Fall 1-31-2004

Magneto-rheological fluid orthosis for suppressing tremor

Hyoung-Joo Yeo
New Jersey Institute of Technology

ABSTRACT

MAGNETO-RHEOLOGICAL FLUID ORTHOSIS FOR SUPPRESSING TREMOR

by

Hyoung-Joo Yeo

Tremor is a common movement disorder that occurs with specific neurological conditions. This condition may seriously impact daily living activities. The aim of the present study is to evaluate the possibility of the development of a wearable technology that is capable of exerting torques at a user's joints for suppressing tremor.

This thesis is based on the concept of "smart structures" which are made of Magneto-Rheological (MR) fluid that can dynamically alter its viscosity under magnetic field. The wearable tremor suppressing orthosis needs several conditions. It should be safe, light weight, simple and small in structure, and easily attachable. An MR fluid orthosis satisfies these conditions. This thesis shows the physical properties of MR fluid and the basic concept of a rotational MR fluid damper for suppressing tremor. Specifically, an MR fluid friction damper experimentally provides a damping coefficient capable of suppressing tremor. A simulation confirms that the damping moment of the MR fluid friction damper is sufficient to suppress that of the wrist tremor, with realistic peak to peak torque 0.022 N·m. This allows slower intentional movement to occur with only moderate attenuation.

The results of this work show that it is possible to design an MR fluid orthosis that is wearable and capable of suppressing tremors at the wrist. The proportionality of the tremor-reducing torque to electric current allows the potential for both user adjustment as well as automatic feedback control.

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FOR SUPPRESSING TREMOR

by

Hyoung-Joo Yeo

A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
In Partial Fulfillment of the Requirements for the Degree of
Master of Science in Mechanical Engineering

Department of Mechanical Engineering

January 2004

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APPROVAL PAGE

MAGNETO-RHEOLOGICAL FLUID ORTHOSIS FOR SUPPRESSING TREMOR

by

Hyoung-Joo Yeo

Dr. Richard A. Foulds, Thesis Advisor — Date
Associate Professor and Associate Chair for Research of Biomedical Engineering, NJIT

Dr. Zhiming Ji, Committee Member — Date
Associate Professor of Mechanical Engineering, NJIT

Dr. Rong-Yaw Chen, Committee Member — Date
Professor of Mechanical Engineering, NJIT

BIOGRAPHICAL SKETCH

Author: Hyoung-Joo Yeo

Degree: Master of Science

Date: January 2004

Undergraduate and Graduate Education:

- Master of Science in Mechanical Engineering,
  New Jersey Institute of Technology, Newark, NJ, 2004

- Bachelor of Science in Mechanical Engineering,
  Korea University, Seoul, Korea, 1995

- Bachelor of Science in Horticultural Science,
  Korea University, Seoul, Korea, 1993

Major: Mechanical Engineering

To my father, Youngjun Yeo (존경하는 아버님께)
To my mother, Jaejeong Yoo (사랑하는 어머님께)
To my wife, Kyoungai Choi (사랑스런 아내에게)

ACKNOWLEDGMENT

I would like to express my sincere gratitude to Dr. Richard A. Foulds, the professor and research advisor who has inspired me to imagine, learn, and create by providing me with constant supervision and guidance, many suggestions, new ideas, encouragement, and support toward the completion of this work.

My gratitude is extended to Dr. Zhiming Ji and Dr. Rong-Yaw Chen for serving as members of my thesis committee to guide, comment on, and suggest my future work.

It is a high pleasure to express my gratitude to my family, especially my wife, Kyoungai Choi, I really appreciate her support and patience.

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CHAPTER 1

INTRODUCTION

1.1 Definition of Tremor

Tremor is a rhythmic involuntary oscillatory movement of body parts, with a relatively fixed frequency and amplitude. It can be observed in healthy subjects as well as in patients with various diseases [1].

Most clinical forms of tremor have a rapid rate, fine amplitude, and an irregular rhythm. The finest and most rapid tremors are found in mild hyperthyroidism and in anxiety neuroses, and the amplitude may be so small that the movement can only be detected by palpation. However, there is no constancy of character since severe hyperthyroidism or hysteria can produce tremor of much larger amplitude. In marked contrast, the tremors due to organic disease of the central nervous system have a remarkable constancy of character. Attempts have been made to classify tremor on the basis of aetiology, anatomy, or physiology, or on the basis of amplitude and frequency. A survey of the various classifications is given by Brumlik and Yap (1970), and the classification used here will be that devised by those authors on the basis of the degree of postural innervation that exaggerates the tremor.

Two main groups, normal (physiological) and abnormal (pathological), relate to the absence or presence of disease in the subject. Each main group may be subdivided into three sections of rest, postural, or intentional tremor, each of the six groups having their own characteristic frequency, amplitude, wave-form, and temporospatial distribution. 'Rest' indicates that the voluntary muscles involved are relaxed, and 'postural' ('static') that the part involved is held still against gravitational forces as in the outstretched hand. In this latter position, involving an isometric muscular contraction, no effort is made to reach a goal. 'Intentional', synonymous with 'kinetic', 'action', or 'volitional', implies that the part is moving towards a purposive goal with involvement of an isotonic and not an isometric contraction of the affected muscles. The designation of a tremor as abnormal applies to one that appears in a disease state with a peripheral appearance characteristic of that state, criteria with often, but not invariably, coincide. For example, while Parkinsonian rest tremor appear as a slow, rhythmic oscillation there are some Parkinsonian patients who exhibit only normal tremor at rest. Conversely, it is possible to simulate Parkinsonian tremor in the normal person by the administration of drugs. Thus we have a normal tremor in an abnormal state and an abnormal tremor in a normal state.

Table 1.1 summarizes the characteristics of some clinical forms of tremor; in this monograph 'fine' will be taken to include tremors of amplitude less than 5 mm., 'moderate' of amplitude 5-20 mm., and 'gross' of amplitude greater than 20 mm [2].

Among the pathological cases, essential and pakinsonian tremor are the most often observed types. Parkinson's disease is a growing problem, with 120-180 victims in each 100,000 people. Most patients are over 40 years old although the disease can appear in younger subjects. Essential tremor affects even up to 5,000 people in each 100,000. The mean age at onset is 45 years, but the disorder may start in adolescence and early adulthood [1].

Specific clinical features of the tremor are carefully observed and characterized, and the approximate frequency of the tremor is recorded. Tremor frequency is usually characterized as low (<4 Hz), moderate (4 to 6 Hz), or high (>6 Hz) [3].

1.2 Types of Tremor

1.2.1 Rest Tremors

Tremor exists at rest in the normal human extremities; such physiological tremor is fine in amplitude (less than 80 μ), irregular in its wave-form, and has a frequency of about 10 Hz. (Brumlik and Yap 1970). This frequency is much slower in children and gradually rises to the adult value on the same time-scale as the alpha-wave frequency. Abnormal rest tremors are most frequently observed in Parkinson's disease, where they are slow (5-6 Hz) and more rhythmic than the normal rest tremors, displaying characteristic wave-forms of amplitude periodicity, spindle formation, and harmonic waves (Wachs and Boshes, 1961). Indeed, the almost clockwork rhythm of Parkinsonian tremor at rest is a valuable aid to the diagnostician. The tremor tends to be of identical frequency in simultaneously measured extremities, in contrast to the more variable normal rest tremor, and shows an increase in amplitude in muscles which are subjected to passive stretch (French, 1960). In Parkinsonism, those parts in which rigidity is greatest are least likely to exhibit tremor, and this accounts for its predominance in the smaller and more peripheral muscles of the upper limbs. The tremor may move from one group of muscle to another, the typical 'pill-rolling' movement of the finger and thumb suddenly giving way to a pronation-supination of the forearm, which in turn change to a flexion-extension of the wrist. Parkinsonian tremor is strongly affected by stress and anxiety which increase the amplitude, while sudden emotional shock or strong effort of will can control the tremor for several minutes.

A typical Parkinsonian rest tremor of 4-6 Hz. has been observed in green monkey after surgical lesions in the ventromedial tegmental region of the brain-stem (Poirier and Sourkes, 1965; Goldstein, Anagnoste, Owen, and Battista, 1967; Battista, Goldstein, Nakatani, and Anagnoste, 1969a). The tremor appeared in the contralateral extremities in 60-70 per cent the animals about 5-7 days after the operation, and, like that of Parkinsonism, involved the upper extremities more than the lower. Moreover, excitement intensified the tremor while voluntary movement abolished it. Kaelber and Hamel (1961) produced a rest tremor of frequency 4-6 Hz. in the cat by stimulation of the basal forebrain, although the frequency was measured on the electromyogram as 10 Hz. Bursts of tremor lasting 1, 1.5, and 2 seconds were recorded; it is significant that similar bursts of tremor are evident from the tremor tracings reported by Battista and others (1969) [2].

1.2.2 Postural Tremor

Postural Tremor plays little part in Parkinsonism as can be seen by the similarity of the tremor frequency and wave-form recorded before and after the extremity is placed in the static position. However, as noted above, there is an increase in amplitude on going from the relaxed to the static positions (French, 1960; Wachs and Boshes, 1961). Physiological tremors, such as those of thyrotoxicosis, hysteria, anxiety states, and delirium tremens, lie in the range 8-12 Hz., but the latter condition often shows a slower of 6 Hz. (Brumlik and Means, 1969). All four tremor are more rhythmic than normal rest tremor but less so than Parkinsonian tremor, and show spindle formation and amplitude periodicity. Brumlik and Means (1969) have designated a subgroup of abnormal postural tremor, the shuddering tremors, which includes physiological shivering in response to cold, the limb tremor of acute cerebellar ataxia and brain-stem encephalitis, and a number of tremors in experimental animals. This subgroup is characterized by the lack of continuity and presence of 1-2 second bursts of tremor separated by periods of quiescence. They show the usual 8-12 Hz. frequency range shared by all postural tremors and an asymmetrical, asynchronous time distribution. It is debatable whether shivering should be regarded as an abnormal tremor since it occurs in the non-drugged or healthy subject, but its peripheral characteristics are so similar to those of the shuddering tremors that it is classified with them.

Postural tremors have also been induced in experimental animals. Ward, McCulloch, and Magoun (1948) report that lesions of the mesencephalic and pontine tegmentum in monkeys gave an 8-9 Hz. rest and postural tremor. This tremor shifted from one part of the limb to another and disappeared with sleep (Cordeau, Gybels, Jasper, and Poirier, 1960), much as did the Parkinsonian tremors described above. Kaelber (1963) observed postural tremors in cats with mesencephalic lesions, characterized by 1-1.5 second bursts of tremor; similar shuddering tremors of frequency 4-6 Hz. were reported in monkeys by Poirier and Sourkes (1965), Sourkes and Poirier (1966), Goldstein and others (1967), and by Goldstein and others (1969b) after surgical lesions in the ventromedial tegmental area. Bursts of tremor are clearly seen in the tracings of Goldstein and co-workers (Battista and others, 1969; Goldstein and others 1969b), although they make no attempt to relate these to the shuddering tremors of Brumlik and Means (1969) [2].

Table 1.1 Characteristics of Some Clinical Forms of Tremor [2]

Tremor Group	Condition	Frequency (Hz.)	Amplitude	Features of Interest
Normal rest	Physiological	8 - 12	Fine	Ballistocardiographic, irregular
Normal postural	Physiological	8 - 12	Fine	Irregular
Normal intentional	Physiological	8 - 12	Fine	Irregular
Abnormal rest	Parkinson's disease	5 - 6	Fine-gross	Regular rhythm, amplitude periodicity, spindle formation, harmonic waves
Abnormal postural	Thyrotoxicosis, hysteria	8 - 12	Fine-gross	Continuous, amplitude periodicity, spindle formation
	Delirium tremens	6	Fine-gross	Amplitude periodicity, continuous
	Shivering, limb tremor of acute cerebellar ataxia, brain-stem encephalitis	8 - 12	Fine-moderate	Asynchronous, asymmetrical shuddering bursts of tremor
Abnormal intentional	Wilson's disease, multiple sclerosis, cerebellar disease	3 - 8	Usually fine, sometimes gross	Rhythmic, sinusoidal

1.2.3 Intentional Tremors

An intentional tremor, like postural tremor, plays little part in Parkinson's disease; indeed, the rest tremor of Parkinsonism is often diminished or abolished by volitional movement. In the normal subject intentional tremor bears the same relationship to rest tremor as does postural tremor, that is, it is irregular with a frequency range of 8-12 Hz. and a much coarser, though still fine, amplitude (Brumlik and Yap, 1970). Diseases of the cerebellum may produce intentional tremor in apparently resting muscles such as those of the head and neck; these movements are called 'titubations' and are also slow (4-5 Hz), irregular, and show a rhythmic, sinusoidal wave-form, as seen in Wilson's disease or multiple sclerosis. They are readily distinguished by their relationship to movement. Characteristic intentional tremors can be produced in animals in which the neo- as well as the paleocerebellum is damaged or removed. Since the characteristic effect of the cerebellum is to add smoothness and precision to voluntary movements, the removal of its influence leads to an effort to correct errors in performance with resulting tremor. Other manifestations of this phenomenon are nystagmus (a rapid movement of the eyeballs) and 'scanning', a speech defect in which each syllable is pronounces separately and which is apparently due to intentional tremor of the muscles involved in speech [2].

1.3 Tremor Treatments

There is no single treatment for tremor. Stimulants such as caffeine are best avoided. One of several drugs that affect the involuntary (autonomic) nervous system may be recommended. These drugs are called beta blockers [4].

In January 2002, the FDA approved bilateral subthalamic nucleus and globus pallidus deep brain stimulators to treat other movement symptoms of Parkinson's disease including rigidity, bradykinesia [slowness of movement], tremor, and freezing. Deep brain stimulation has the advantage that instead of destroying the overactive cells that cause symptoms in Parkinson's disease it instead temporarily disables them by firing rapid pulses of electricity between four electrodes at the tip of the lead. The lead is permanently implanted and connected to a pacemaker controller installed underneath the skin of the chest [5].

Treatment of tremor however, is not always possible with the aid of drugs or surgery. For those patients left with severe disabilities (due to magnitudes of the tremors often related with action to be performed), other approaches have been followed based on external mechanisms attached to the arm. External devices in the form of orthoses mechanisms that act in the form of mechanical loading in the affected limb are often cumbersome, do not completely preserve voluntary movement and limit range of motion.

Active devices are very difficult to control and passive devices need to be customised for each individual [6].

1.4 External Tremor Suppression Orthosis

External mechanical devices have been developed over the years following two distinctive approaches: actively or passively compensation based on grounded or wearable orthosis. Grounded devices have been developed to assist in the daily living, such as eating or controlling an electrical wheelchair. The MIT damped joystick is an example of a 4-DOF device designed to aid in the control of a wheelchair by people suffering from tremor. CEDO (Controlled Energy Dissipation Orthosis) developed by Rosen and colleagues, is a 3-DOF grounded device that can be attached to a wheelchair or table permitting assistance for activities on a table. The device applies a velocity-proportional resistance to the forearm driven by particle brakes controlled by a computer. Experimental results with the device have reported a considerable tremor reduction with tracking tasks.

The only commercial available grounded device to assist in eating activities is the “Neater eater” manufactured by Michaelis Engineering. The device is a 2-DOF counter balanced spring based linkage arm that lifts and brings a spoon to an adjustable position near the mouth eliminating uncontrolled movements. The most far reaching study on wearable orthosis has been introduced by Kotovsky & Rosen with a viscous damping orthosis mechanism (Viscous Beam). Their mechanism works by applying a viscous resistance to motion at wrist level. This single degree of freedom device reduces flexion/extension tremor amplitude by means of a constrained-layer-damping system able to damp rotary deflections of the wrist. A bending transmission converts flexion/extension of the wrist to linear displacement within the damper. Initial experimentation with the Viscous Beam showed that although the compactness of the device allowed for damping of tremor with some degree of amplitude, the device added elastic stiffness to normal movements and concluded that the device needed to be customized to each individual [6, 7].

CHAPTER 2

MATERIALS

2.1 Magnetorheological (MR) Fluid

Magnetorheological (MR) fluids are materials that respond to an applied magnetic field with a change in rheological behavior. Typically, this change is manifested by the development of a yield stress that monotonically increases with applied field. Interest in magnetorheological fluids derives from their ability to provide simple, quiet, rapid-response interfaces between electronic controls and mechanical systems.

The MR fluids are considerably less well known than their electrorheological (ER) fluid analogs. Both fluids are non-colloidal suspensions of polarizable particles having a size on the order of a few microns. The initial discovery and development of MR fluids and devices can be credited to Jacob Rabinow at the US National Bureau of Standards (Rabinow, 1948a, 1948b, 1951) in the late 1940s. The late 1940s and early 1950s actually saw more patents and publications relating to MR than to ER fluids. Except for a flurry of interest after their initial discovery, there has been scant information published about MR fluids. Only recently has a resurgence in interest in MR fluids been seen (Shtarkman, 1991; Kordonsky, 1993; Weiss et al., 1993; Carlson et al.,1994; Carlson, 1994; Carlson and Weiss, 1994). A number of MR fluids and various MR fluid-based systems have been commercialized including an MR fluid brake for use in the exercise industry (Anon., 1995; Chase, 1996), a controllable MR fluid damper for use in truck seat suspensions (Carlson, Catanzarite and St.Clair, 1995; Lord, 1997) and an MR fluid shock absorber for oval track automobile racing. The magnetorheological response of MR fluids results from the polarization induced in the suspended particles by application of an external field. The interaction between the resulting induced dipoles causes the particles to form columnar structures, parallel to the applied field. These chain-like structures restrict the motion of the fluid, thereby increasing the viscous characteristics of the suspension. The mechanical energy needed to yield these chain-like structures increases as the applied field increases resulting in a field dependent yield stress. In the absence of an applied field, MR fluids exhibit Newtonian-like behavior. Thus the behavior of controllable fluids is often represented as a Bingham plastic having a variable yield strength (e.g., Phillips, 1996) [8].

The viscous medium is comprised of a base fluid (silicon oil or ethanol glycol) that contains ferrous particles. These particles polarize when introduced to a magnetic field (see Figure 1). The polarization of the particles causes a magnetic attraction, which in turn results in the formation of chains and columns of particles. The presence of the chains and columns result in an increase of the apparent viscosity of the fluid. As the fluid moves through the field normal to the vector of the field lines, the change in viscosity translates to a change in damping force [9].

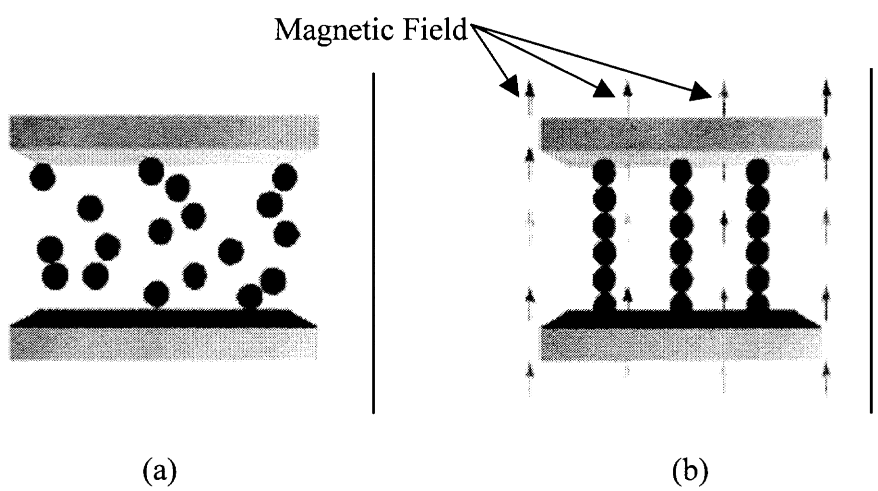


Figure 2.1 An illustration of MR fluid at rest (a), and within a magnetic field (b).

2.2 The Advantages of MR Fluid for Tremor Suppression Orthosis

The most strong point of MR fluid for tremor suppression orthosis is that it is the flowing liquid which is safe for human body and not heavy but its viscosity can be remarkably changed instantaneously in the magnetic field. That is to say that its viscosity changes from water to peanut better in a moment. It means that we can make real-time controllable and wearable damper for suppressing tremor by making wearable electromagnet system. Because each tremor patient has his/her own frequency, if the author makes programmable orthosis which can adjust its stiffness according to the cycle of trembling, the patients could do basic daily activities without any trouble. In case of irregular frequency tremor, the feed back system should be needed. The system should detect the acceleration or displacement of the tremor and adjust the timing of sending electric currents.

In case of the biological effects of static magnetic fields, it will be very safe. Because static magnetic fields of up to 2.0 Tesla are now used in current FDA-approved and several million people a year experience these fields, but magnetic fields of MR fluid orthosis will not exceed 1.0 Tesla [10].

The MR fluid orthosis is comparatively simple, safe, and lightweight and shows very high performance.

CHAPTER 3

USEFUL PHYSICAL PROPERTIES FOR TREMOR SURPPRESSION

3.1 Pressure Resistance Force of MR Fluid

3.1.1 Commercial Linear MR Fluid-based Damper

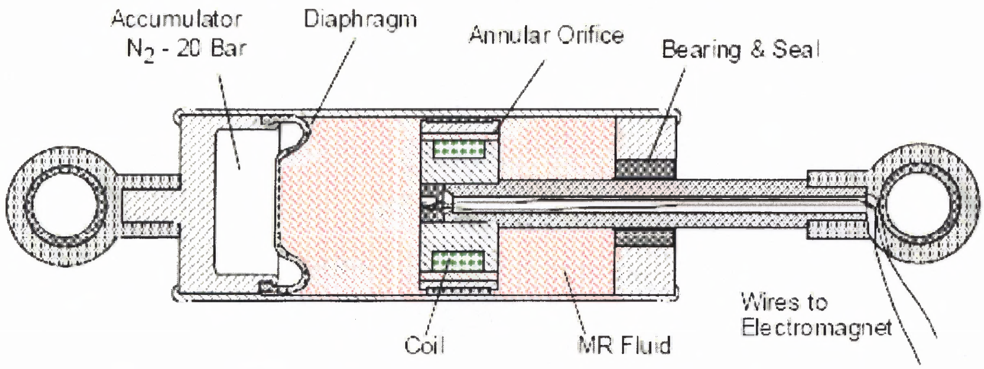


Figure 3.1 Commercial linear MR fluid-based damper.

