of the wrist joint, such as abduction, adduction, flexion and extension.

In order to extend functionality of the magnetic spring system to include all potential orientations, a seesaw-like actuator was designed to resolve this issue.

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[19] If the arm is rotated so that the palm is faced forward
[20] If the arm is rotated so that the palm is faced backward

5.5 Seesaw-Like Actuator: Directional to Rotational functionality

The actuator was designed to transform the axial movements of the magnetic spring system into rotational motions, turning the two degree of freedom system into a single degree of freedom system. This design is based on seesaws that used in playgrounds where a T-shaped arm is connected to a board using a joint placed in the middle of the arm. In the actuator design magnets are located at the ends of both the arm and the board, causing the magnets on the arm to be positioned directly over top of the magnets on the board as shown in **Figure 5.2**. As the magnets on the arm and the board are placed to have similar magnetic poles facing each other, balance can be attained for the T-shaped arm.

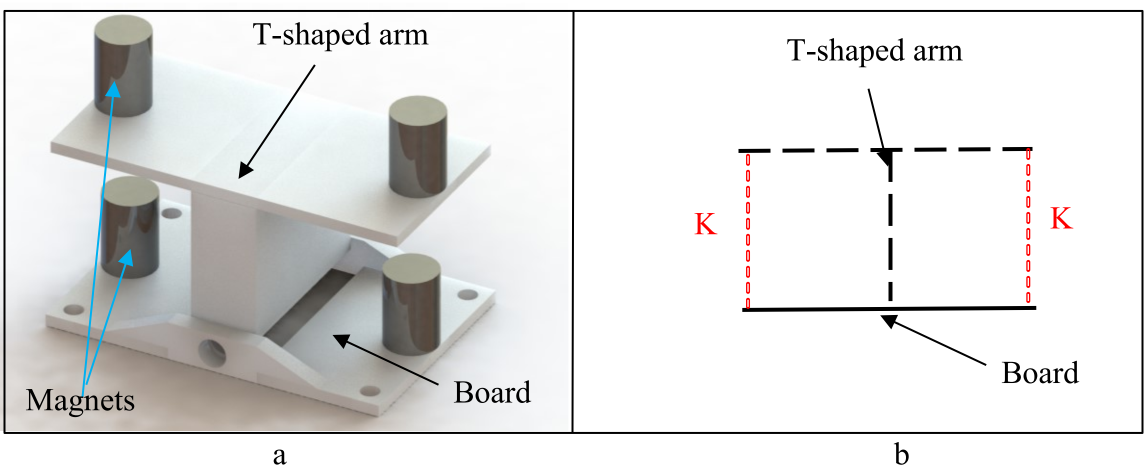


Figure 5.2 a) The view of the seesaw-like actuator, b) Free-Body-Diagram of the seesaw-like actuator; K representing the stiffness of the magnetic springs.

The actuator functions due to by the forces that are developed between the magnets on the board and the T-shaped arm. When the arm is tilted magnets will repel each other, causing the arm to return the arm back to its rest position. During testing over each periodic cycle the two magnetic springs were each activated once in order to cause the arm to return to rest position. The behavior the T-shaped arm experiences during this harmonic motion is displayed in **Figure 5.3**.