Recently a small, MR fluid-based damper (shown in Figure 3.1) has been commercialized for use in a heavy-duty vehicle seat suspension system for large highway vehicles.

The controllable MR damper is capable of providing a wide dynamic range of force control for very modest input power levels as shown in Figure 3.2.

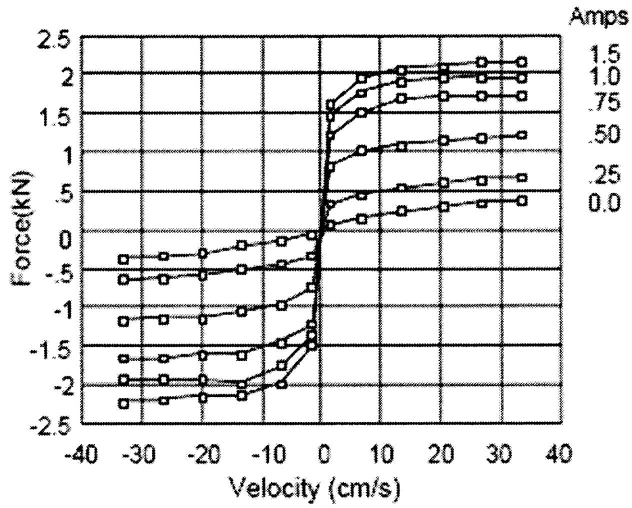


Figure 3.2 Performance curves for the linear MR damper.

The damper is 4.1 cm in diameter, has a 17.9 cm length at mid-stroke and has a ±2.9 cm stroke. The MR fluid valve and associated magnetic circuit is fully contained within the piston. Current is carried to the electromagnetic coil via the leads through the hollow shaft. An input power of 5 watts is required to operate the damper at its nominal design current of 1 amp. Although the damper contains about 70 cm^3 of MR fluid, the actual amount of fluid activated in the magnetic valve at any given instant is only about 0.3 cm^3 [8]. The basic concept of electromagnet controlled MR Fluid-based Damper is shown in Figure 3.3.

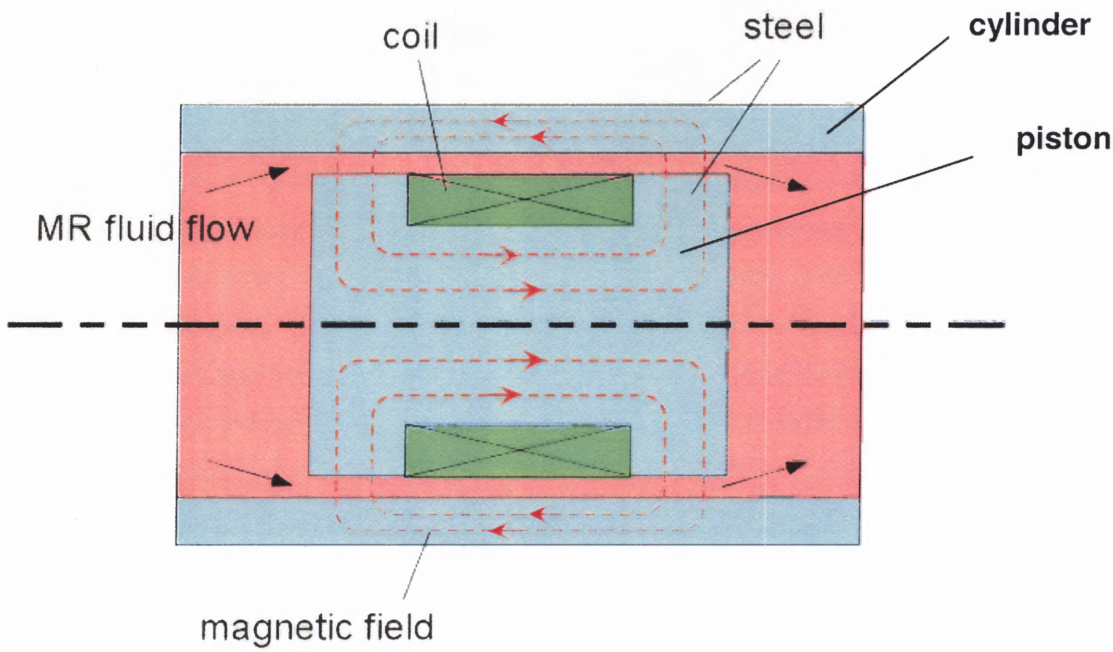


Figure 3.3 Basic concept of MR fluid damper [12].

3.1.2 Usefulness of Pressure Resistance Force for MR Fluid Suppression Orthosis

3.1.2.1 Cylinder and Piston System of Pressure Damper. The same mechanism in Figure 3.1 can be applied to tremor suppression orthosis. The pressure resistance force is strong enough to prevent any kind of tremor. However, if the cylinder and piston system is used for the damping system, there are several disadvantages for a tremor suppression orthosis. The size of the orthosis would be too large and the system too complicated to wear under normal clothing. The weight would be very heavy because of steel parts and the amount of MR fluid. In addition, the MR fluid should be completely sealed because this system uses pressure resistance. The sealing would cause the system to be more complicated and would introduce cost impact and maintenance problems. However, this system can be suitable for a very strong suppression force, for example, elbows and knees.

3.1.2.2 Valve System of Pressure Damper. This system will be suitable for relatively needing small damping force, for example, an upper arm tremor. This system has several advantages compared to the cylinder and piston system. First of all, the main material is flexible vinyl so that it can be directly worn under the normal clothing. This system is relatively lightweight compared to the piston and cylinder system. Complete sealing will be no problem because the main material is the vinyl. However, the vinyl is the weakest point of this system because the vinyl is a very weak material.

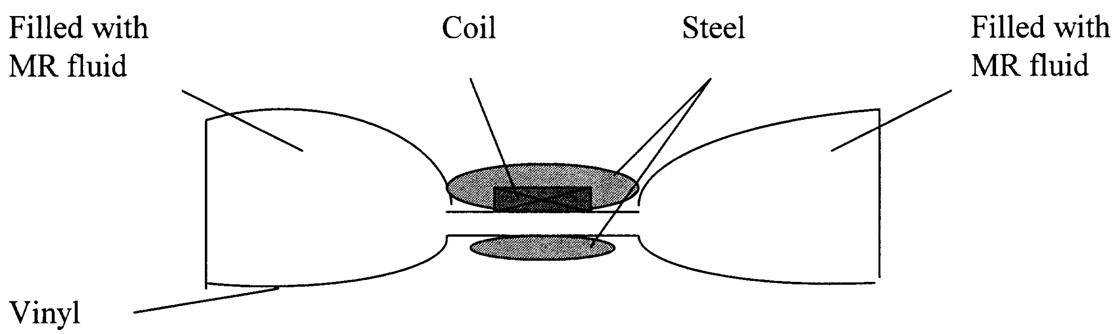


Figure 3.4 Basic concept of MR fluid valve.

3.2 Friction Resistance Force of MR Fluid

3.2.1 MR Controllable Friction Damper

Recently, a new way of using MR fluids in which the fluid is contained in an absorbent matrix has been developed. The basic elements of a simple MR sponge damper are shown in Figure 3.5. No seals or bearings are required and only 3 ml of MR fluid is used. A layer of open-celled, polyurethane foam saturated with MR fluid surrounds the steel bobbin and coil. Together, these elements form a piston on the end of the shaft that is free to move axially inside a steel housing that provides the magnetic flux return path.

Damping force is proportional to the sponge's active area. Maximum on-state force for this type of damper is typically on the order of 100 N.

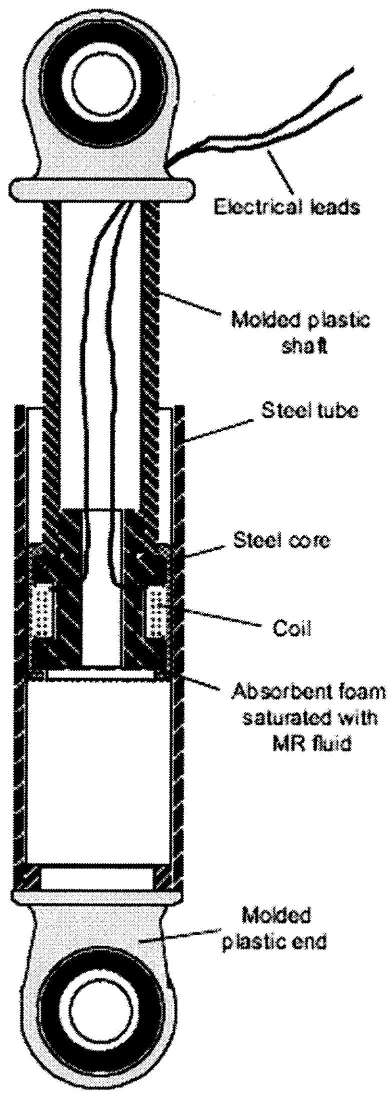


Figure 3.5 Axial cross section of basic MR sponge damper.

The fluid in an MR sponge device is constrained by capillary action in an absorbent the matrix. Most commonly, this matrix is made from an open-celled sponge material. Woven and non-woven fabrics and felts also perform well as matrix materials.

As illustrated in Figure 3.6, the absorbent matrix keeps the MR fluid located in the active region of the device between the poles where the magnetic field is applied. The matrix is normally attached to one of the poles. Application of the magnetic field causes the MR fluid in the matrix to develop yield strength and resist shear motion. The amount of force produced is proportional to the area of MR sponge that is exposed to the magnetic field. In a typical MR sponge device, about 5 N/cm^2 is possible. This basic arrangement can be applied in both linear and rotary configurations, wherever a direct shear mode of operation would be used. Functionally, such dampers behave as variable friction elements in a dynamic mechanical system.

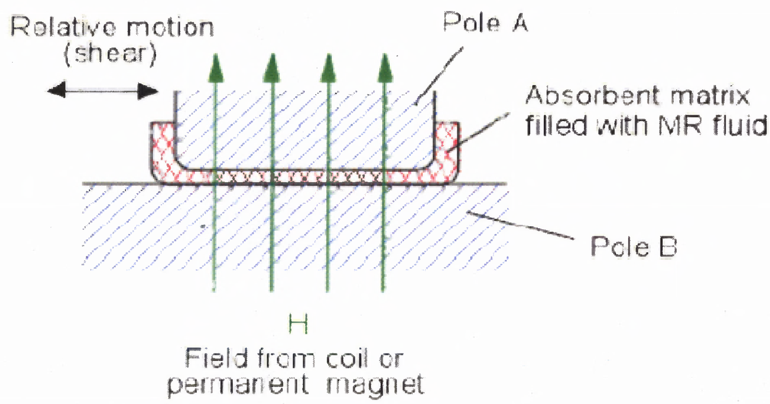


Figure 3.6 Elements of basic MR sponge device.

Because of their open structure, the shape of a MR sponge device is less constrained than a normal controllable fluid device. Multiple degrees of freedom are easily accommodated. Linear devices such as dampers may be tubular, flat or planar while rotary brakes may take on the form of a localized magnetic "caliper" operating on a thin disc. Fluids in these devices are resistant to gravitational settling or sedimentation of the MR fluid because of the wicking action of the matrix. Typically, the matrix material used in these devices is open-celled polyurethane foam. Reticulated foam varieties having a very high an open volume 95% or more are preferred. Pore sizes typically range from 250 to 500 microns. Other suitable absorbent matrix materials include felts, fabrics, metal mesh and other foams including polymeric or metallic varieties. With polymeric foams, the thickness of the material is normally chosen such that the foam is somewhat compressed when located in the working space. For woven and non-woven fabrics, material thickness is chosen to easily fit into the working gap without compression. The MR fluid used in these devices has the consistency of a light grease. Since the fluid is exposed to the atmosphere, the base oil is chosen to have a low vapor pressure to minimize any evaporation. Synthetic hydrocarbon oils work well.

Force versus displacement and force versus velocity performance curves for an MR sponge damper designed for use as a washing machine damper are shown in Figures 3.7 and 3.8. The low-off state and large dynamic range possible with this type of damper is readily apparent.

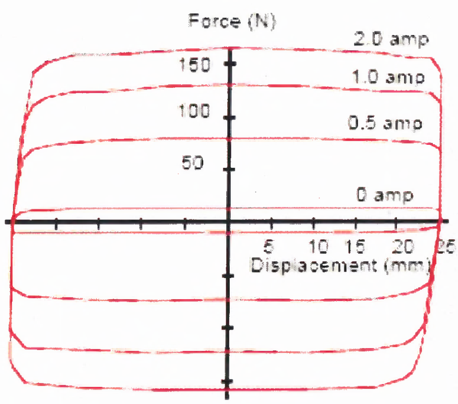


Figure 3.7 Force versus displacement for MR sponge damper.

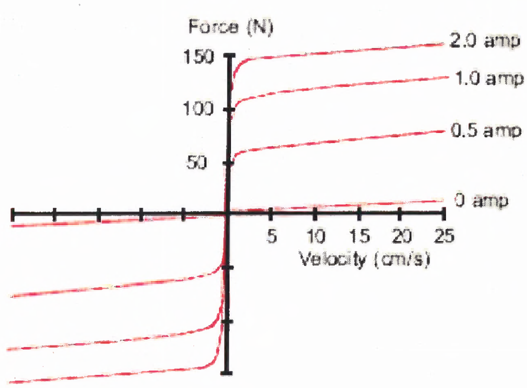


Figure 3.8 Force versus velocity for MR sponge damper.

MR sponge dampers can exhibit long life. Little wear of the sponge occurs as the stresses are primarily carried by the iron particle structure established within the MR fluid. Further, performance is rather unaffected by wear of the sponge. The role of the sponge is simply to hold MR fluid in the working gap. As long as the sponge is able to hold sufficient MR fluid to fill the working space in the region of the magnetic field, this damping force is largely unaffected by the condition of the sponge. A measure of the durability of an MR sponge damper is shown in Figure 3.9 which shows the result of a fatigue test corresponding to the simulated life in a domestic washing machine. In this test the damper was pneumatically driven at ±2 cm at 2 Hz. Every thirty seconds the damper was energized for 5 seconds such that sufficient force was generated to overcome the force of the pneumatic actuator and halt damper motion. The 2 million cycles of this test corresponded to 5000 total loads of wash or 6 loads per week for 15 years. The damper easily maintained a damping force in excess of the design threshold of 60 N.

Shelf life of MR sponge dampers has also proven to not be an issue. MR sponge dampers that had been allowed to sit unmoving for 18 months responded instantly with the same performance characteristics as before sitting [13].

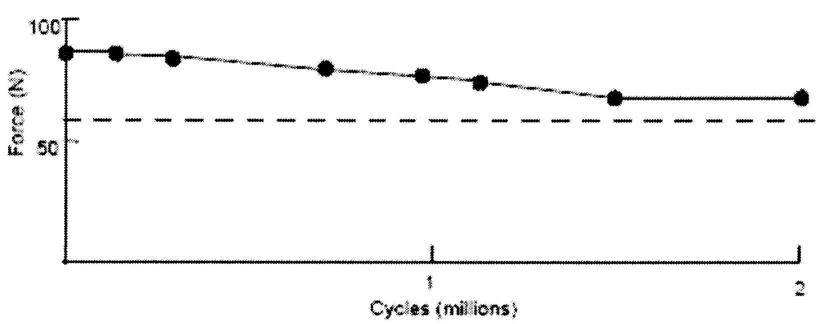


Figure 3.9 Durability of MR sponge damper.

3.2.2 Usefulness of Friction Resistance Force for MR Fluid Suppression Orthosis

3.2.2.1 Cylinder and Piston System of Friction Damper. The same mechanism in Figure 3.5 can also be directly used for a tremor suppression orthosis. The friction resistance force is weaker than the pressure resistance force but it is still enough to suppress most types of tremors. An MR friction damper has some advantages compared to an MR pressure damper.

Such "MR sponge" devices enable low-cost, controllable fluid applications by eliminating the need for most of the high-cost components normally associated with a fluid-filled device. They are particularly appropriate for less demanding, low-force applications where a high degree of control is desired. MR sponge devices contain MR fluid that is constrained by capillary action in an absorbent matrix such as a sponge, open celled foam, felt or fabric. The sponge serves to keep the MR fluid located in the active region of the device where the magnetic field is applied. The sponge allows a minimum volume of MR fluid to be operated in a direct shear mode without seals, bearings or precision mechanical tolerances. They are not susceptible to gravitational settling or sedimentation of the MR fluid suspension [13]. However, the mechanism will be basically the same as the cylinder and piston system of friction damper.

3.2.2.2 Rotating Friction Damper. The MR sponge damper can be used for a rotating friction damper. Actually, most human joints exhibit rotational motion. As a result of this, tremors are also rotational trembling (though the mechanism may not be just one degree of freedom) so that it will be the most effective way to apply to human joints. The rotating friction force is also enough to suppress tremors, and the size of the orthosis can be made small enough to wear under normal clothing or gloves. The Ball Joint system will be very effective for wrist tremor suppression.

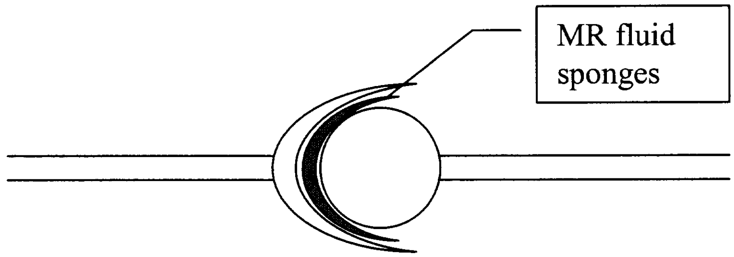


Figure 3.10 An example of rotating friction damper (Ball Joint).

3.3 Bending Resistance Force of MR Fluid

There are no commercial products which use bending resistance force of MR fluid yet because the bending resistance force of the MR fluid itself is not strong enough to use commercial product. However, if we make it strong enough to suppress the tremor, this system can be the most ideal system of suppression tremor orthosis because only sponge, coil and steel wire are essential parts for the system. Therefore, this system can be the simplest structure.

CHAPTER 4

INSTRUMENTATION AND METHODS

4.1 Required Moment for Wrist Tremor Suppression

The governing equation of motion about a single point is

$$M = I\,\theta'' + \mathrm{B}\,\theta' \tag{4.1}$$

Where $\boldsymbol{M}$ is the moment of the hand muscle force causing the angular acceleration $\boldsymbol{\theta''}$. $\boldsymbol{I}$ is the moment of inertia of hand and **B** is the damping coefficient of hand. $\boldsymbol{M}$ has units of N·m, $\boldsymbol{\theta''}$ is in rad/s^2, $\boldsymbol{\theta'}$ is rad/s^2, **B** is in kg·m^2/s, and $\boldsymbol{I}$ is in kg·m^2. Stiffness has been ignored.

$$I = m\chi^2 \tag{4.2}$$

Where $\boldsymbol{m}$ is mass of hand, and $\boldsymbol{\chi}$ is the radius of gyration for proximal end of hand.

From Table 4.1, in case of hand, the segment mass is 0.006 and the radius of gyration/segment length for proximal end is 0.587. So that, if the body weight is 73kg and the length of hand is 18.5cm,

$$I = m\chi^2 = (0.006)(73)(0.587 * 0.185)^2$$

$$= (0.0438)(0.108595) = 0.00517 \text{ kg·m}^2 \tag{4.3}$$

$$\theta'' = \mathrm{a} / r \tag{4.4}$$

Where $\boldsymbol{\theta''}$ is the angular acceleration, **a** is linear acceleration, and $\boldsymbol{r}$ is radius.

From the literature, the acceleration range of wrist tremor is known to range from 1.1 cm/s^2 to 37.0 cm/s^2 (Elble, 2003).