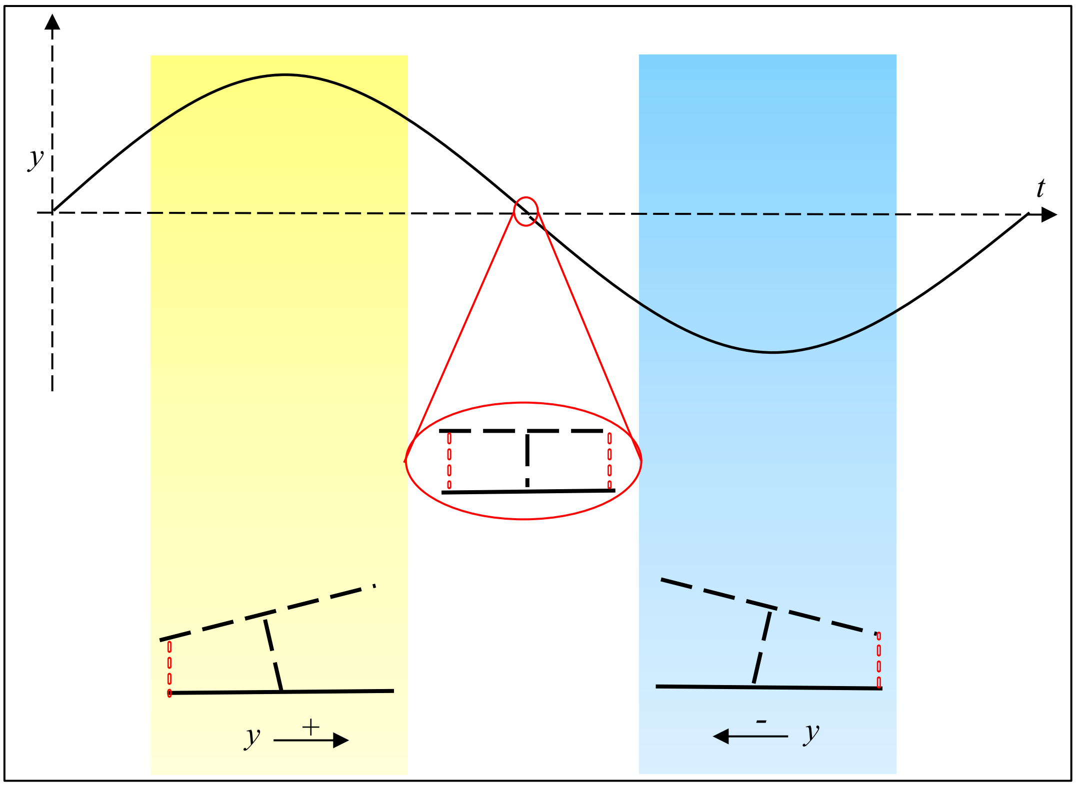
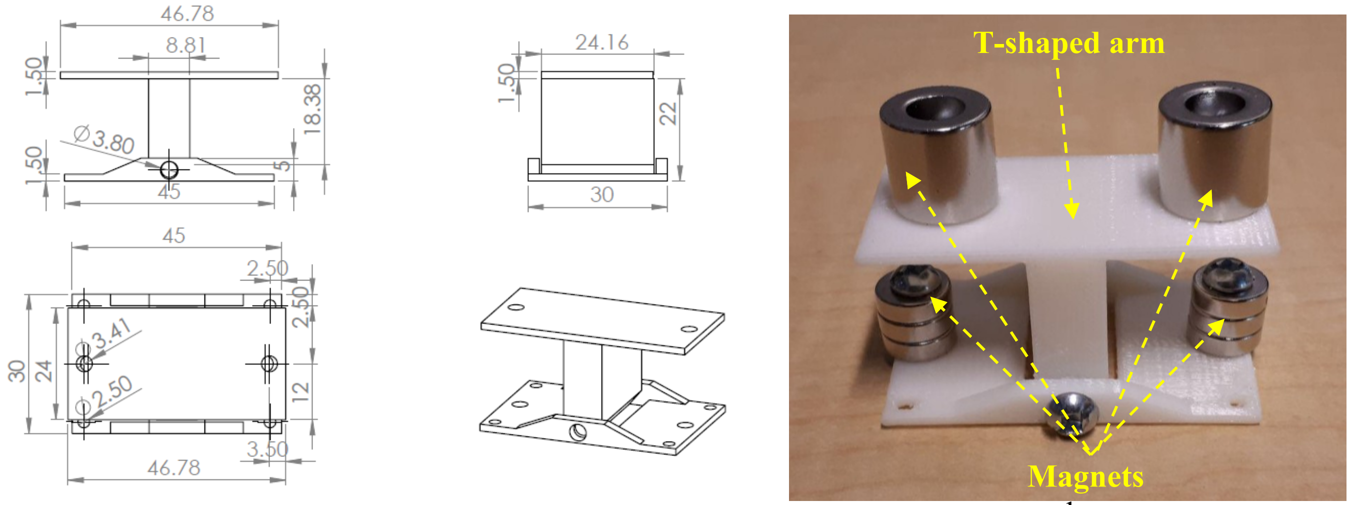


Figure 5.3 The behavior of the seesaw-like actuator behavior over a single period outlining two tilted positions (in yellow and blue) and the rest position of the T-shaped arm (in red).

The design for the body of the actuator, fully inclusive of the various dimensions of components is available in **Figure 5.4-a** This particular design has the greatest possibility of effective integration into the wearable gadget due to its capability to respond to rotational motions. Additionally, along with the relatively small distance between the magnets, the strong repelling magnetic force allows for heavier masses to be incorporated into the system. This creates a viable option to increase the overall effectiveness of the actuator if needed. Also, the magnetic forces that are developed have a greater influence on the mass that is integrated into the actuator than gravity does. These factors combined allow the seesaw-like actuator to address most of the problems that are faced by gadget While still satisfying all of the previously discussed parameters. The fully assembled 3D printed result of the model is shown in **Figure 5.4-b**.



a b

Figure 5.4 a) Technical drawings of the seesaw-like actuator with dimensions in millimeters, b) the fully completed the seesaw-like actuator with the 3D printed components and magnets positioned on the both ends of T-shaped arm as well as under the T-shaped arm.

5.6 The Body of Wearable Gadget

The design of the proposed wearable gadget is basis of a conventional elastic wrist brace with the magnetic actuators stitched onto the back of the brace. The exact placement of the actuator on the back of the wrist brace was determined through a variety of experiments. One of the main considerations for the actuator placement is that the actuator must not limit the movement of the wrist as it is one of the most flexible joints in the arm (Sarah & Mohamad, Parkinson's Disease Treatment as Seen from a Mechanical Point of View, 2016) (Peng, Dingguo, & Mitsuhiro, 2012).