In the extreme case of angular acceleration,

$$\theta''_1 = a_1 / r_1 = 37 / (18.5*0.5) = 4 \text{ rad/s}^2 \qquad (4.5)$$

B is 0.063 kg·m^2/s [14] and ***θ'*** is 0.022 rad/s [15]

Finally, from Equation (4.1) an estimates of the peak torque related to this tremor is found.

$$M = I\,\theta'' + B\,\theta' = (0.00517 \text{ kg·m}^2)(4 \text{ rad/s}^2) + (0.063 \text{ kg·m}^2\text{/s})(0.022 \text{ rad/s})$$

$$= 0.022 \text{ N·m} \qquad (4.6)$$

Table 4.1 Anthropometric Data

Segment	Definition	Segment Weight/ Total Body Weight	Center of Mass/ Segment Length		Radius of Gyration/ Segment Length			Density
			Proximal	Distal	C of G	Proximal	Distal	
Hand	Wrist axis/knuckle II middle finger	0.006 M	0.506	0.494 P	0.297	0.587	0.577 M	1.16
Forearm	Elbow axis/ ulnar styloid	0.016 M	0.430	0.570 P	0.303	0.526	0.647 M	1.13
Upper arm	Glenohumeral axis/ elbow axis	0.028 M	0.436	0.564 P	0.322	0.542	0.645 M	1.07
Forearm and hand	Elbow axis/ ulnar styloid	0.022 M	0.682	0.318 P	0.468	0.827	0.565 P	1.14
Total arm	Glenohumeral joint/ ulnar styloid	0.050 M	0.530	0.470 P	0.368	0.645	0.596 P	1.11
Foot	Lateral malleolus/ head metatarsal II	0.0145 M	0.50	0.50 P	0.475	0.690	0.690 P	1.10
Leg	Femoral condyles/ medial malleolus	0.0465 M	0.433	0.567 P	0.302	0.528	0.643 M	1.09
Thigh	Greater trochanter/ femoral condyles	0.100 M	0.433	0.567 P	0.323	0.540	0.653 M	1.05
Foot and leg	Femoral condyles/ medial malleolus	0.061 M	0.606	0.394 P	0.416	0.735	0.572 P	1.09
Total leg	Greater trochanter/ medial malleolus	0.161 M	0.447	0.553 P	0.326	0.560	0.650 P	1.06
Head and neck	C7-T1 and 1st rib/ ear canal	0.081 M	1.000	- PC	0.495	1.116	- PC	1.11
Shoulder mass	Sternoclavicular joint/ glenohumeral axis	-	0.712	0.288	-	-	-	1.04
Thorax	C7-T1/T12-L1 and diaphragm*	0.216 PC	0.82	0.18	-	-	-	0.92
Abdomen	T12-L1/L4-L5*	0.139 LC	0.44	0.56	-	-	-	-
Pelvis	L4-L5/ greater trochanter*	0.142 LC	0.105	0.895	-	-	-	-
Thorax and abdomen	C7-T1/L4-L5*	0.355 LC	0.63	0.37	-	-	-	-
Abdomen and pelvis	T12-L1/ greater trochanter*	0.281 PC	0.27	0.73	-	-	-	1.01
Trunk	Greater trochanter/ glenohumeral joint*	0.497 M	0.50	0.50	-	-	-	1.03
Trunk head neck	Greater trochanter/ glenohumeral joint*	0.578 MC	0.66	0.34 P	0.503	0.830	0.607 M	-
HAT	Greater trochanter/ glenohumeral joint*	0.678 MC	0.626	0.374 PC	0.496	0.798	0.621 PC	-
HAT	Greater trochanter/ mid rib	0.678	1.142	-	0.903	1.456	-	-

*NOTE: These segments are presented relative to the length between the greater trochanter and the glenohumeral joint. Source Codes: M, Dempster via Miller and Nelson; Biomechanics of Sport, Lea and Febiger, Philadelphia, 1973. P, Dempster via Plagenhoef; Patteerns of Human Motion, Pretice-Hall, Inc. Englewood Cliffs, N.J., 1971. L, Dempster via Plagenhoef from living subjects; Patterns of Human Motion, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1971. C, Calculated [11].

4.2 The MR Fluid Friction Damper Pendulum

A prototype rotary damper has been fabricated. The damping coefficient of this device is determined experimentally using a pendulum and varying both the area of MR fluid sponge and the current of the electromagnet.

The pendulum is modeled as a 500g mass at the end of a slender rod with the only variable being the damping coefficient of the MR fluid friction damper. The result will be compared with the value of equation (4.6) to determine if damping is sufficient to suppress the wrist tremor.

4.2.1 The Moment of Inertia of the Pendulum

The axis of the moment of inertia is z-axis and the center of the moment of inertia is the point O and variables are defined as follows.

m_1 : mass of rod

L : length of rod

I_1 : moment of inertia of rod with the center of the point O

I_{C1} : moment of inertia of rod with the center of the mass

m_2 : mass of weight

R : radius of weight

I_2 : moment of inertia of weight (the center of the point O)

I_{C2} : moment of inertia of weight (the center of the mass)

I : total moment of inertial of the system (the center of the point O)

$$I_1 = I_{C1} + 0.25m_1L^2$$
$$= (1/12)m_1L^2 + 0.25m_1L^2 = (1/3)m_1L^2$$

$$I_2 = I_{C2} + m_2 (L + R)^2$$
$$= 0.5 m_2 R^2 + m_2 (L + R)^2$$

$$I = I_1 + I_2 = 0.495 \text{ kg}\cdot\text{m}^2 \tag{4.7}$$

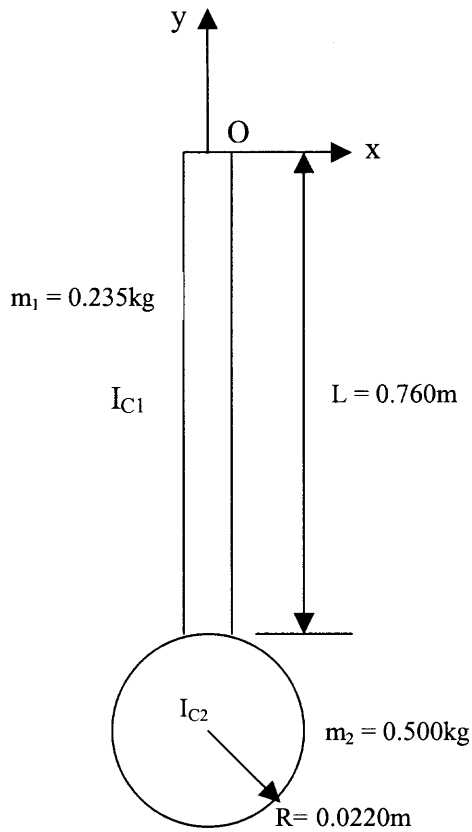


Figure 4.1 The Geometry of Pendulum.

4.2.2 The Pendulum System with Damping

The damping (friction) is proportional to the angular velocity of the pendulum.

Variables of the pendulum system are defined as follows.

m : total mass of the pendulum ($m = m_1 + m_2 = 0.735$ kg)

Lc : length of rod with the center of mass of the pendulum (0.725m)

θ : angle of pendulum (0 = vertical)

g : gravitational constant

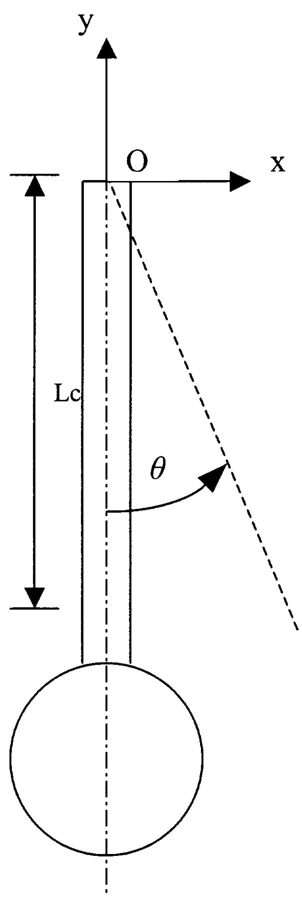


Figure 4.2 The Pendulum Motion.

The equation of motion for the pendulum is driven by using the rotational analog of Newton's second low for a fixed axis (Σ M = I α).

Σ M : sum of applied moments

I : moment of inertia

θ : angle (radian)

θ' : angular velocity

$\alpha = \theta''$: angular acceleration

B : damping coefficient

The moment due to gravity is $M = -m\,g\,Lc \sin\theta$.

The moment due to damping is $M = -B\,\theta'$.

From $\Sigma M = I\alpha$,

$$I\theta'' + B\theta' + m\,g\,Lc \sin\theta = 0 \tag{4.8}$$

is obtained.

4.2.3 The Structure of the MR Fluid Friction Damper Pendulum

The pendulum is consisted of a base body, a plastic housing, a MR fluid friction damper, a slender rod, a weight, and a sensor base (shown as Figure 4.3, 4.4, 4.5 and 4.6).

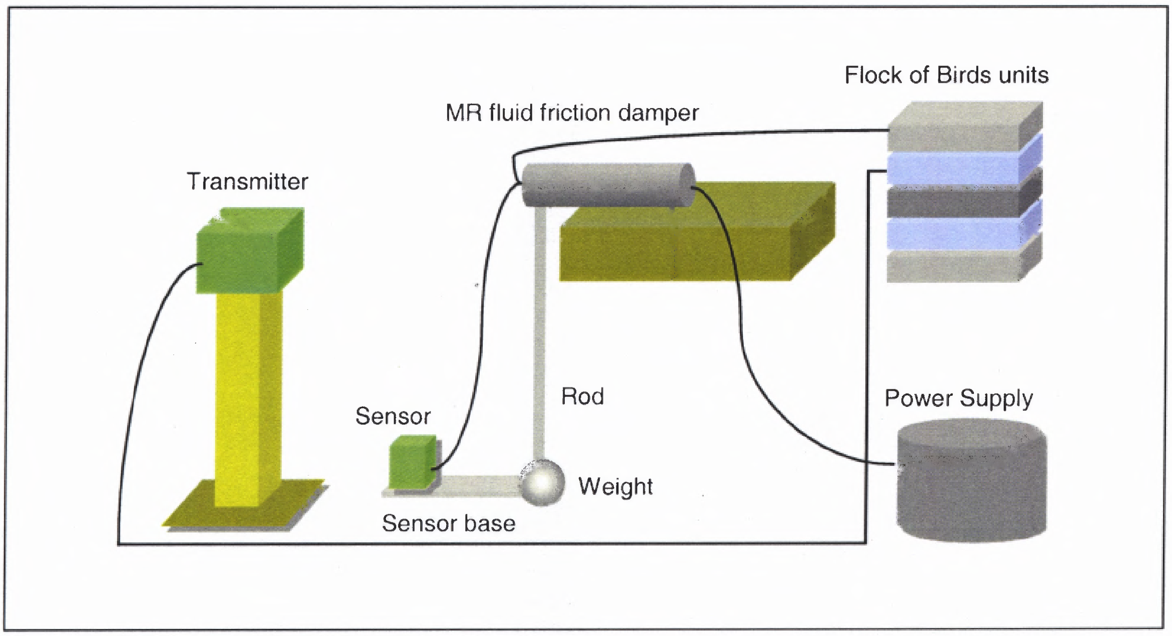


Figure 4.3 Schematic diagram of MR fluid friction damper pendulum system.

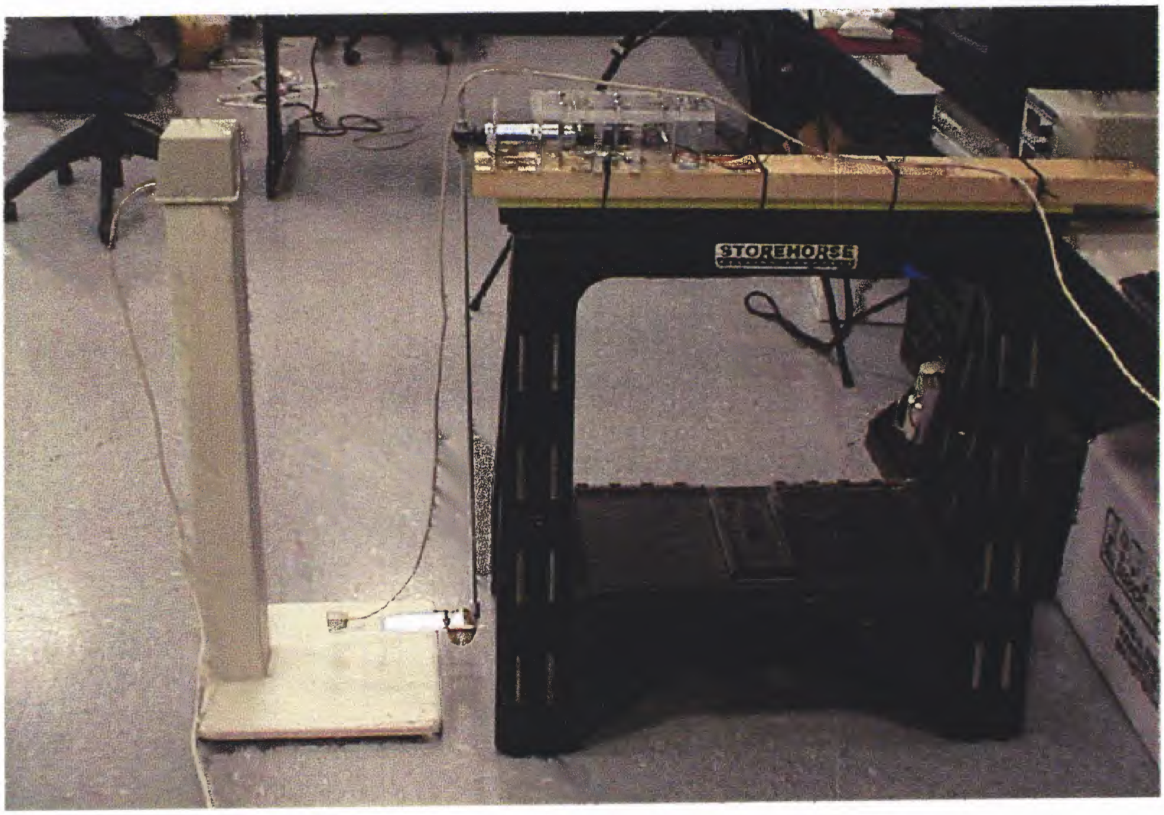


Figure 4.4 MR fluid friction damper pendulum system.

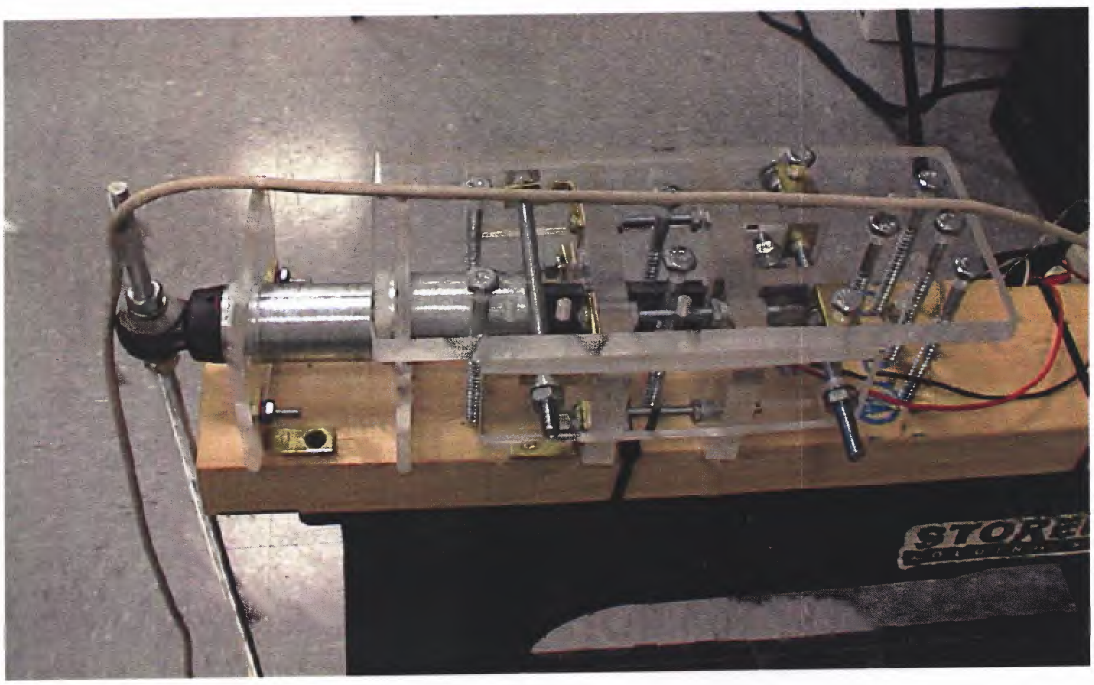


Figure 4.5 A MR fluid friction damper and a plastic housing.

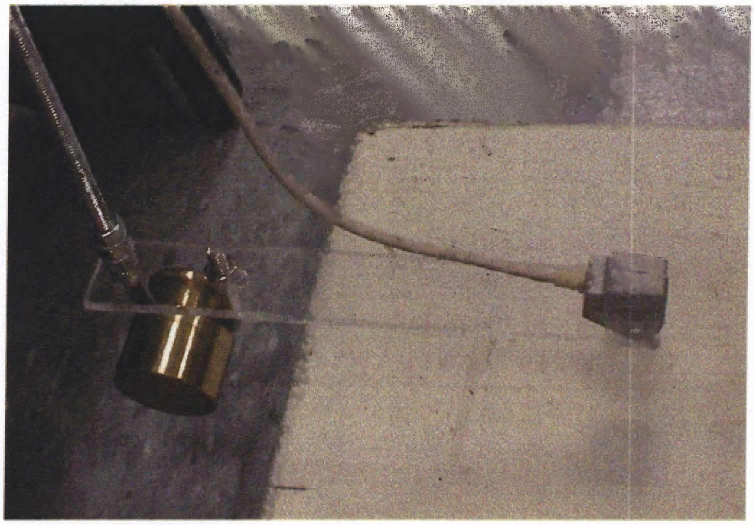


Figure 4.6 A sensor, a sensor base and a weight.

4.3 Flock of Birds

The device that will be used to record pendulum movements is known as Flock of Birds (FOB) manufactured by Ascension Technology Corporation. The Flock of Birds is a six degree-of-freedom measuring device that can be configured to simultaneously track the position and orientation of multiple sensors by a transmitter [16]. The Flock of Birds system consists of a transmitter (Figure 4.7), transmitter driver circuit, sensor (Figure 4.8) and signal processing electronics. The transmitter driver and the signal processing electronics are contained within one unit (Figure 4.9). Each sensor is capable of making 144 measurements per second per sensor when measuring position and orientation in a standalone configuration. Each Bird unit in the Flock contains two independent serial interfaces. The first interface is for communications between your host computer and the Flock of Birds system. The interface is a full duplex RS-232C connection. The second interfaces is a dedicated RS485 which is known as the Fast Bird Bus (FBB) [17].

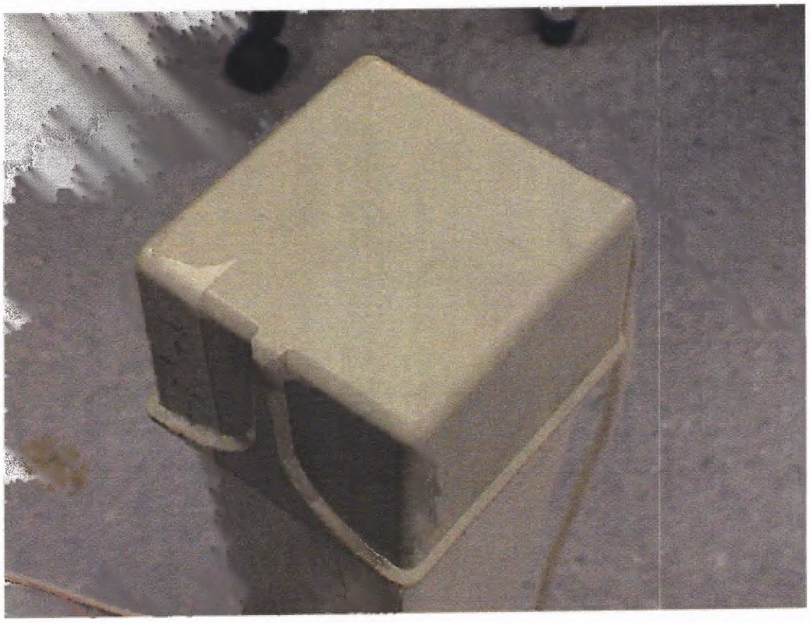


Figure 4.7 The transmitter for the Flock of Birds.

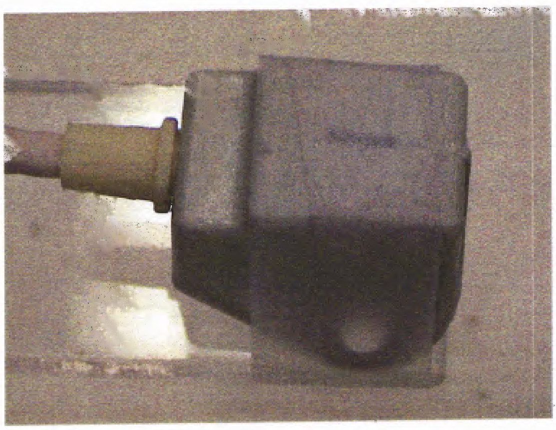


Figure 4.8 The sensor for the Flock of Birds.

Figure 4.9 The Flock of Bird units where the transmitter driver and the signal processing electronics are contained.

4.3.1 Magnetic Tracking

The direct current (DC) Flock of Birds magnetic tracing system allows for tracking of multiple sensors and overcomes many operational weaknesses that can be linked with an alternating current (AC) magnetic tracking system.

The transmitter consists of three individual antennae arranged concentrically and orthogonally that generate a pulsed DC magnetic field. This pulsed DC current generates the magnetic field produced by the transmitter. The sensors consist of three axes of antennae that are sensitive to these magnetic fields. The output from the sensor goes directly to the signal processing electronics. The Flock of Birds determines their position and orientation in space by measuring magnetic fields and comparing the difference between fields. For the first magnetic field, the sensor measures the x, y and z components of the Earth's magnetic field. Using a differential amplifier the sensor signal processing electronics subtract the Earth's magnetic field from the antennae signal from the transmitter. This signal passes through an analog-to-digital converter that converts the DC signal into a digital format that can be read by the computer (Figure 4.10) [17].

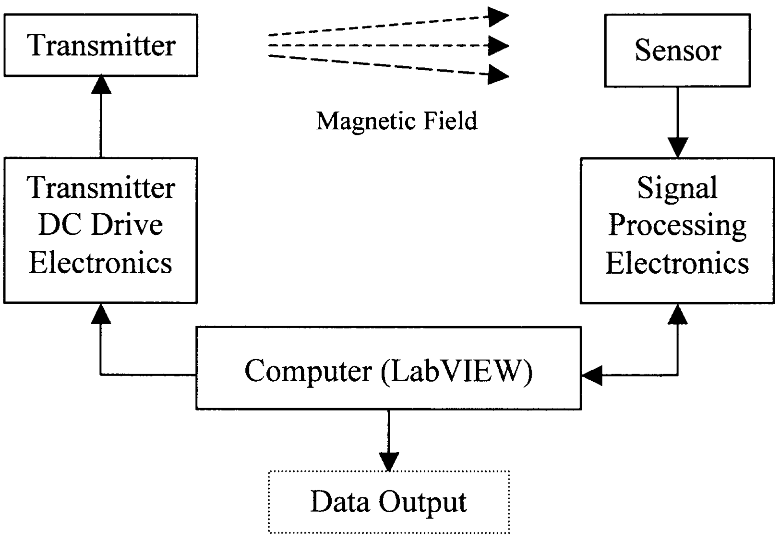


Figure 4.10 Flock of Birds flow chart showing the data flow between all components.