5.7 The Final Prototype

The final prototype was developed out of a glove-like wristband with two magnetic actuators attached on the back of the wristband as shown in **Figure 5.5**. The combination of the wristband and the two actuators yielded a total weight of approximately 120 grams. The distance between the two actuators in regards to each other was maximized in order to best minimize the effect that their respective magnetic fields have on each other and reduce possible complication that can arise from this, such as unwanted magnet attachment.

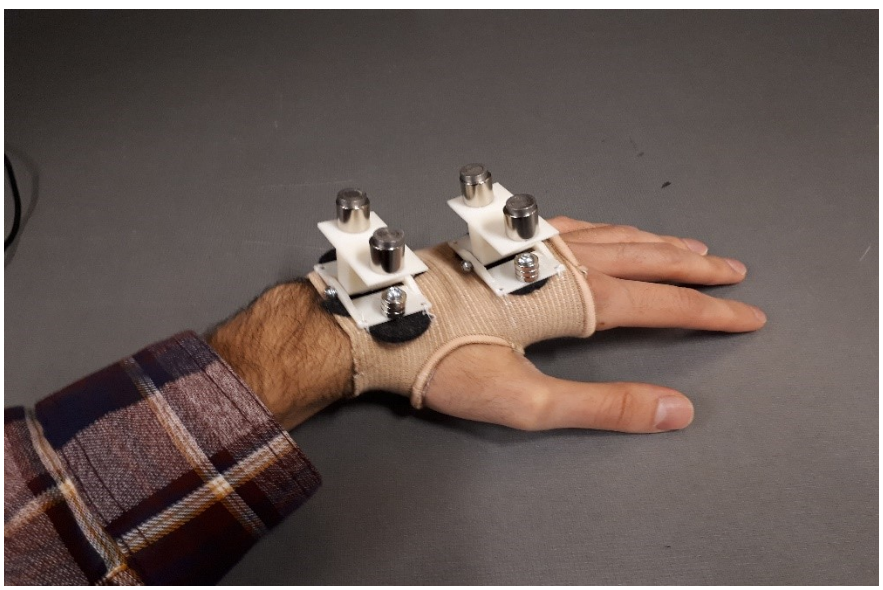


Figure 5.5 The final prototype of the wearable gadget

5.8 Hand Tremor Simulator

Due to sensitivities around human testing and the requirement of clinical trials and the respective paperwork, hand tremors were simulated by the use of two machines, each worn just before the wrist as to simulate sinusoidal motion of the hand. Accurate placement of the machine as well as its general components are depicted in **Figure 5.6**.

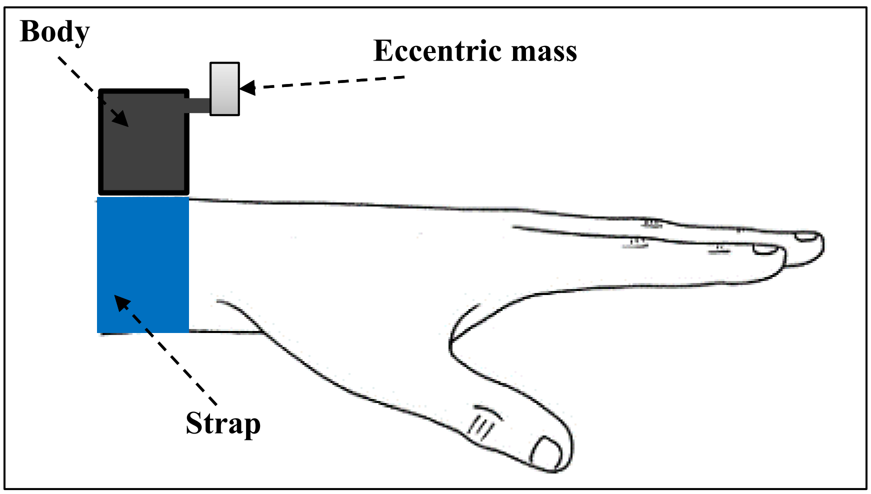


Figure 5.6 Correct placement of which the hand tremor simulator on the wrist

Each machines consists of an eccentric mass, a DC motor and its required components (inclusive of wire, a nine-volt battery and a key), a solid body, and a strap as shown in **Figure 5.7**. The machines generate torque by rotating an unbalanced mass, causing vibrations in the hand. Both machines produce frequencies of approximately 6 and 11 Hz when the eccentric mass is 32 grams, allowing, the machines the capability of obtaining similar frequencies to those of hand tremors caused by neurological disorders, particularly PD and the Essential Tremor. Information about the hand tremor simulates regarding the maximum force that can be generated is provided in Appendix C.