4.3.2 Communication Setup

The Flock of Birds can be configured in two ways for multiple sensors. The first is to provide each sensor its own serial port on the computer. This method is known as a stand-alone configuration (Figure 4.11). The benefit of this setup is the Flock of Birds achieves the maximum bandwidth. The disadvantage of this setup is the number of serial ports needed to run multiple sensors. For each sensor, one serial port is needed, and most modern computers the number of serial ports is limited to one or two.

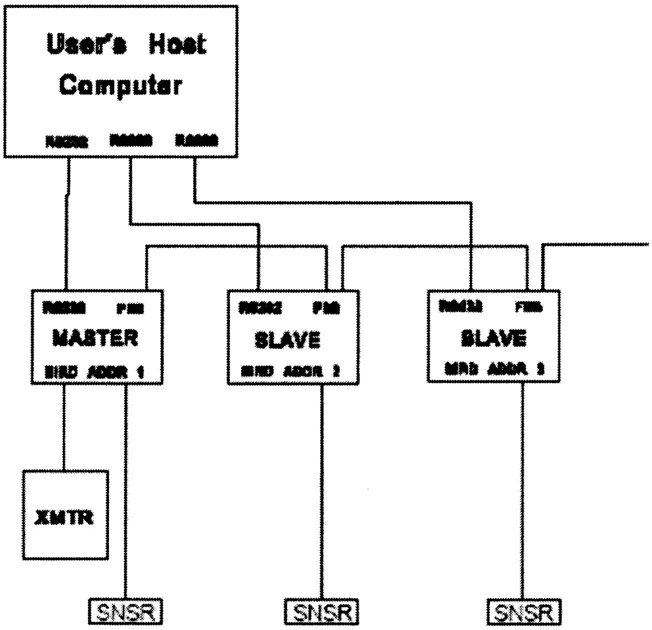


Figure 4.11 Flock of Birds configured for multiple sensors by giving each sensor its own dedicated serial connection to the computer. The XMTR is the transmitter and the RCVR is the sensor [16].

The other method of communication is through a master-slave configuration. Only the master sensor connects directly to the computer through a serial port. An additional sensor is added by directly connecting to the master sensor through the FBB. Subsequent sensors are connected to the previous slave sensor. Hence all slaves are daisy chained to the master through the FBB (Figure 4.12). The benefit of this setup is that only one serial port is needed. However, the disadvantage is, as more sensors are added, the sampling rate is limited by the bandwidth of the single serial line [17].

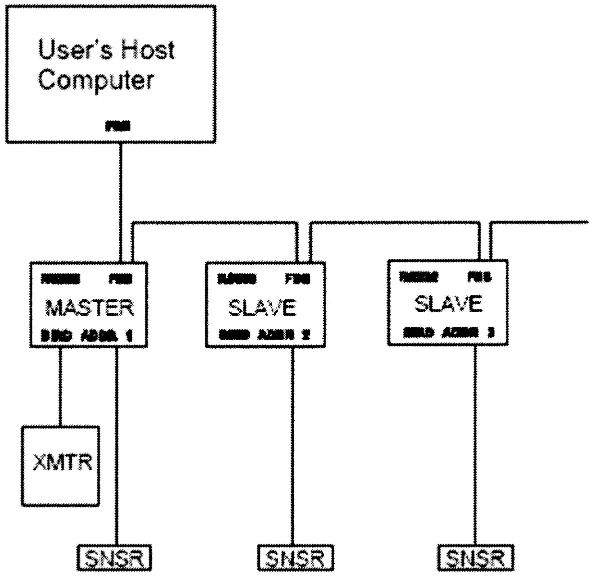


Figure 4.12 Flock of Birds configured for multiple sensors by using the master slave configuration, which utilized the FBB. For each bird, The XMTR is the transmitter and the RCVR is the sensor [16].

4.3.3 Output Types

The Flock of Birds system is capable of multiple output types. There are four main types of outputs as well as various combinations of the four. The first output type is position and reports bask an x, y, and z coordinate of each sensor with respect to the transmitter. Each sensor coordinate is represented by two bytes giving a total of six bytes to report x, y and z coordinates of a single sensor. The position accuracy has a resolution of 0.5 millimeters. The second type of output is angles, which is the yaw, piths and roll of the sensor relative to the transmitter (Figure 4.13). Each orientation is also represented by two bytes giving six bytes total to represent yaw pitch and roll. The yaw, pitch and roll have a resolution of 0.1 degrees. The third type of output from the Flock of birds is a position matrix. This matrix outputs a nine-element rotation matrix that defines the orientation of the sensor's X, Y and Z-axes with respect to the transmitter's x, y and z-axes [17].

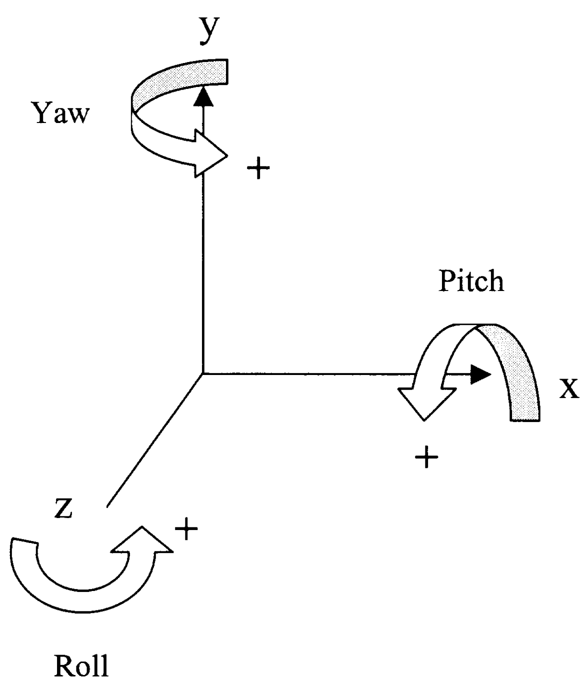


Figure 4.13 An example of what yaw, pitch and roll looks like.

4.4 Software

4.4.1 LabVIEW

LabVIEW (National Instruments, TX) is a graphical programming language with built-in functionality for data acquisition, instrument control, measurement analysis, and data presentation [18]. LabVIEW is used to present in screen and save the data from the Flock of Birds in computer. LabVIEW gives the flexibility of a powerful programming language without the complexity of other traditional development environments. The object oriented graphical environment of LabVIEW allows developers to develop programs without writing a single line of code unlike text-based languages. Programs are built using pre-developed blocks, called Virtual Instruments (VI's), which perform specific tasks. The developer interconnects these blocks by using "wires" similar to a flowchart. When the final code is complied its execution speeds are comparable with a complied C program. One most notable trait of LabVIEW is its ability to interface with outside hardware and to digitize data from these devices at real time [17].

4.4.2 Table Curve 2D 5.0

Table curve 2D is used for curve fitting. By going through a large number of generic linear and nonlinear models it automatically finds candidate equations which best fit the data. The results can also be arranged such that the models which achieve very good 2 dimensional curve at the expense of few parameters are ranked highest. Thereby it is possible to generate new scientific insights by discovery of possibly meaningful mathematical models and parameters.

- Local regression digital filters for data reduction, enhancement, or uniform X spacing
- First and second order analytic derivatives for all built-in equations
- Apply calculations to X, Y and Weight values Spreadsheet-like data editing with optional [19].

4.4.3 MATLAB (Simulink)

MATLAB Simulink is used for the simulation of wrist tremor suppuration in this thesis.

MATLAB Simulink is one of the most interactive tools for modeling, simulating, and analyzing dynamic, multidomain systems. This software makes it possible to accurately describe, simulate, evaluate, and refine a system's behavior through standard and custom block libraries. Simulink integrates seamlessly with MATLAB, providing immediate access to an extensive range of analysis and design tools. These benefits make Simulink the tool of choice for control system design, signal processing system design, communications system design, and other simulation applications.

4.5 Methods

4.5.1 Data Acquisition

The Flock of Birds system is used to measure the angle (θ) of the pendulum (Figure 4.2). The FOB recorded the data by using the output types with position/angle and position/matrix (Figure 4.14).

The experimental system consist of one FOB and a pendulum. At the bottom of the pendulum, an FOB sensor is attached and set in an orientation so that only the roll value changes while yaw stays 180 and pitch stays zero. So that the experiment system should be set up starting point at yaw=180, pitch=0, and roll=0. The goal is to measure the roll angle, which is the only data changed from the FOB.

Once the experimental setup is completed, the data is recorded in the vertical orientation zero degree determined by gravity, and the starting point is +90 degrees and zero second. The angle data is recorded at every 1/30 second by the FOB.

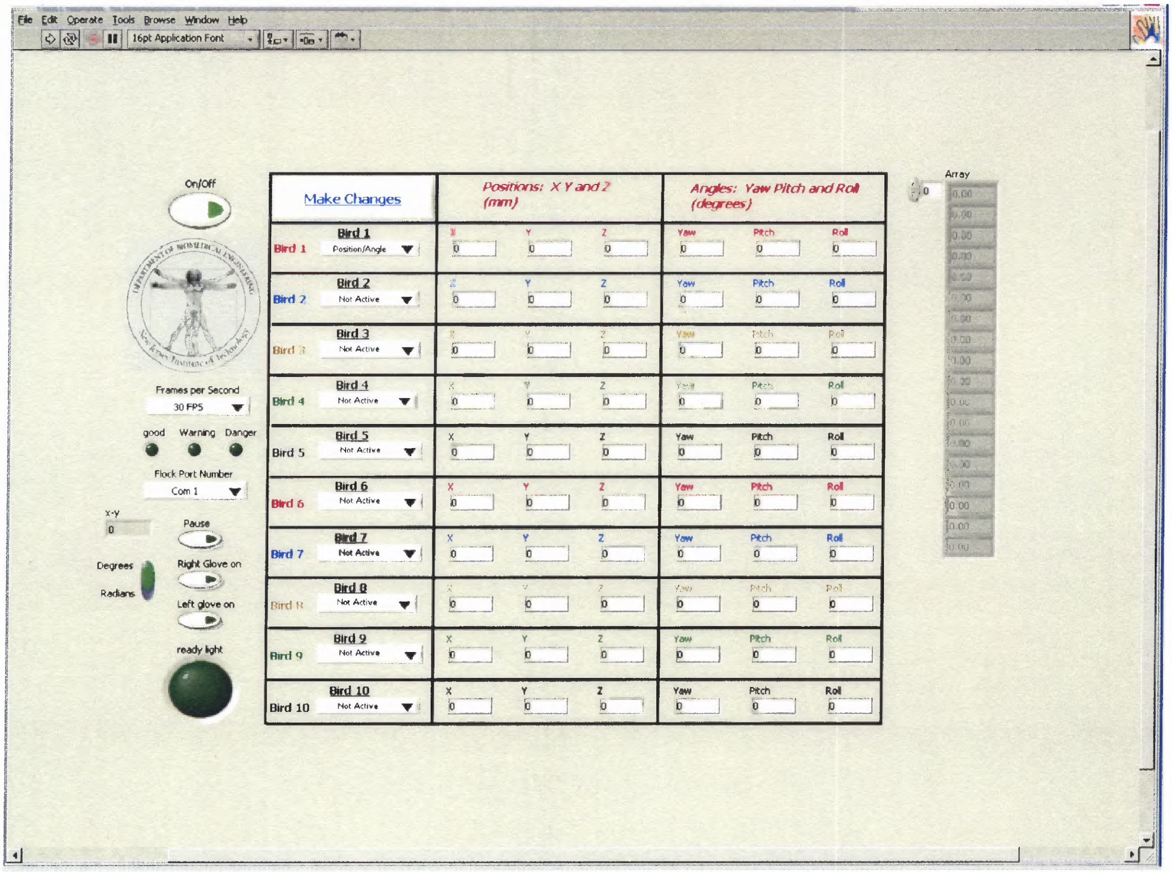


Figure 4.14 Front panel design of the Cyber Flock program.

4.5.2 Data Processing

The angle (degree) data acquired from experiment should be converted into radian values. Then Table curve 2D program is used for curve fitting angle (radian) versus time graph (Appendix A). When the curve fitting is completed, the program automatically calculates the first derivatives which are angular velocities and the second derivatives which are angular accelerations (Appendix B). Finally, using these values, damping coefficients can be calculated from equation (4.8). The different damping coefficients will be acquired depending on the strength of current and the friction area.

CHAPTER 5

RESULTS

5.1 Pendulum Motion with Damping

The following figures are the results of damped pendulum system.

There are three groups. They are classified by the fiction area which are 17.6 cm^2, 30.8 cm^2 and 43.9 cm^2. The current is also changed from 0.25 amp to 1 amp.

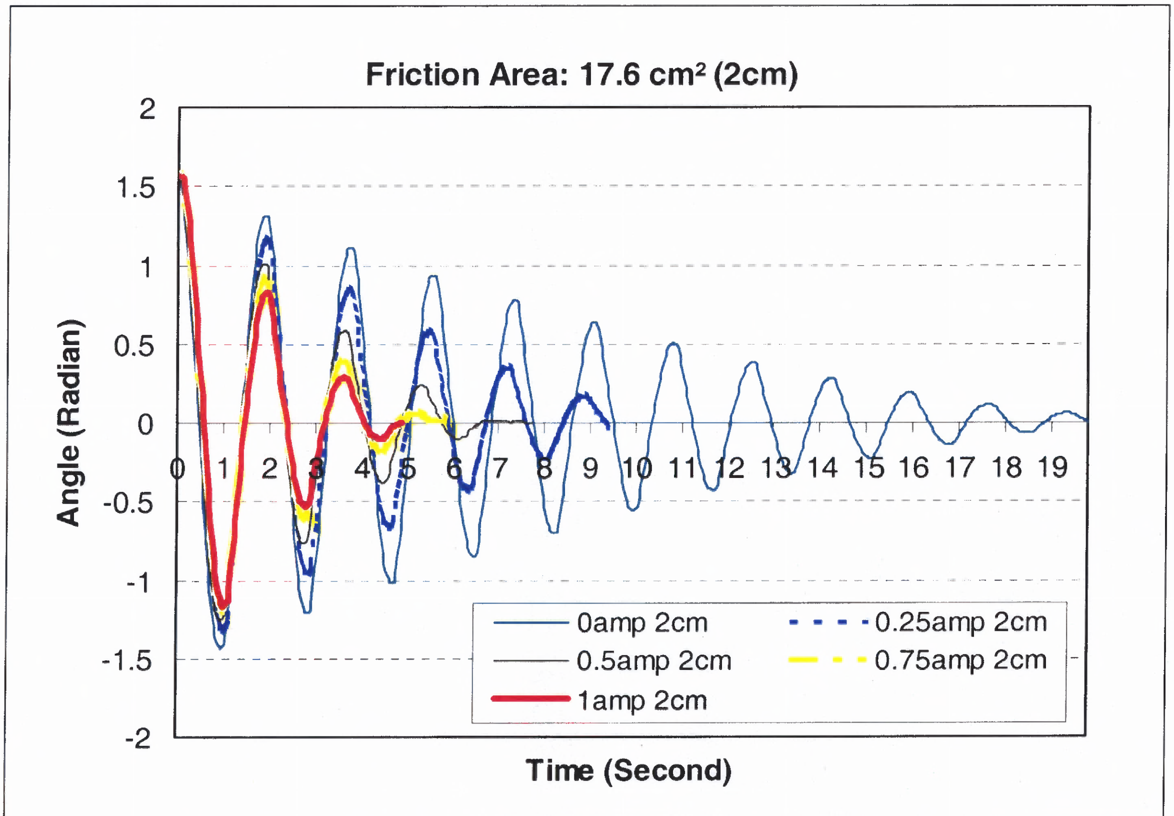


Figure 5.1 Damped pendulum motion with friction area 17.6cm^2.

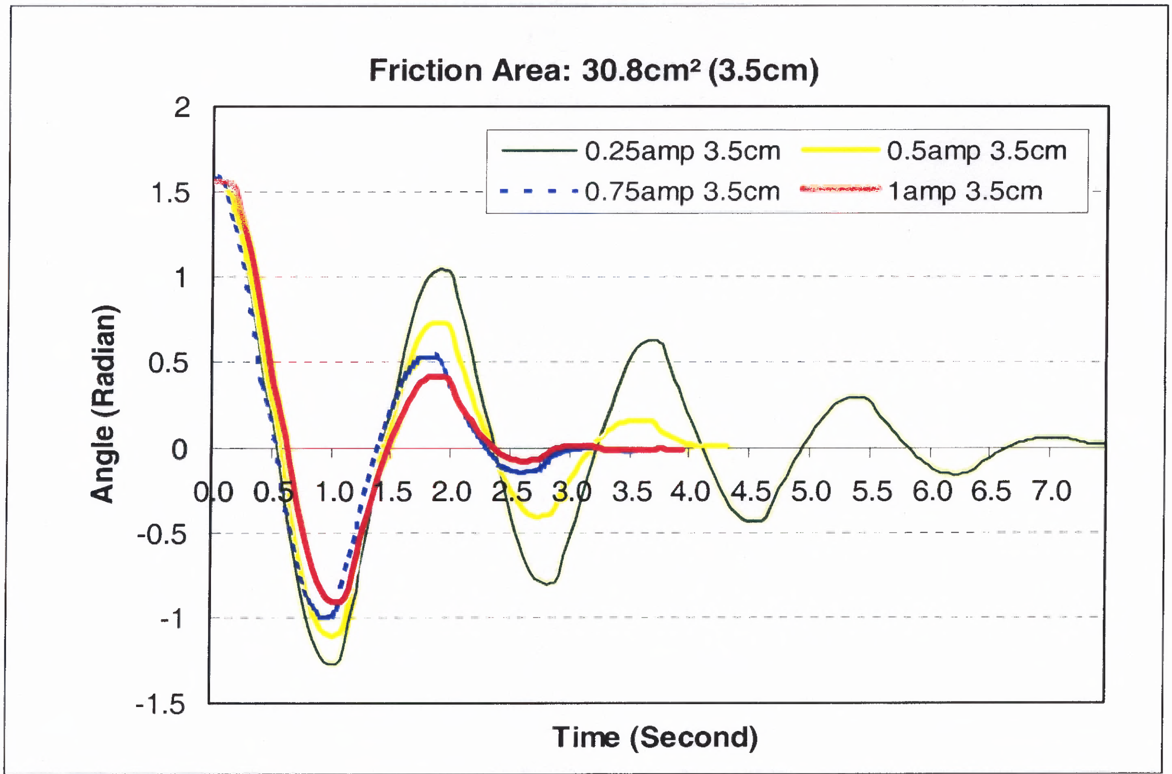


Figure 5.2 Damped pendulum motion with friction area 30.8cm^2.

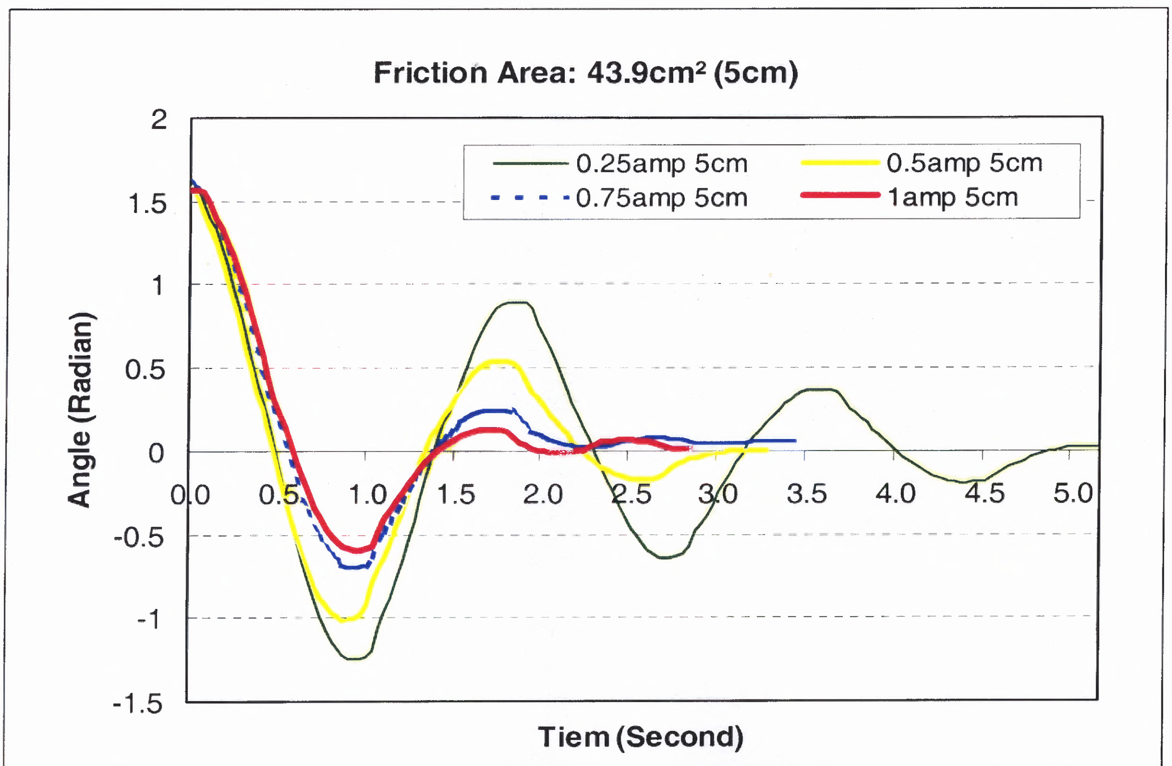


Figure 5.3 Damped pendulum motion with friction area 43.9cm^2.

5.2 The Angular Velocity and Angular Acceleration

The angular velocity and angular acceleration is calculated by Table curve 2D program when this program do curve fitting. The data is shown as following figures which are from figure 5.4 to figure 5.16. These figures are based on the data of Appendix B.