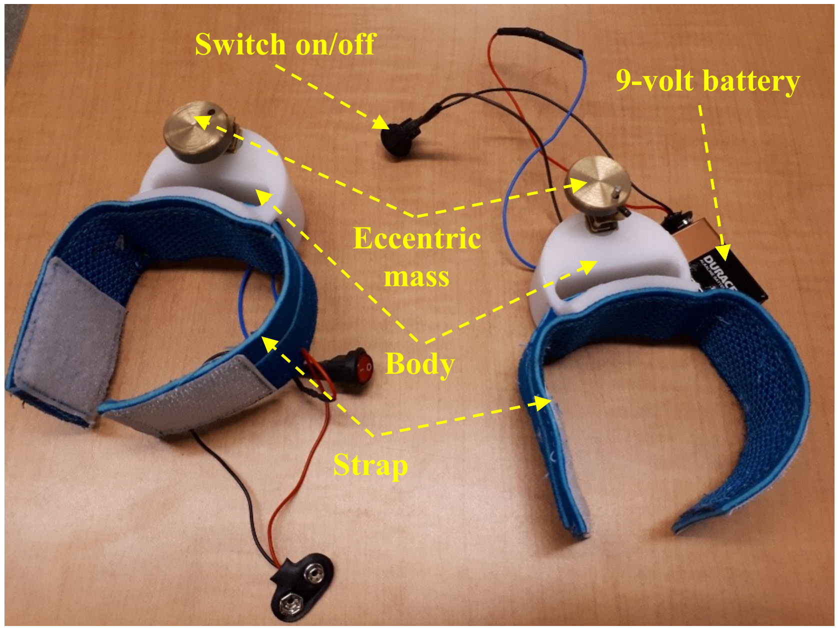


Figure 5.7 Hand tremor simulators

5.9 Results and Discussion

The wearable gadget was tested using the hand tremor simulators in simple experiments that were designed based on the daily needs and activities of the majority of individuals who experience tremors in the upper extremities. The first experiment was designed to simulate drinking water from a cup which was performed using a beaker of water that was held using the same arm the hand tremor simulator was placed on as shown in **Figure 5.8**

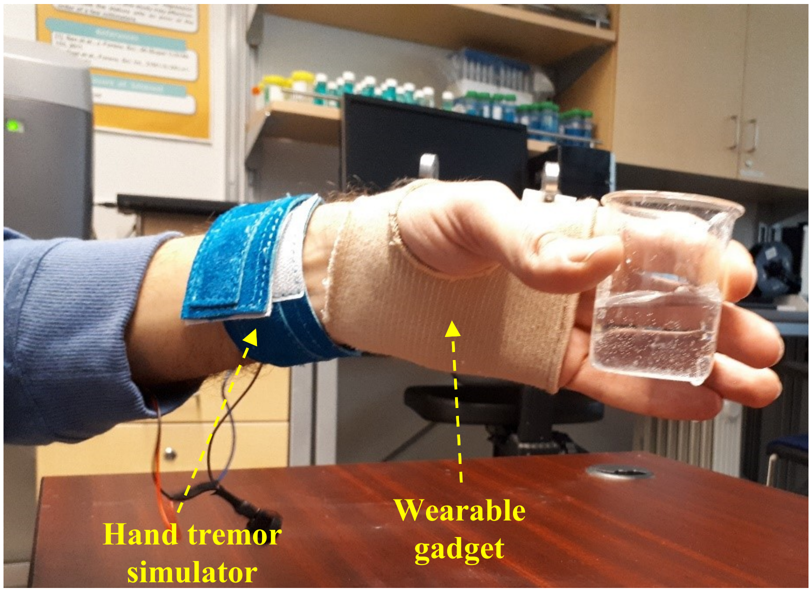


Figure 5.8 Apparatus of the first experiment: drinking water from a cup

The experimentation was carried out in three different situations: with no functioning actuators, with only one functioning actuator, and with two functioning actuators as shown in **Figure 5.9**, to **Figure 5.11** respectively. The actuators were restricted from functioning during testing by using pieces of metal bars to prevent them from moving. During the first test, the water became turbulent and a noticeable amount of spillage occurred, however during the second and third tests the water surface remained smooth with less than 1 cm and 0.5 cm of displacement in height respectively as shown in **Figure 5.12.** The result of the observation that the magnetic actuators are able to mitigate the vibration caused by the hand tremor simulator enough to effectively avoid spillage from the beaker.

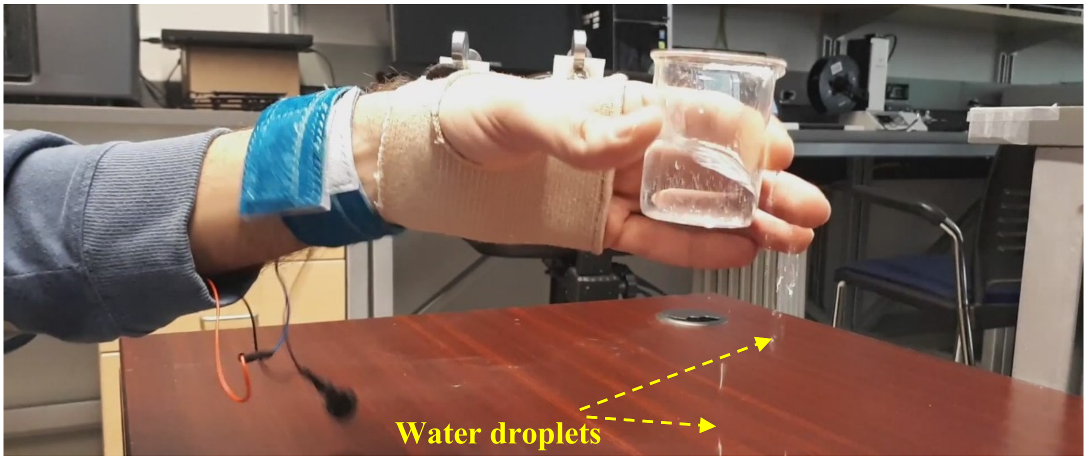


Figure 5.9 First experiment with no functioning actuators

Figure 5.10 First experiment with one functioning actuator

Figure 5.11 First experiment with two functioning actuators

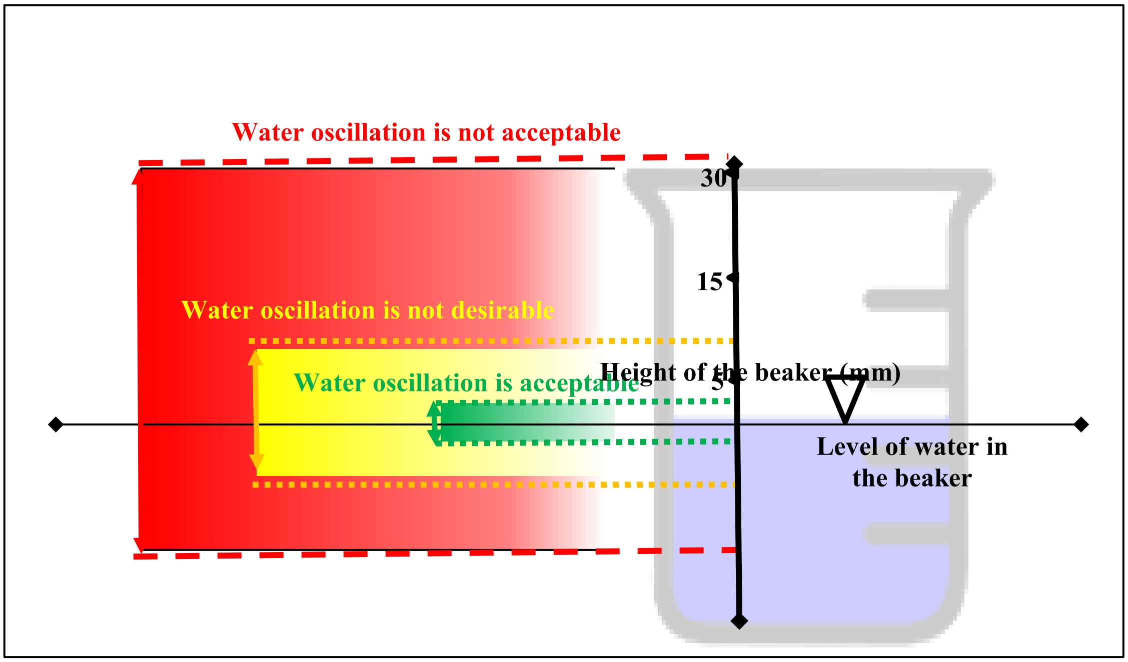


Figure 5.12 Experimental amplitudes of the water oscillation during the first experiment with the red, yellow, and green zones, outlining the amplitudes of water in from the first, second and third tests respectively

The second experiment was designed to simulate drinking soup using a spoon. This experiment was similar to the previous experiment, where the functionality of the magnetic actuators was altered throughout testing in order to determine the effect of the actuators on the task. With only a single actuator functioning it can be seen that a considerable amount of liquid is spilled from the spoon as shown in Figure 5.13, however when were working much less spillage occurred as shown in Figure 5.14.