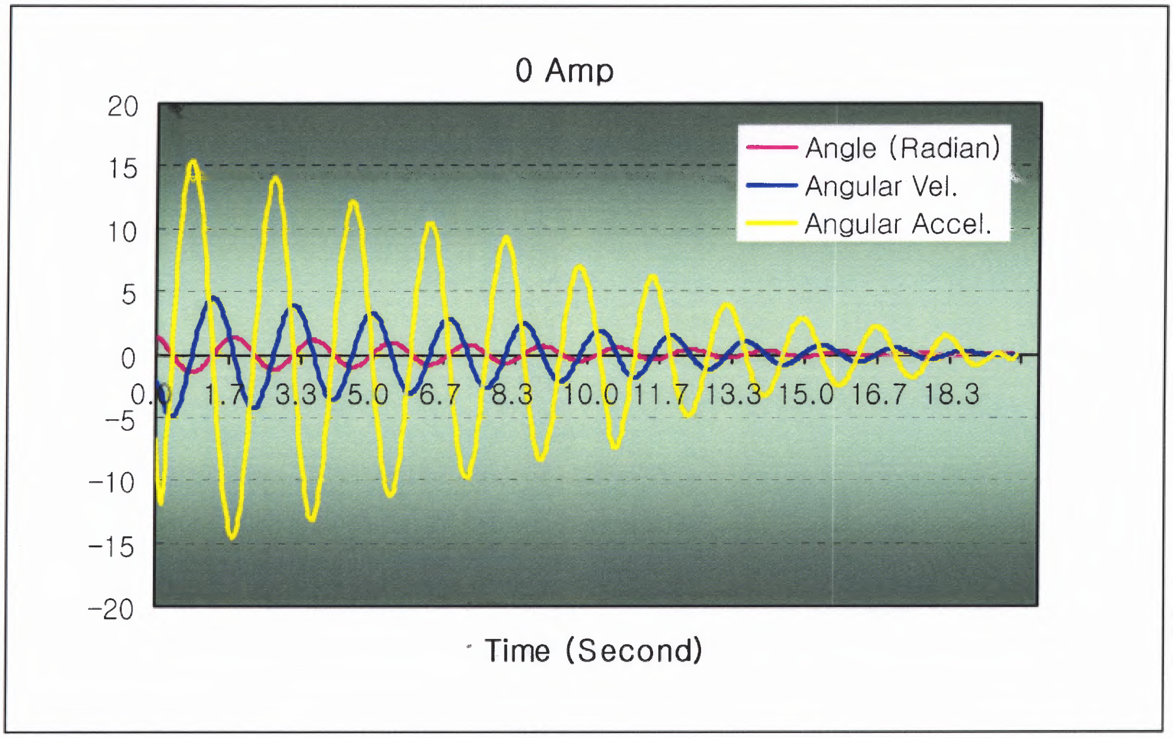


Figure 5.4 The angular velocity and angular acceleration with 0 amp.

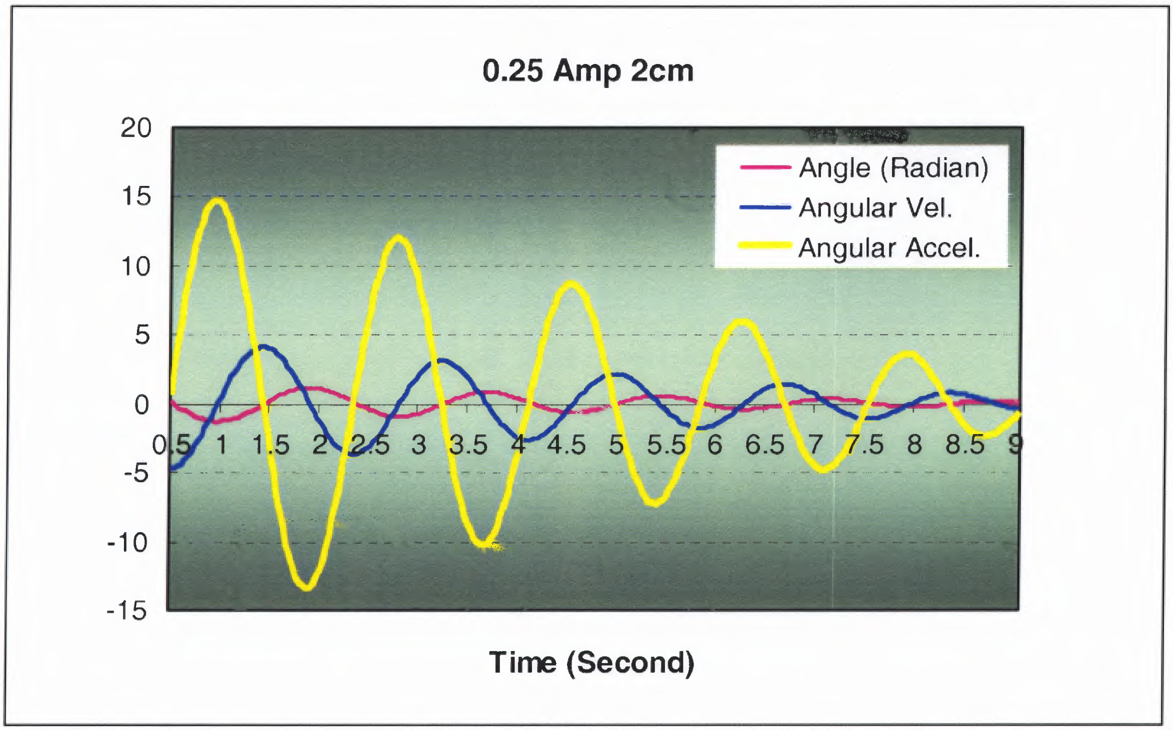


Figure 5.5 The angular velocity and angular acceleration with 0.25amp and friction area 17.6cm^2.

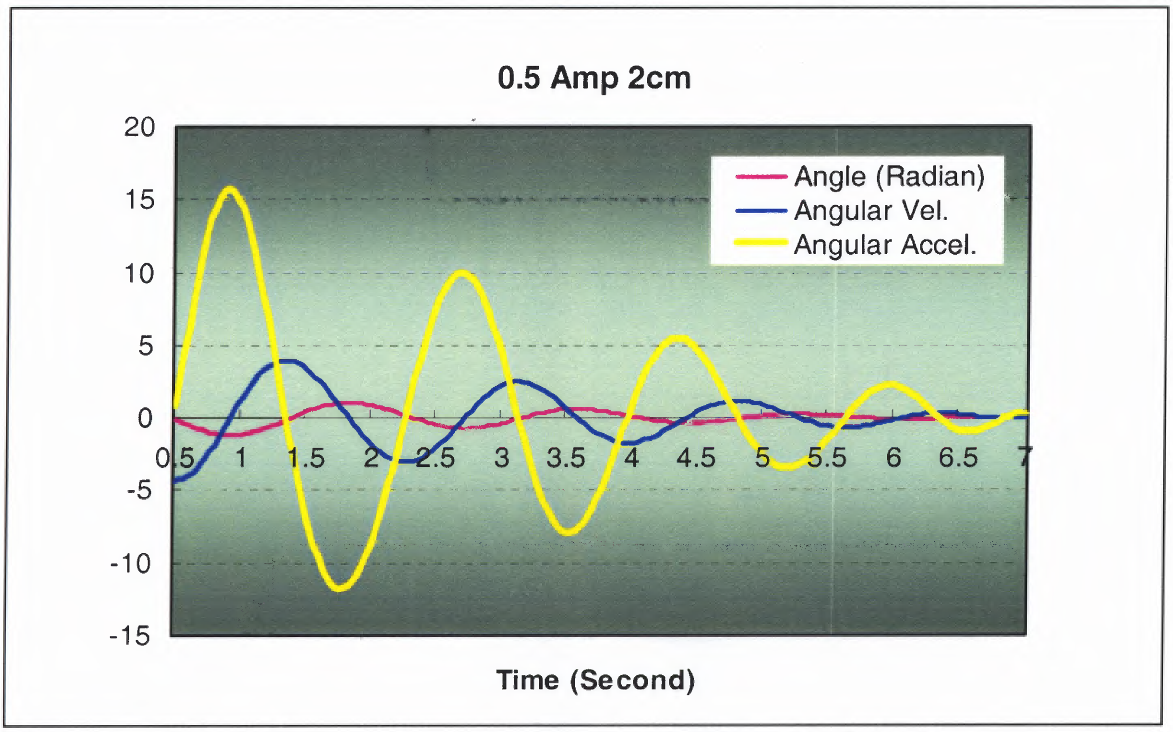


Figure 5.6 The angular velocity and angular acceleration with 0.5amp and friction area 17.6cm^2.

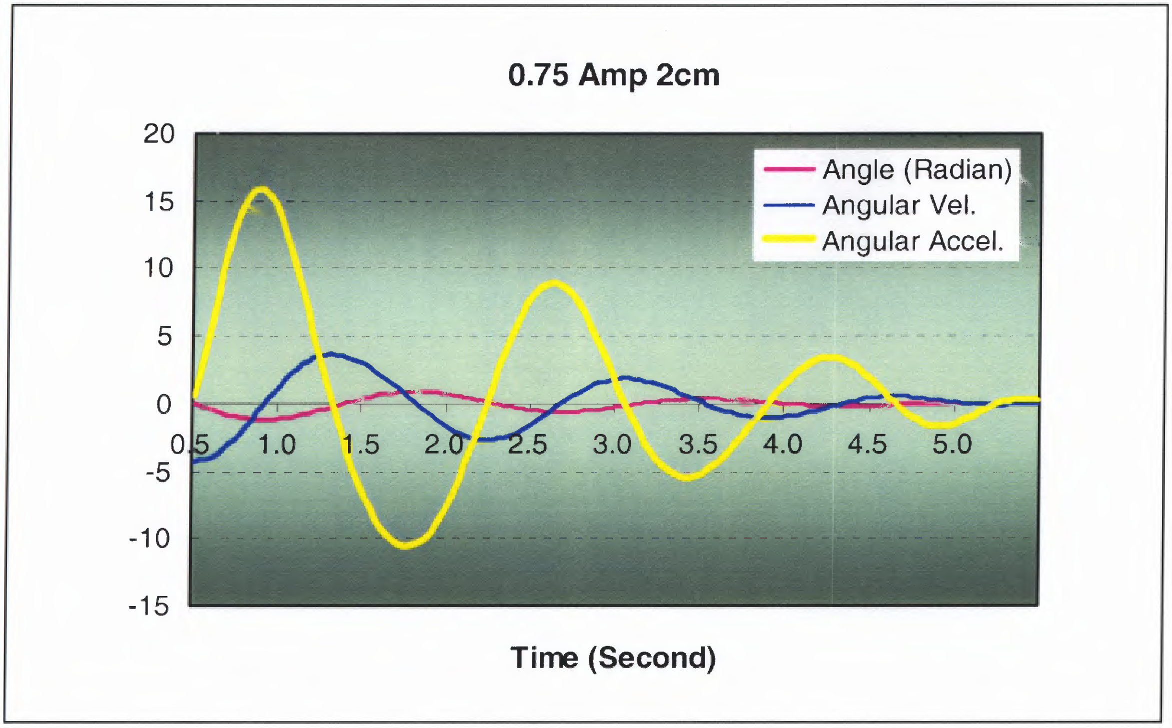


Figure 5.7 The angular velocity and angular acceleration with 0.75amp and friction area 17.6cm^2.

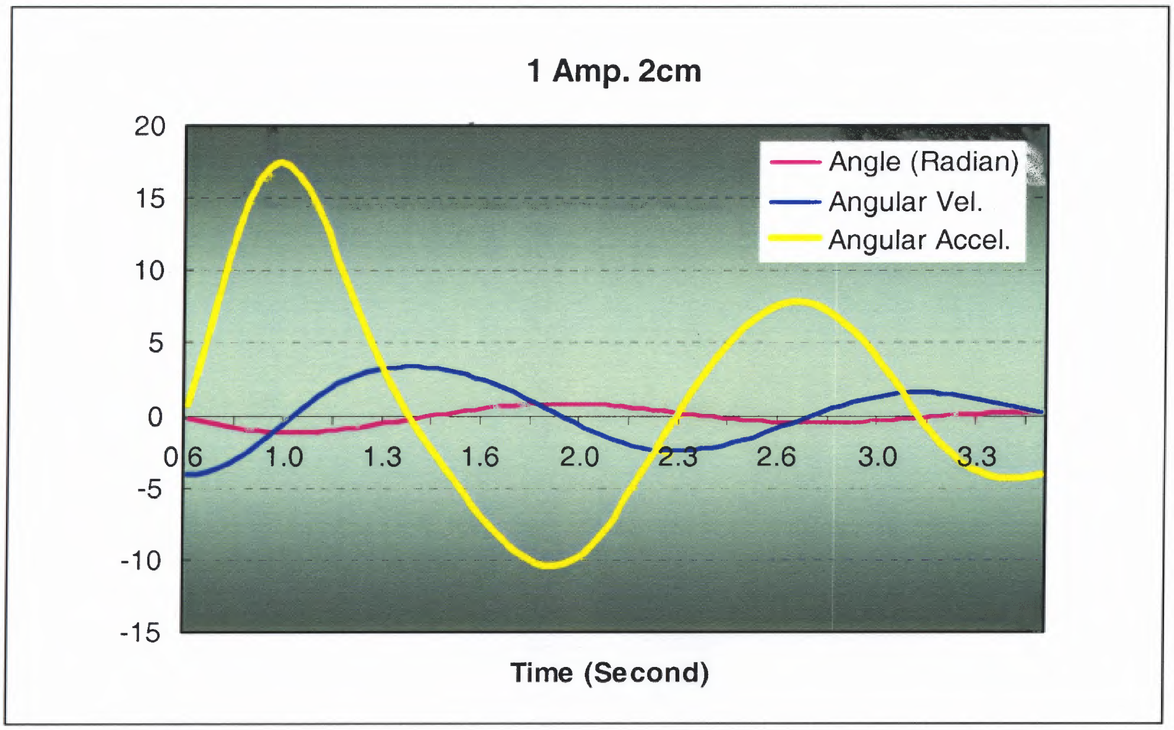


Figure 5.8 The angular velocity and angular acceleration with 1amp and friction area 17.6cm^2.

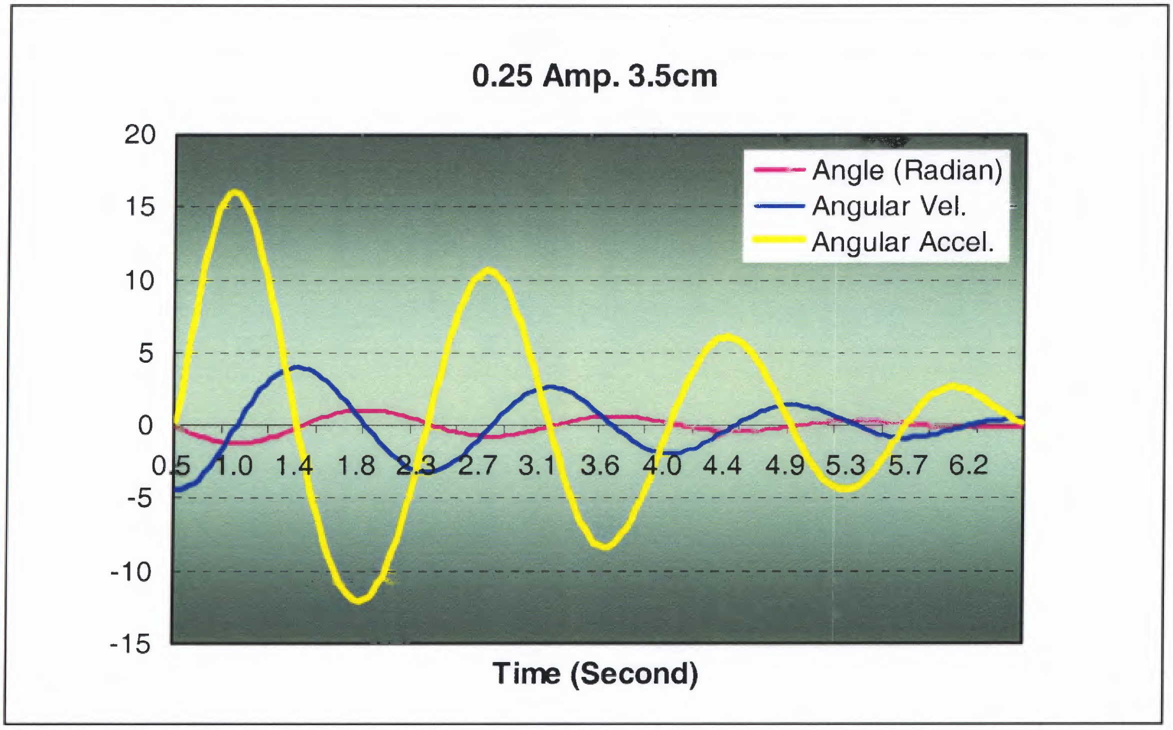


Figure 5.9 The angular velocity and angular acceleration with 0.25amp and friction area 30.8cm^2.

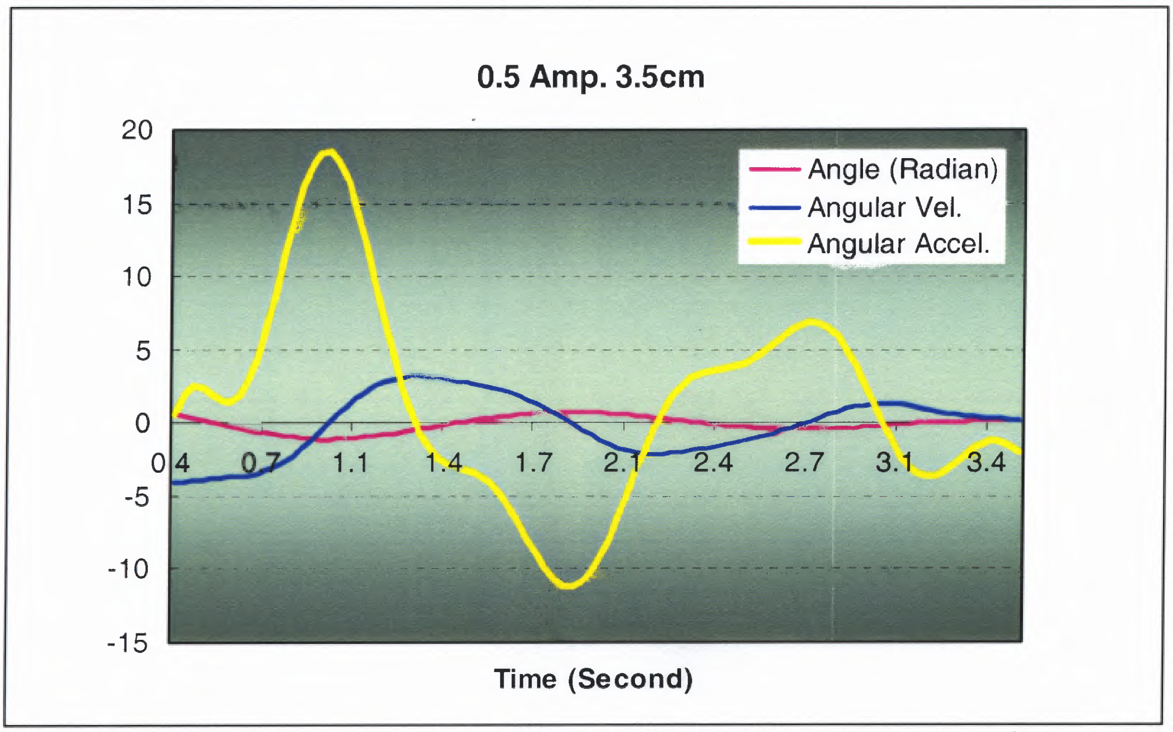


Figure 5.10 The angular velocity and angular acceleration with 0.5amp and friction area 30.8cm^2.

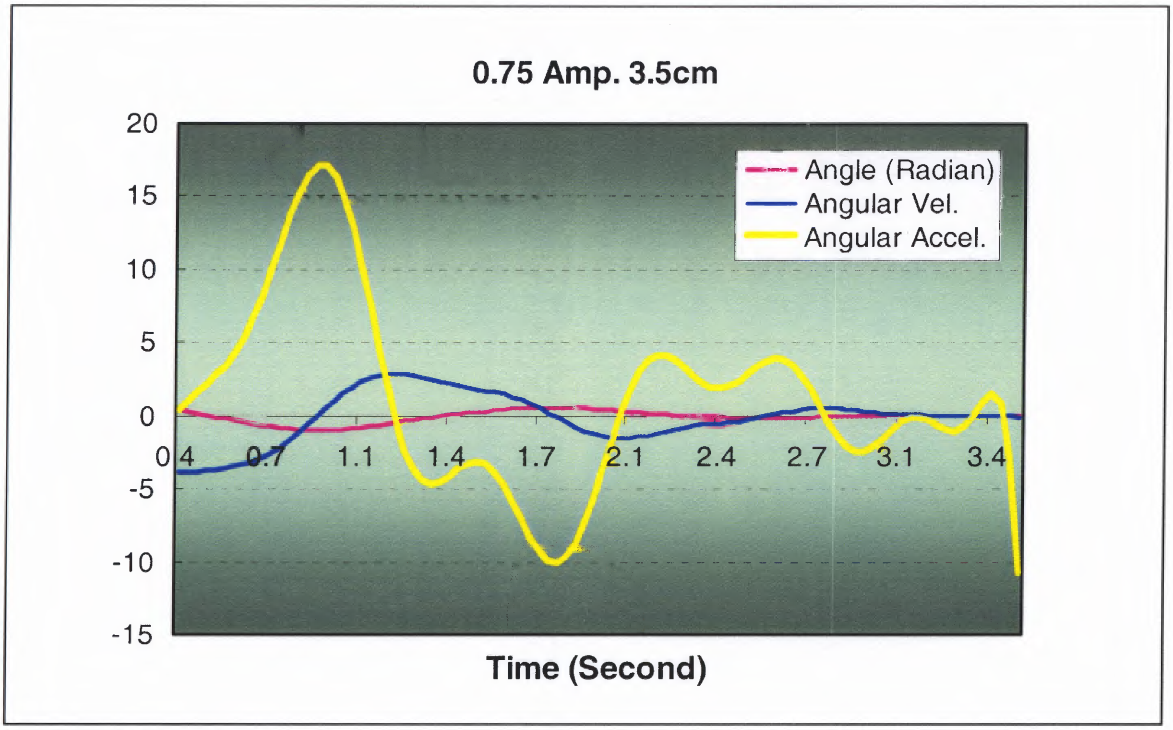


Figure 5.11 The angular velocity and angular acceleration with 0.75amp and friction area 30.8cm^2.

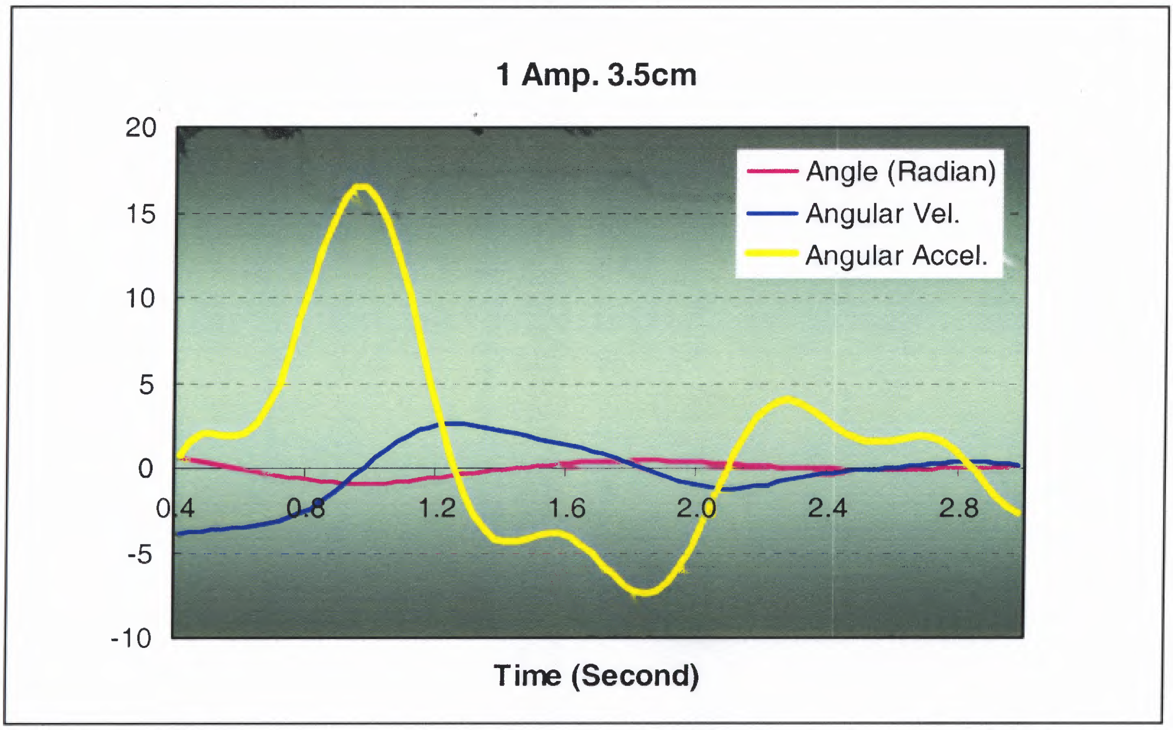


Figure 5.12 The angular velocity and angular acceleration with 1amp and friction area 30.8cm^2.

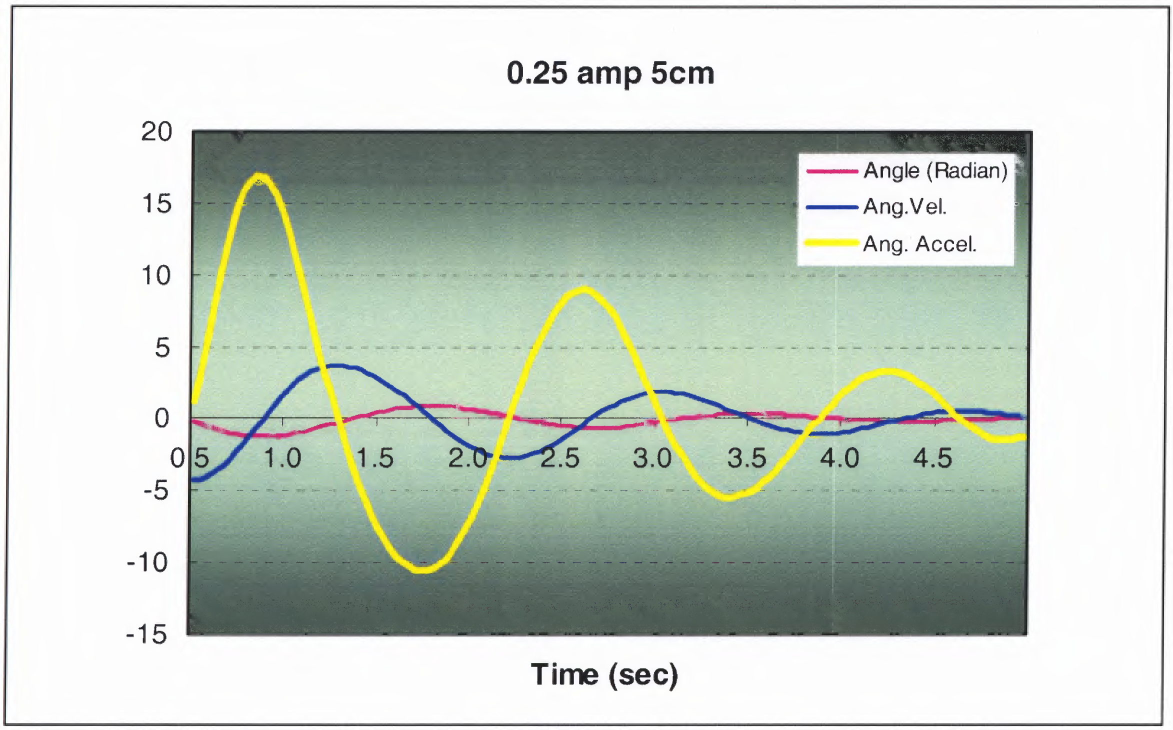


Figure 5.13 The angular velocity and angular acceleration with 0.25amp and friction area 43.9cm^2.

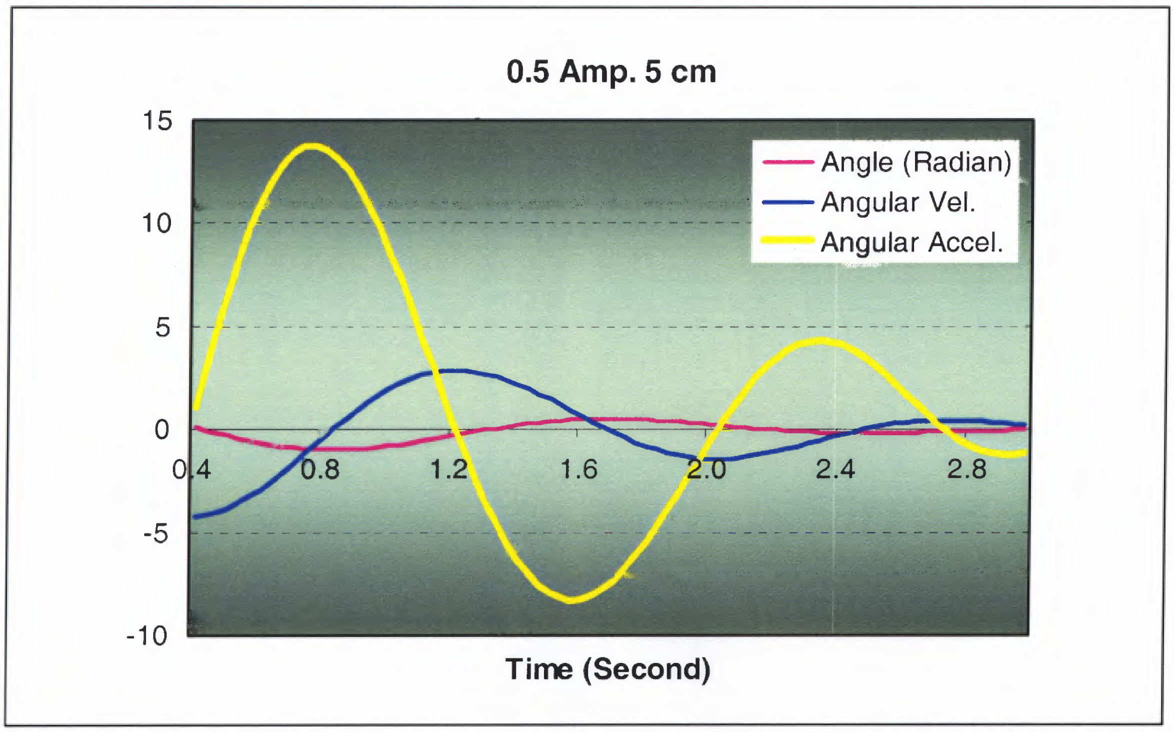


Figure 5.14 The angular velocity and angular acceleration with 0.5amp and friction area 43.9cm^2.

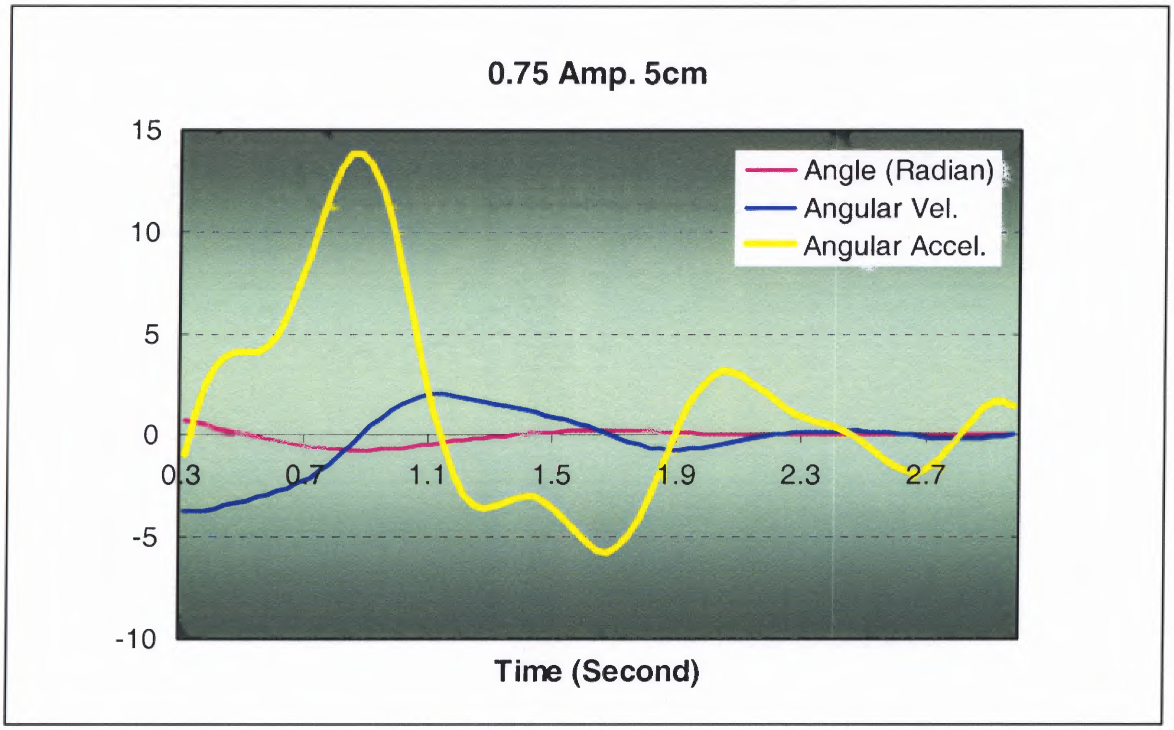


Figure 5.15 The angular velocity and angular acceleration with 0.75amp and friction area 43.9cm^2.

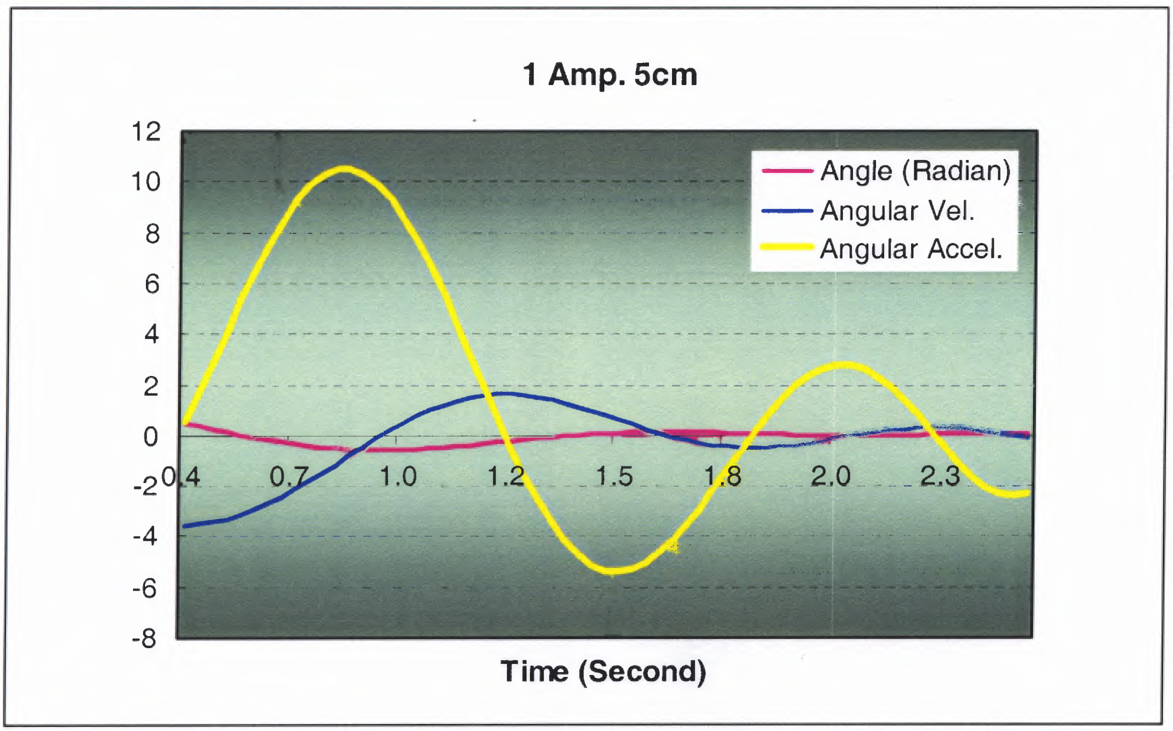


Figure 5.16 The angular velocity and angular acceleration with 1amp and friction area 43.9cm^2.

5.3 The Damping Coefficient B

Using data of angular velocities and angular acceleration in Appendix B, and second order differential equation (4.8), the values of the damping coefficient B are calculated as Table 5.1 and Figure 5.16.

Table 5.1 Data of the damping coefficient with various current and friction area

	Current (amp)				
Friction Area(cm^2)	**0**	**0.25**	**0.5**	**0.75**	**1.00**
17.6	1.22	1.70	2.04	2.96	3.40
30.8	1.22	1.89	2.58	3.10	3.89
43.9	1.22	2.08	3.05	3.93	4.76

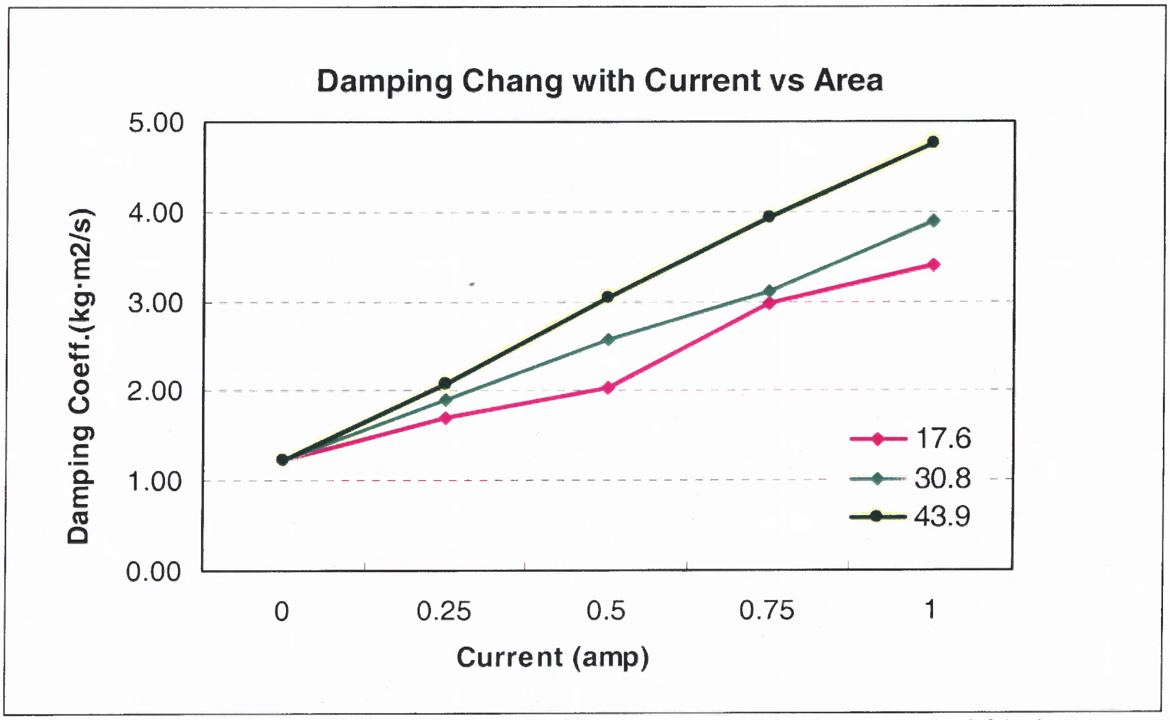


Figure 5.16 The graph of the damping coefficient with various current and friction area.

5.4 The Simulation of Suppressing Wrist Tremor

This simulation use the data of hand tremor (figure 5.17).

The data information is as follows.

The mass of hand : 0.438 kg

The length from the center of hand mass to wrist : 0.0936 m

The damping coefficient of wrist : 0.063 kg·m^2/s

The hand moment of inertia : 0.00517 kg·m^2

The frequency of hand tremor : 5 Hz

The simulation was executed by changing the damping coefficient of MR fluid damper from 0 kg·m^2/s to 2 kg·m^2/s (figure 5.18 and figure 5.19).

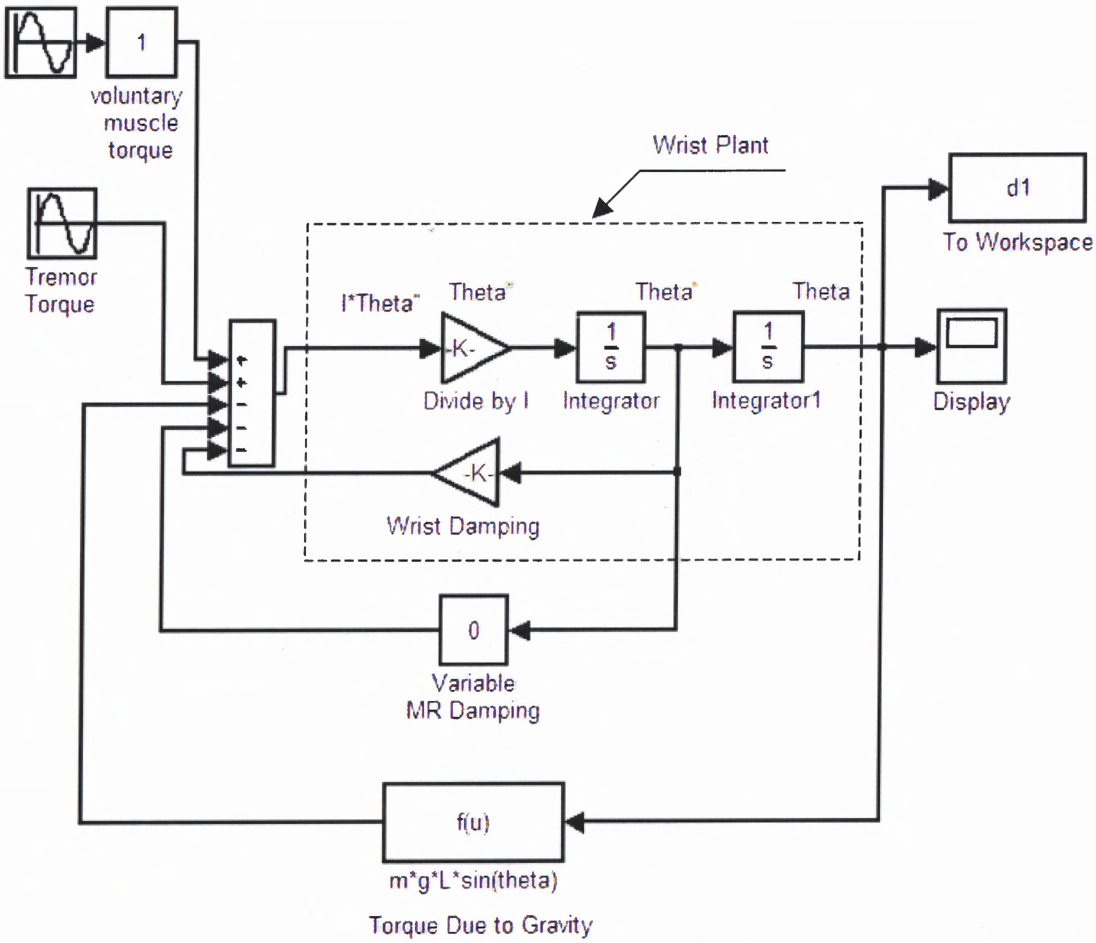


Figure 5.17 The simulation of suppressing hand tremor by MATLAB Simulink.