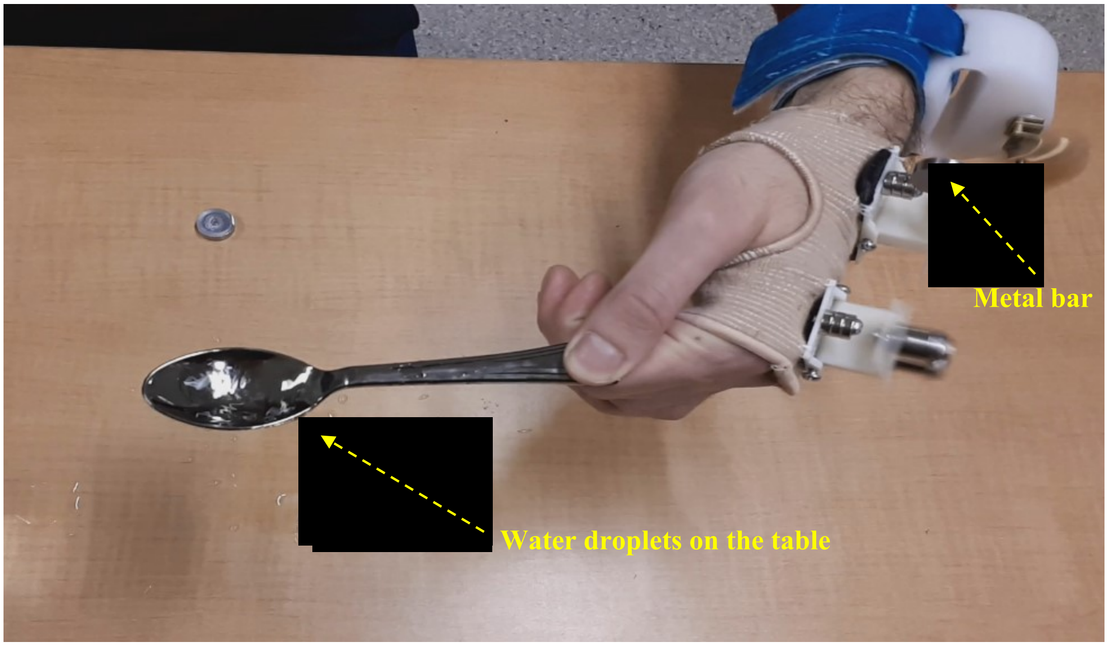


Figure 5.13 Second experiment with only one functioning actuator

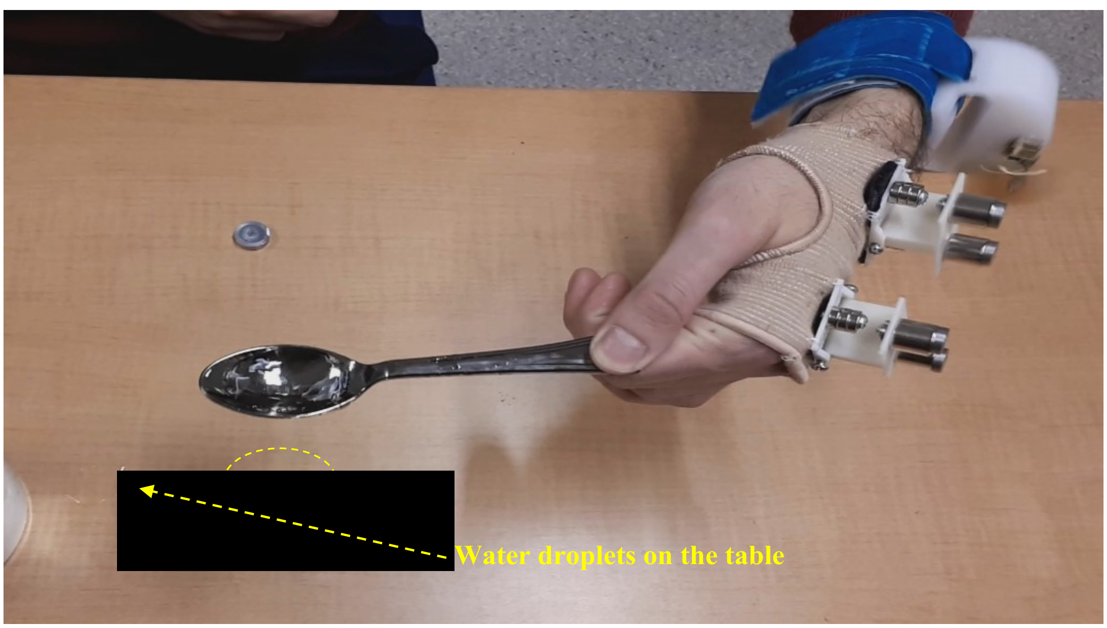


Figure 5.14 Second experiment with two functioning actuators.

Chapter 6: Conclusion

6.1 Contribution of Thesis

This thesis has brought forward major innovations as follows:

A. The damping effect and mechanical behavior of the magnetic spring system are characterized in this study.

B. Unlike many magnetic actuators and dampers which require power sources, this study focuses on a new concept of magnetic damping works passively by using magnetic springs, i.e. the repulsive force between magnets. Based on the magnetic spring the seesaw-like actuator is developed.

C. The principal objective of this study is to invent a unique assistive device as a wearable gadget to address hand tremor among patients with neurological disorders. The wearable gadget consists of the seesaw-like actuators.

6.2 Summary

The major contributions of this thesis are two major innovations:

- The seesaw-like actuator developed based on the principle of magnetic spring concept;
- The wearable gadget for to reduce hand tremors which consists of the seesaw-like actuators.

6.2.1 Seesaw-Like Actuator

This actuator is a vibration absorber, based on the concept of magnetic spring. It is capable of damping harmonic excitations, such as hand tremors. Its unique features are:

- Seesaw-like structure;
- Single degree of freedom configuration;
- Rotational motion (neither axial nor directional motions);

6.2.2 Wearable Gadget

This wearable gadget is the first device that uses a seesaw-like actuator. During the experimental tests on the prototype, it was observed that having two actuators was able to produce better results, which were especially noted during the second experiment. As the water displacement became greater as the number of working actuators was reduced, this demonstrates that the wearable gadget is able to function as an assistive device for patients that experience hand tremors. The final design is able to satisfy all of following:

- The device must be a passive mechanism;
- The device must have a universal application;
- The device must not restrict the fingers and wrist;
- The device must be lightweight;
- The device must be affordable.