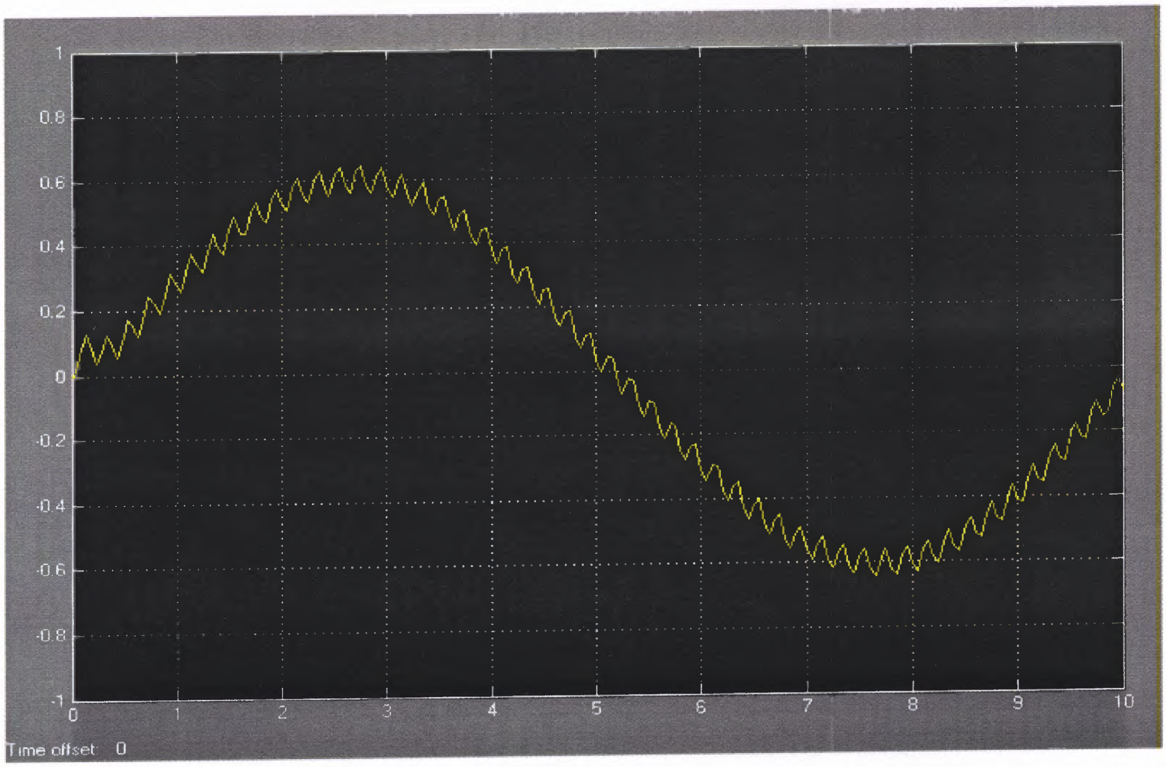


Figure 5.18 The simulation result with the 0 kg·m²/s damping of MR fluid damper.

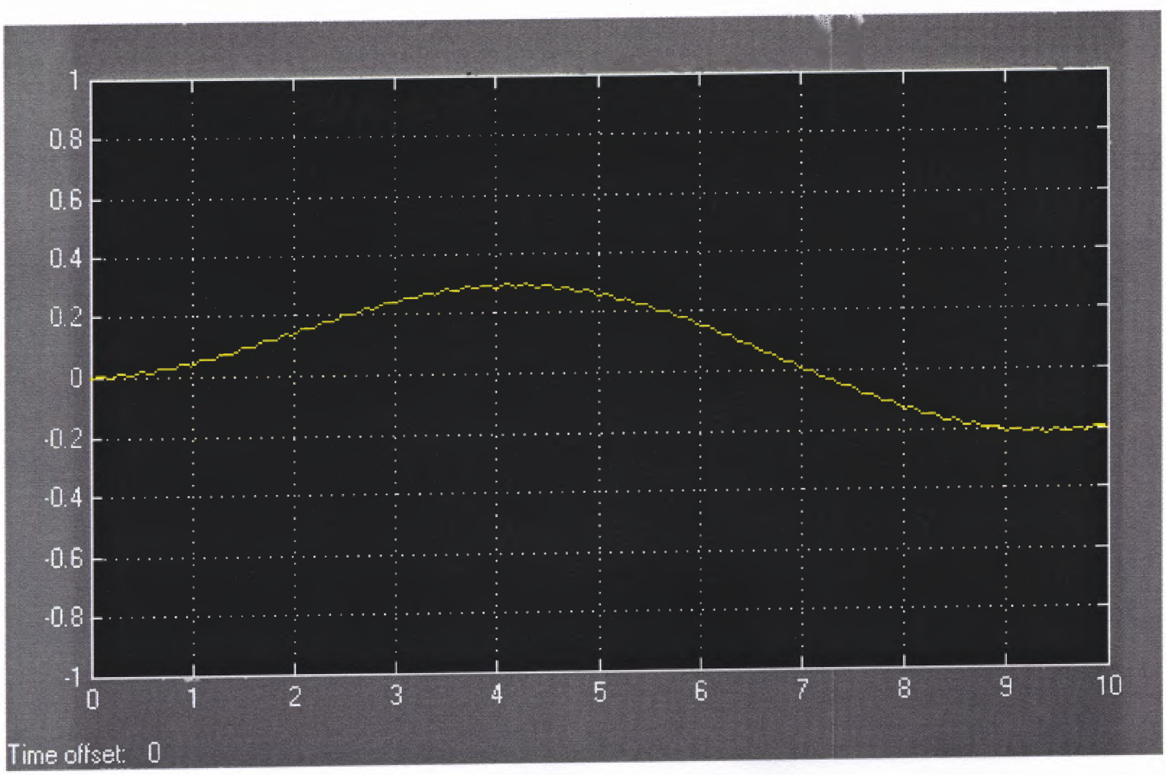


Figure 5.19 The simulation result with the 1.40 kg·m²/s damping of MR fluid damper.

CHAPTER 6

CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

The overall goal of this thesis is to show the possibility of the development of a wearable tremor suppression orthosis which is based on Magneto-Rheological fluid. The simulation results (figure 5.18 and figure 5.19) show that the 1.4 kg·m^2/s damping is good enough for suppressing most wrist tremors. The damping value can be acquired by only 0.25 amp current and 17.6 cm^2 friction area with the MR fluid friction damper which is 1.70 kg·m^2/s in table 5.1. However, there are intrinsic damping which is 1.22 is kg·m^2/s in the MR fluid friction damper in table 5.1. It means the pure damping of the MR fluid itself is 0.68 kg·m^2/s. In case of 0.5 amp current and 17.6 cm^2 friction area, the pure damping of the MR fluid itself is 0.82 kg·m^2/s. If the intrinsic damping of the proto type MR friction damper is around 1 kg·m^2/s, the wearable orthosis will need approximately two ball joints with 0.7cm radius balls and a 3 volt battery to suppress wrist tremor.

Some of the future research that can be done with MR fluid friction damper will be to develop the real time controllable damper. The goal will then be to develop a feed back system to control the damper. Also, the design of a wearable tremor suppressing orthosis prototype is necessary.

APPENDIX A

CURVE FITTING

This appendix contains the angle (radian) versus time (second) graphs which are the results of curve fitting. Table curve 2D program is used for the curve fitting. The program also calculates angular accelerations and angular velocities which are based on the data of this appendix.

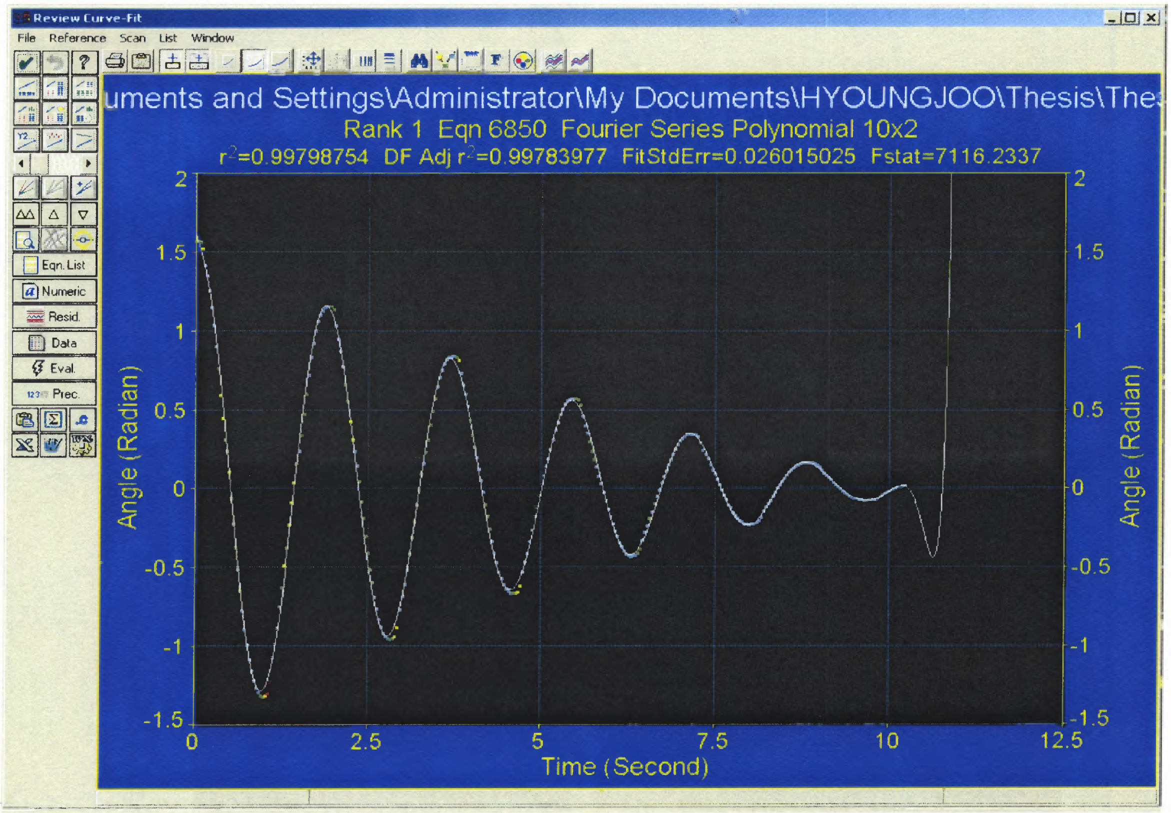


Figure A.1 Curve fitting graph of 0.25 amp and 17.6cm^2 (2cm).

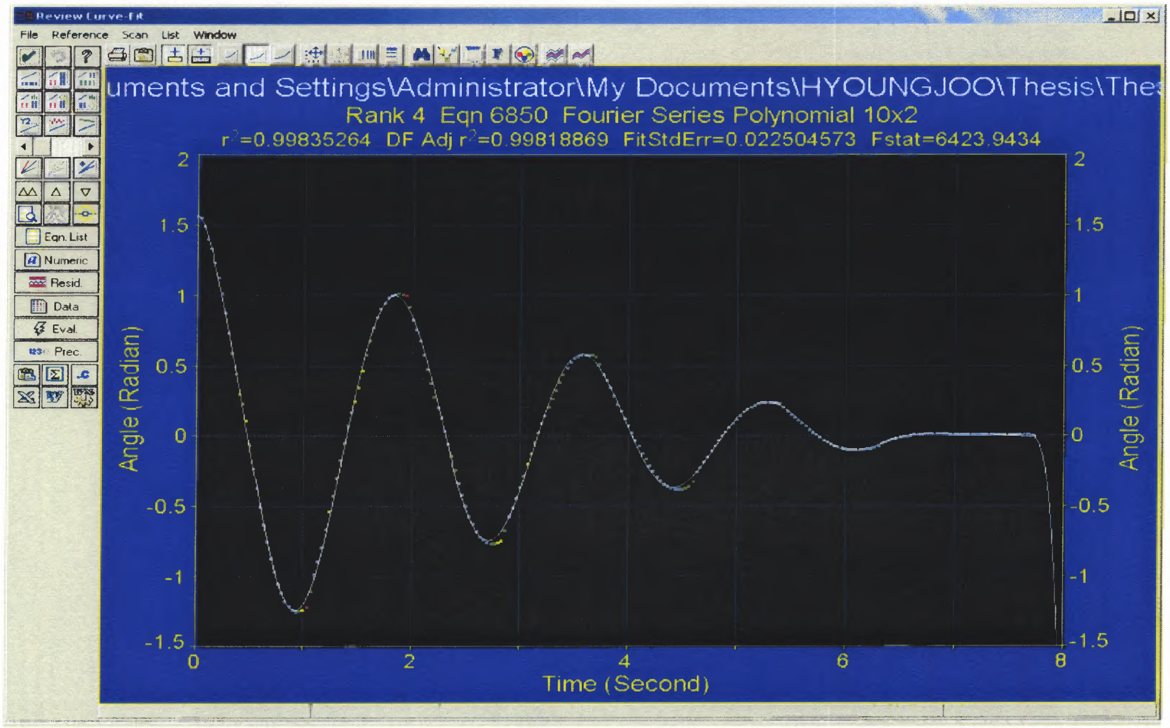


Figure A.2 Curve fitting graph of 0.5 amp and 17.6cm^2 (2cm)

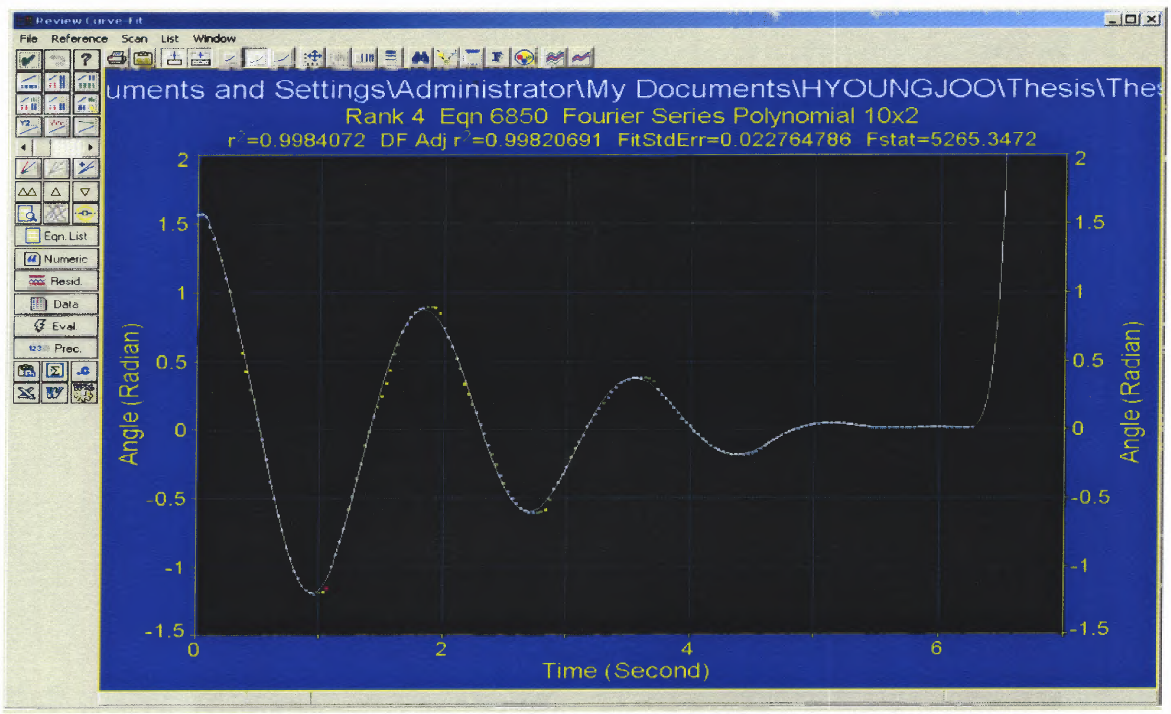


Figure A.3 Curve fitting graph of 0.75 amp and 17.6cm^2 (2cm).

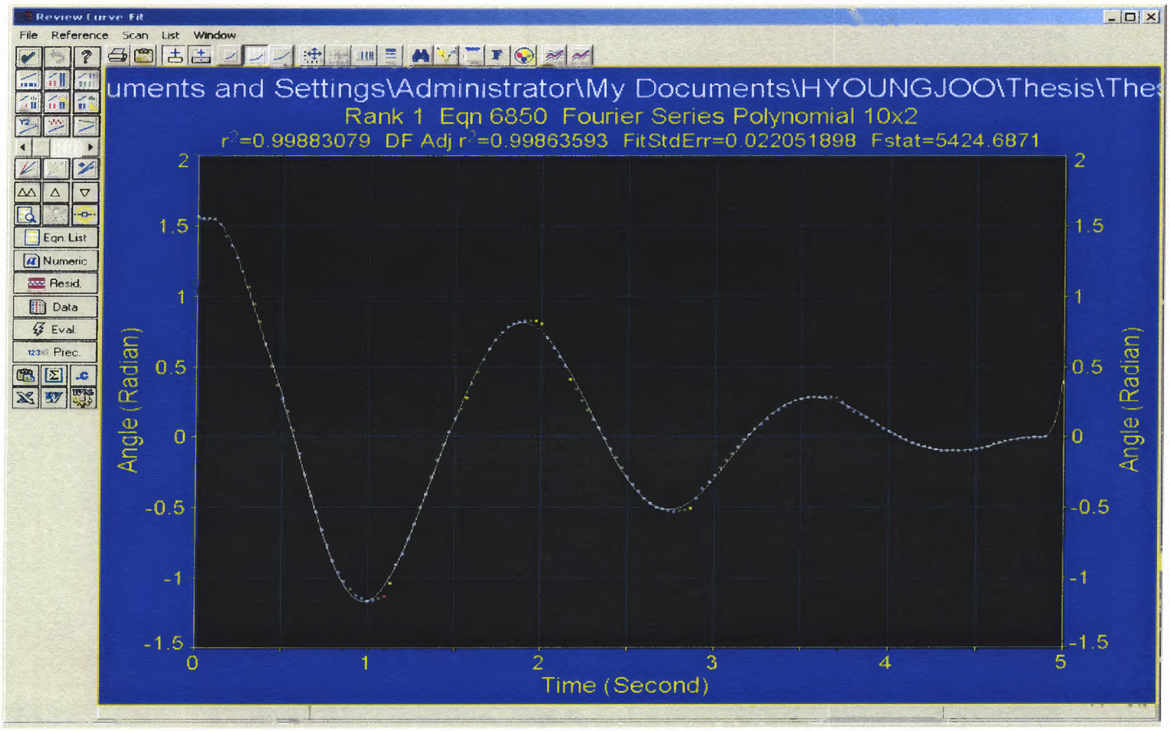


Figure A.4 Curve fitting graph of 1 amp and 17.6cm^2 (2cm).

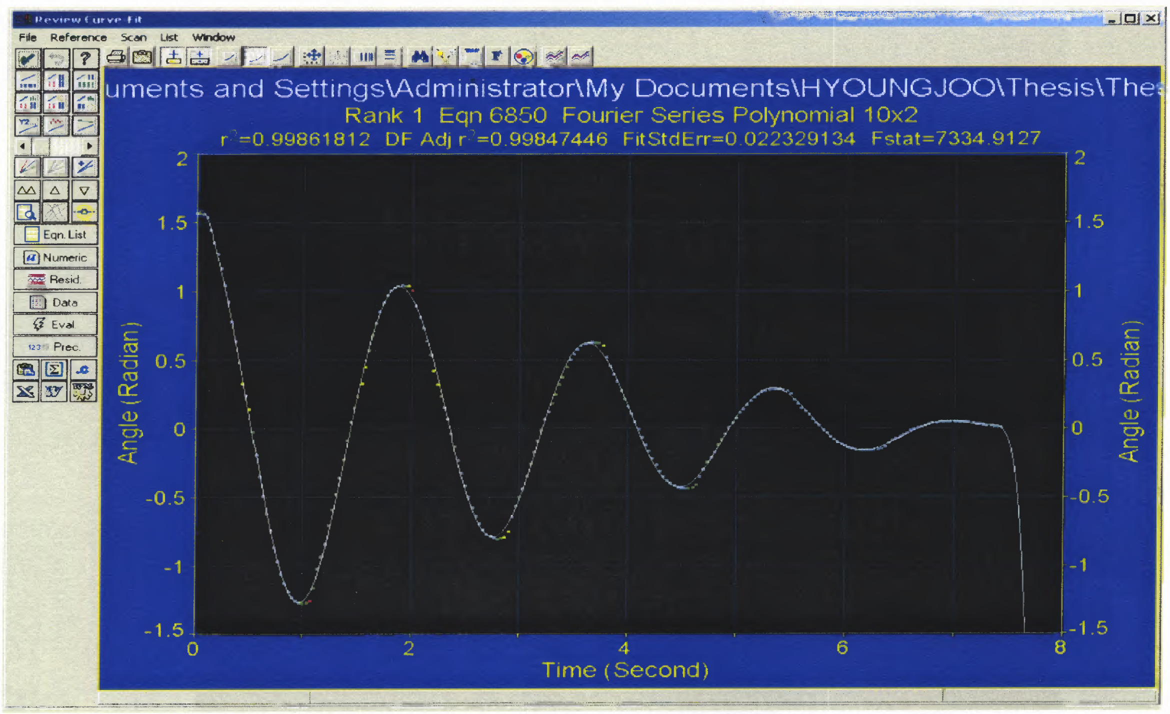


Figure A.5 Curve fitting graph of 0.25 amp and 30.8cm^2 (3.5cm).