6.3 Future Works

This thesis can be improved by considering two additional realms of research. Firstly, this study introduces the innovative seesaw-like actuator into the field of passive magnetic actuators, which is able to dampen rotational motions and vibrations; however, more research is required to understand better both the vibrational behavior and the damping effects of the actuator. However, the vibrational behavior and damping effect can be determined through advanced mathematics and various formulae, further study on this particular actuator will allow it to be integrated into various other applications. For example, the magnetic spring can be incorporated into a device used for vibrational control in machines as well as other medical devices that require control of axial and rotational vibrations, such as robotic surgery and micro-needles in single cell surgery automation where there is little tolerance for vibration. Furthermore, research in this field can easily be improved and expanded regarding the possibility of new materials such as programmable magnets and ferrofluid.

Secondly, this study focuses on the fact that the wearable gadget is used as an assistive device for patients with hand tremors due to various neurological disorders. In order for this device to be marketable, human and clinical trials are needed.

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Appendices

Appendix A

A.1 Data analyses Procedure:

In order to study the damping ratio ζ for the three experiments, interpolation among the maximum points was calculated by MATLAB, as the beam frequency was higher than 20 Hz and the vibration recorder could only record up to 20 Hz. The maximum form of each experiment were chosen from eight-data sets. Due to the fact the goal was to determine the exponential functions, the interpolation was calculated with respect to the maximum points in each experimental data set. In **Figure A.1.1** below, the exponential function of the inertial mass is represented by a as a blue line and is equal to:

$$f(x) = 4.055\ e^{-0.003062t} \tag{A.1}$$

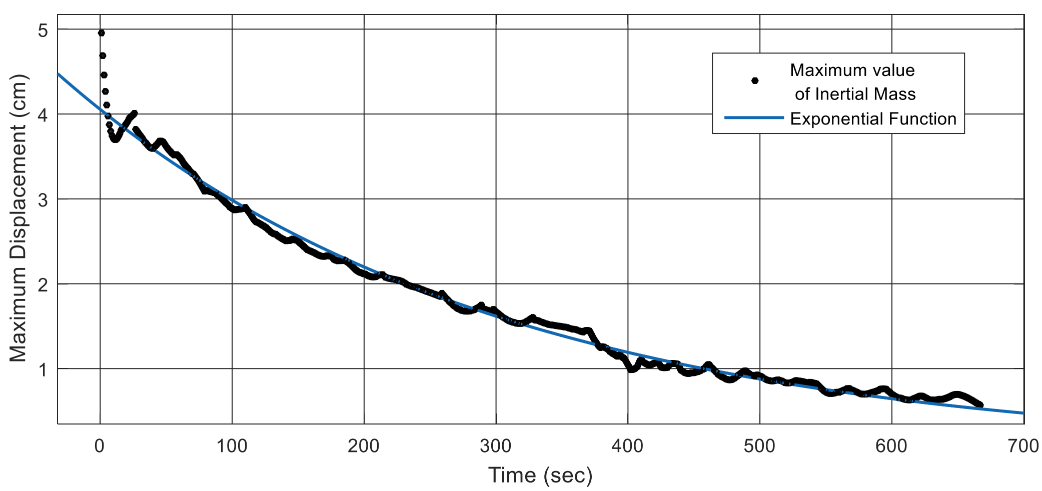

Figure A.1.2 Exponential trend-line of the inertial mass

For the half-filled bottle of water, though resonance has affected the maximum points, the data is interpolated by implementing the exponential function which minimizes the effect of resonance, as illustrated in in **Figure A.1.2**. The exponential function for this experiment is:

$$f(x) = 4.071\ e^{-0.03262t} \tag{A.2}$$

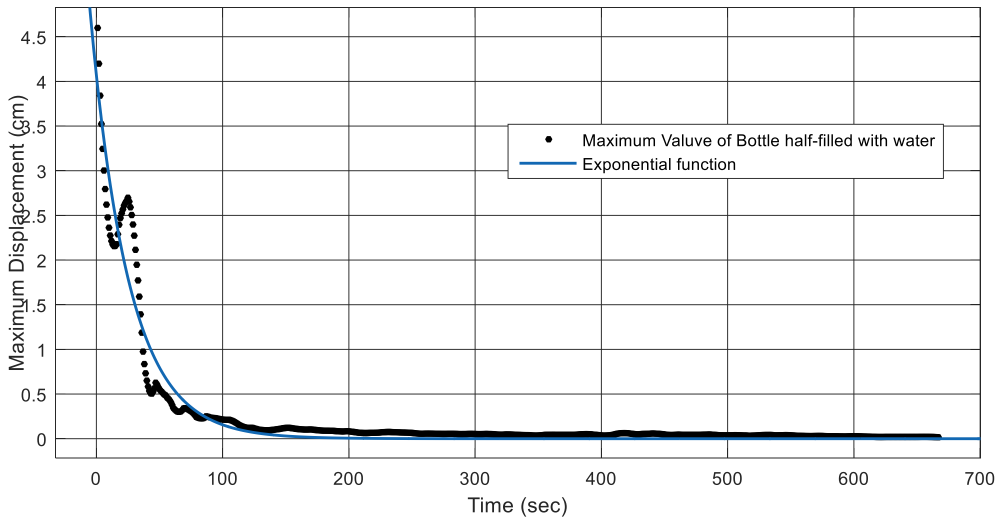

Figure A.1.3 Exponential trend-line of the half-filled with water bottle

The exponential function for the magnetic spring system with respect to the maximum values over oscillation is shown in **Figure A.1.3**. The exponential function is:

$$f(x) = 6.866e^{-0.248t} \tag{A.3}$$

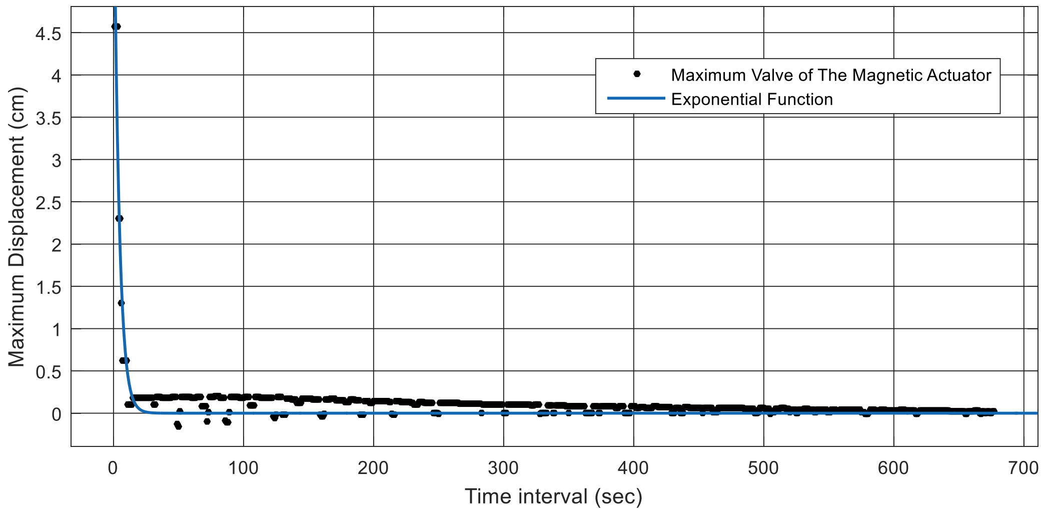

Figure A.1.4 Exponential trend-line of the magnetic spring system

Appendix B

B.1 Vibration of the beam:

Assuming the natural frequency within all experiments are constant, the only variable is the damping ratio (ζ), which is a part of the power in an exponential function.

B.2 Natural frequency:

The natural frequency (ω_n) can be written as:

$$\omega_n = \sqrt{\frac{K}{m}} \tag{B.1}$$

Where *K* is the stiffness and *m* is the mass on the tip of the beam.

The stiffness of the beam is written as:

$$K = \frac{3EI}{l^3} \tag{B.2}$$

Where the modulus of elasticity (*E*) of aluminum is 69 GPa, and *I* is the moment of inertia of the beam which can be written as (William T. & Marie Dillon, 1997):

$$I = \frac{1}{12} w t^3 \tag{B.3}$$

Where *w* and *t* are width and thickness of the beam respectively. Hence *I* and *K* can be found to be $16 \times 10^{-12}\ m^4$ and $31.25\ N/m$ respectively.

The mass of the inertial mass and the half-filled water bottle are equal, whereas the magnetic spring system is 10 grams lighter. The total mass was for the inertial mass and the half-filled water bottle the sum of the mass applied and the mass of the vibration recorder, adding up to 80 grams. The total mass for the magnetic spring system was 70 grams. The natural frequency of the inertial mass and the half-filled water bottle are assumed to be the same at a value of 19.76 rad/sec, however, the natural frequency of the magnetic spring system is 21.11 rad/sec

B.3 Damping ratio ζ :

From the values in the previous section, the damping ratios can be attained for the inertial mass, the half-filled water bottle and the magnetic spring system which are 1.54×10^{-4}, 1.64×10^{-3}, 1.17×10^{-2} respectively.

Hence, it can be determined from the damping ratio that the magnetic spring system is far more effective than the both the inertial mass and the half-filled water bottle.

Appendix C

C.1 Maximum force of the hand tremor simulator

As mentioned before, hand tremor is assumed to be a sinusoidal movement. Therefore, a sinusoidal movement is needed to simulate the hand tremor. The forced vibration of the hand tremor simulator is considered sinusoidal, from the force generated due to the unbalanced rotating mass. The maximum force in this machine can be obtained by:

$$F_{max} = m\ e\ \omega^2 \tag{C.1}$$

Where:

Eccentric mass (m) is 32 grams

Offset length, e, is 9mm

Frequency, ω, is 67.51 rad/sec

$$F_{max} = 0.032\ \times 0.009 \times 67.51^2 = 1.313\ N$$