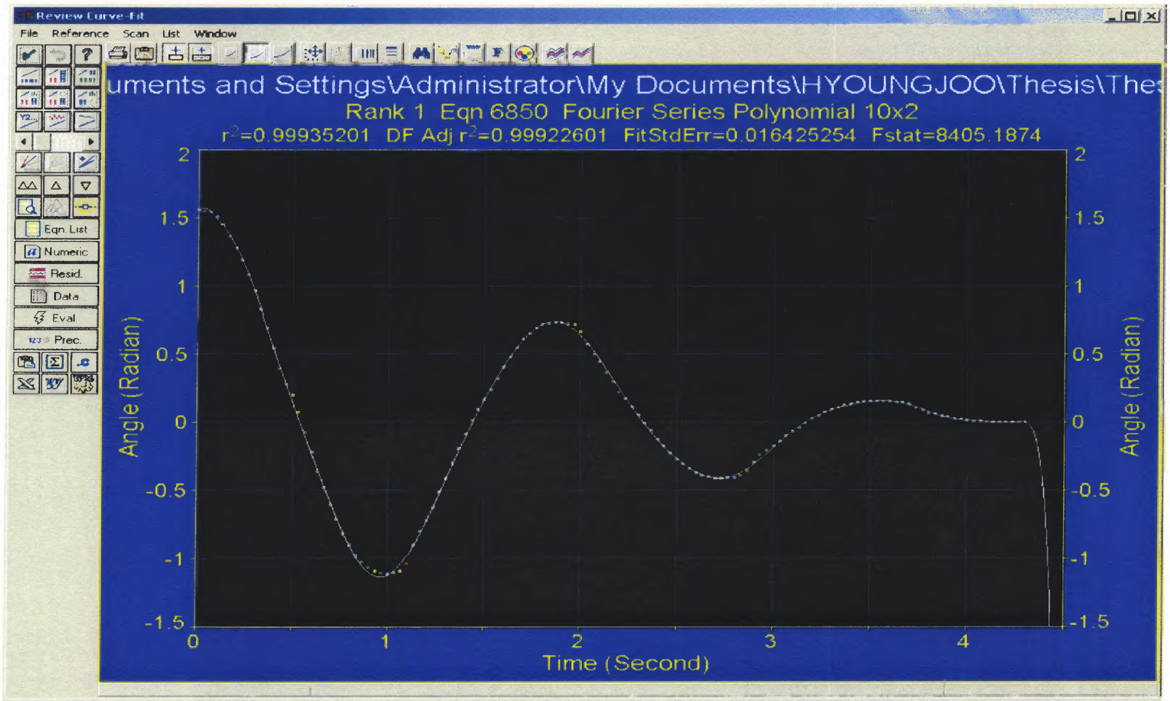


Figure A.6 Curve fitting graph of 0.5 amp and 30.8cm^2 (3.5cm).

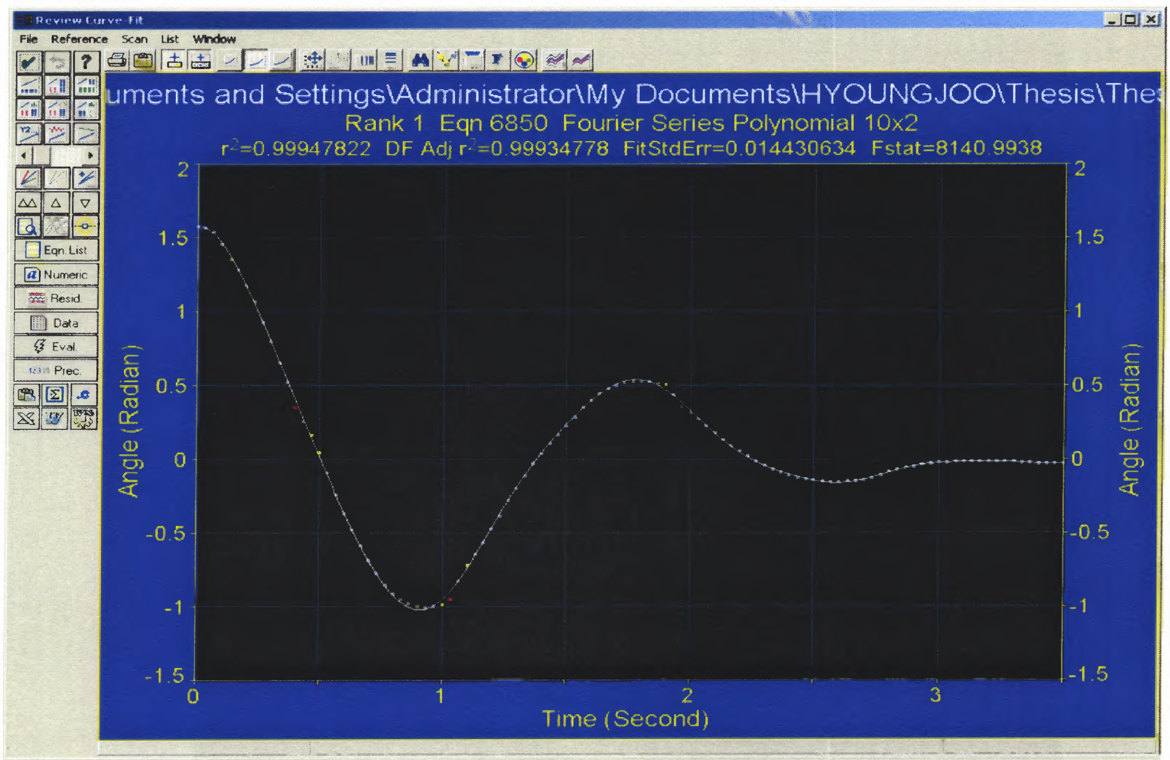


Figure A.7 Curve fitting graph of 0.75 amp and 30.8cm^2 (3.5cm).

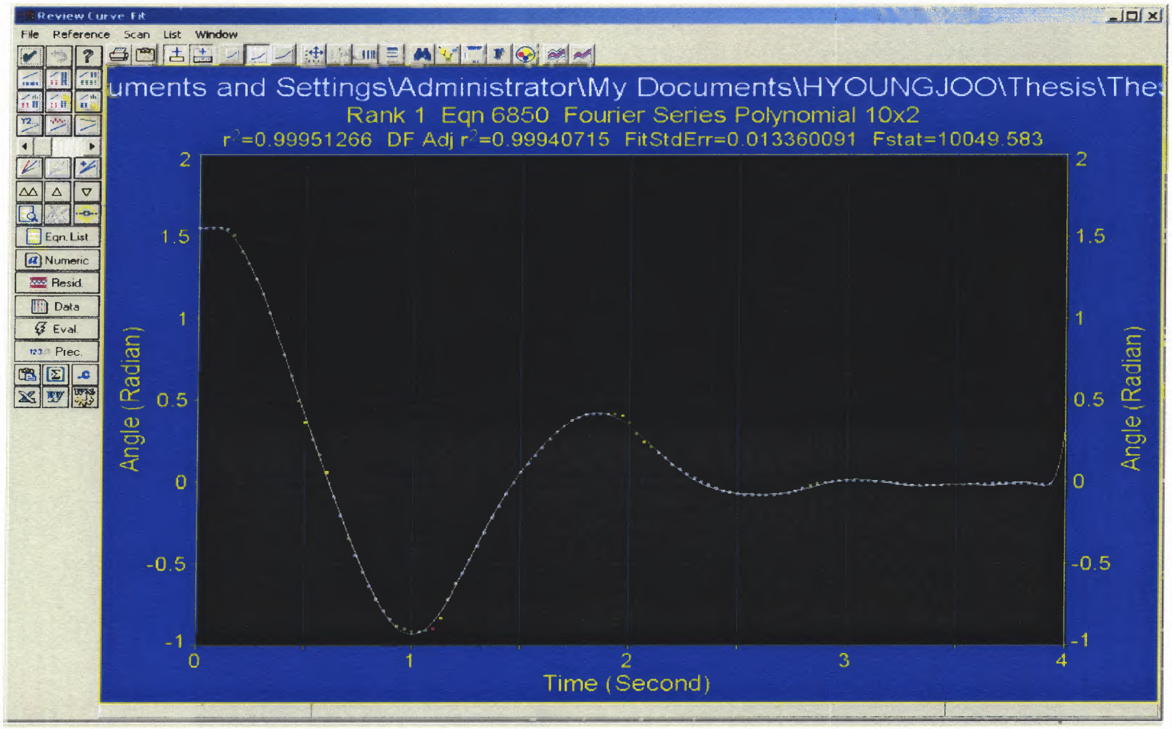


Figure A.8 Curve fitting graph of 1 amp and 30.8cm^2 (3.5cm).

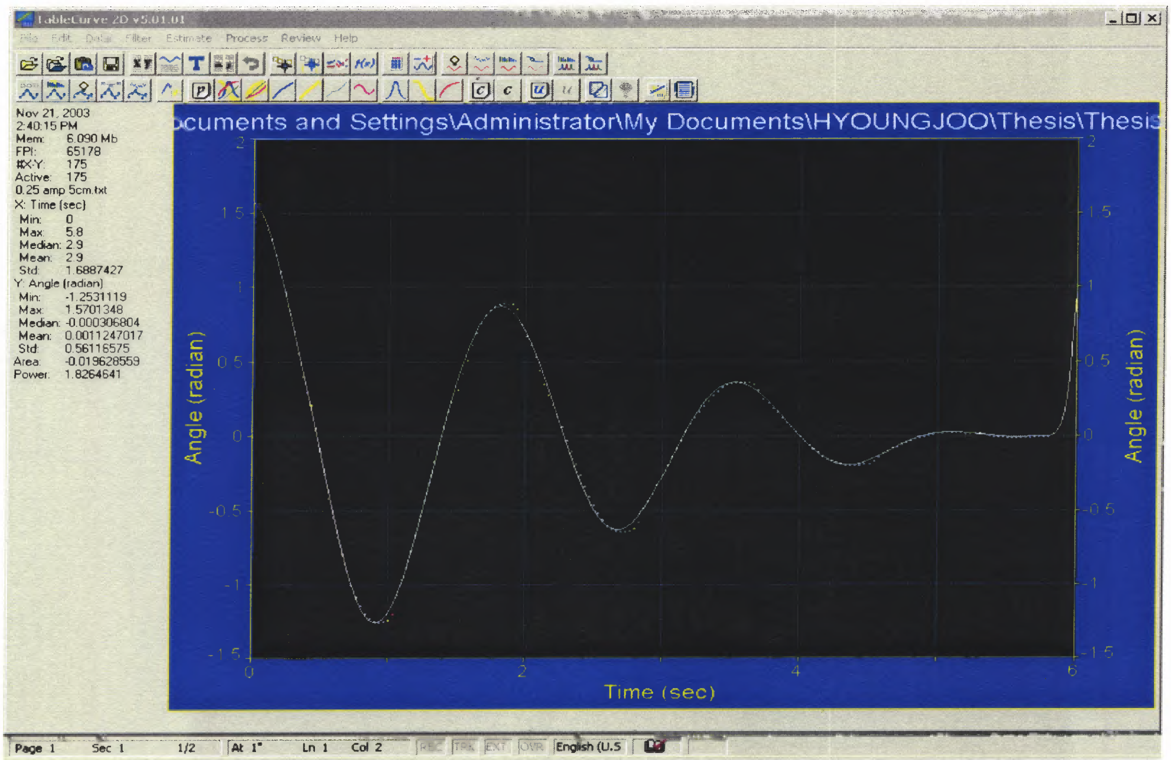


Figure A.9 Curve fitting graph of 0.25 amp and 43.9cm^2 (5cm).

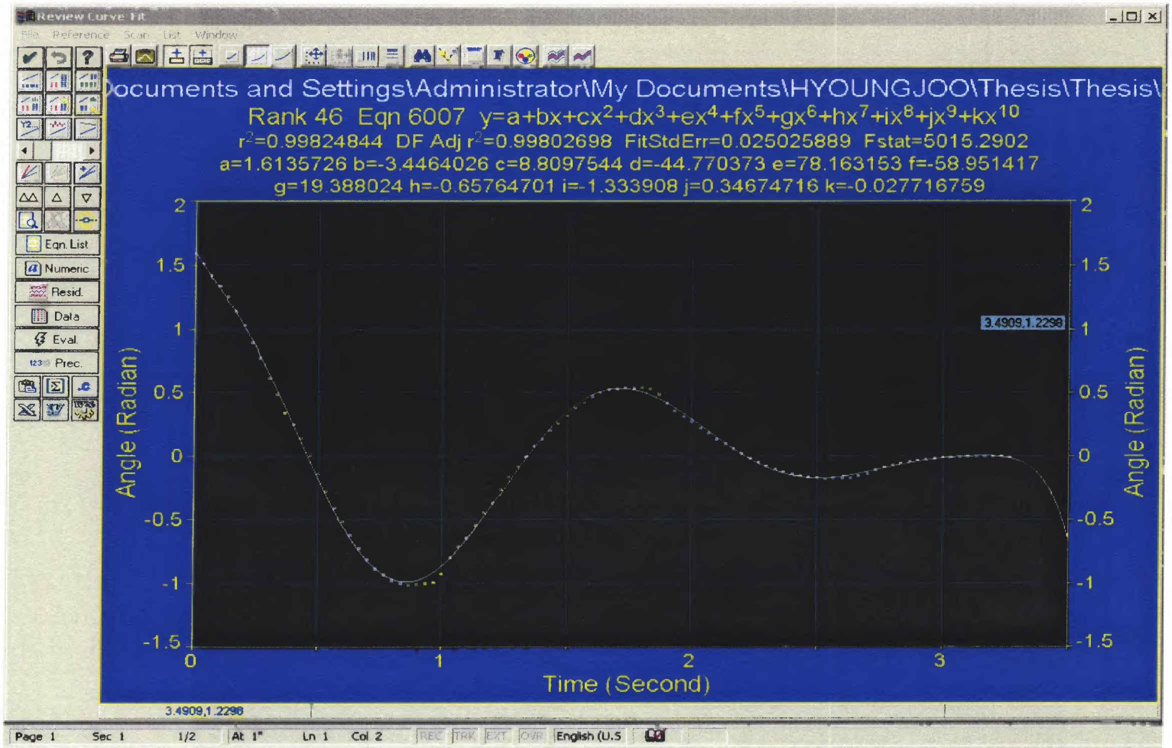


Figure A.10 Curve fitting graph of 0.5 amp and 43.9cm^2 (5cm).

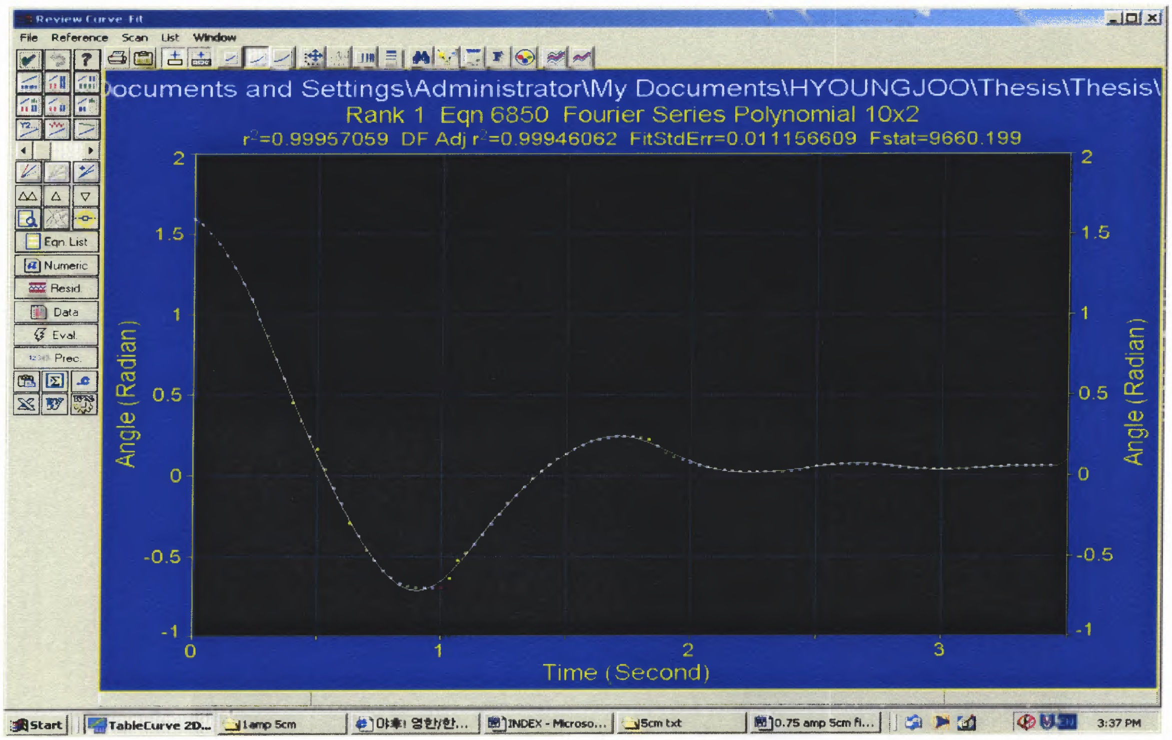


Figure A.11 Curve fitting graph of 0.75 amp and 43.9cm^2 (5cm).

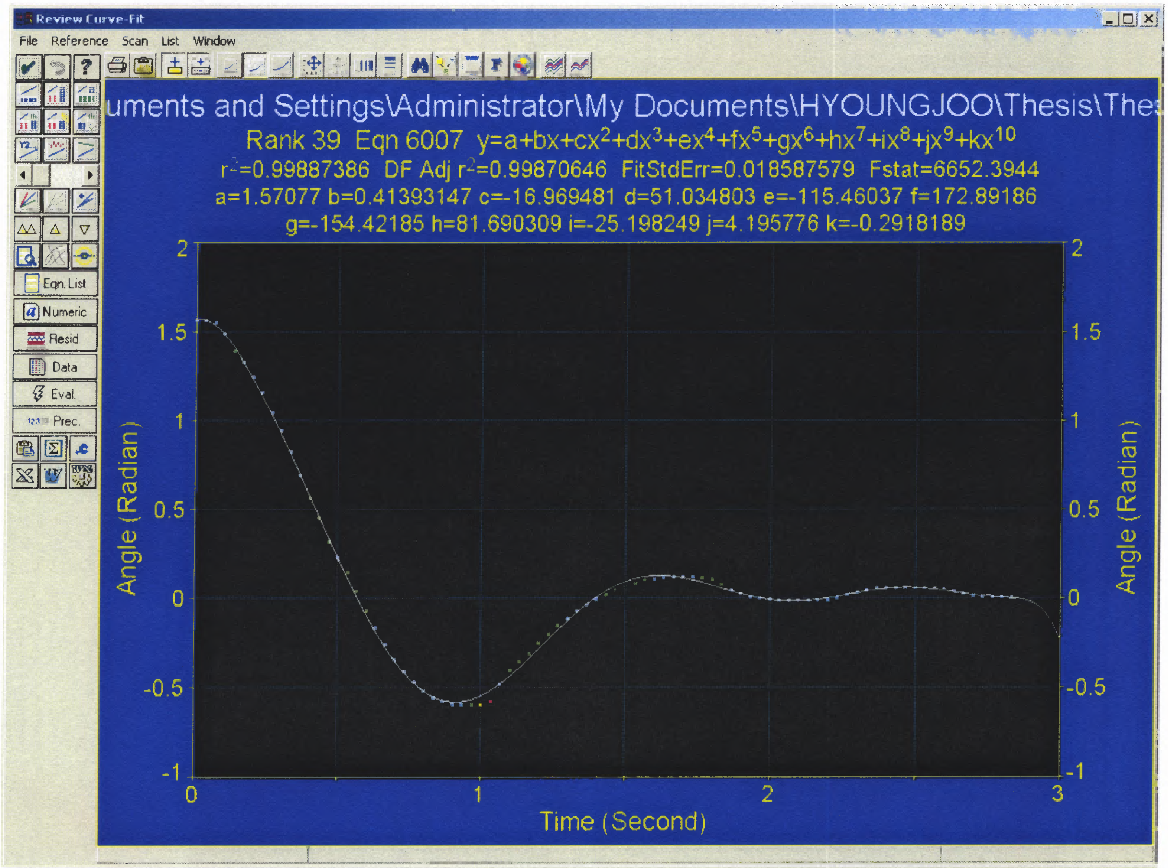


Figure A.12 Curve fitting graph of 0.75 amp and 43.9cm^2 (5cm).

APPENDIX B

CURVE FITTING DATA

This appendix contains data of angular velocities and angular accelerations which is calculated by Table curve 2D. These data are based on the data of angle and time.

Table B.1 Curve Fitting Data of 0.25 amp and 17.6cm^2 (2cm)

Fourier Series Polynomial 10x2

	Parameters	Std Error	T Value	95% Conf Lim	95% Conf Lim
6850	48485.39048	8027.466367	6.039936919	32685.21651	64285.56445
0.997987542	4218.593388	524.5669627	8.042049324	3186.10706	5251.079716
0.997839774	-91193.42673	15037.80306	-6.064278561	-120791.7948	-61595.05861
0.026015025	-75749.10233	12338.59604	-6.139199474	-100034.7181	-51463.48653
7116.233691	-7007.378605	864.2371038	-8.108166814	-8708.425482	-5306.331728
	-7679.038872	933.7073032	-8.224246341	-9516.821449	-5841.256295
	55354.5829	8827.425269	6.270750667	37979.87853	72729.28727
	35332.28595	5460.540956	6.470473573	24584.49915	46080.07275
	6532.066107	777.5864297	8.400437376	5001.570643	8062.561572
	4496.909076	519.6048519	8.65447861	3474.189493	5519.628659
	-19475.14154	2881.681811	-6.758255356	-25147.05243	-13803.23064
	-9108.744801	1270.705563	-7.168257591	-11609.82896	-6607.660642
	-2520.821367	279.5468962	-9.017525864	-3071.043491	-1970.599243
	-1133.774324	118.7439062	-9.548063226	-1367.493693	-900.0549548
	3516.757806	453.0754224	7.761969933	2624.985712	4408.529901
	1070.265023	123.5812412	8.660416526	827.0245012	1313.505545
	394.1424672	38.0010746	10.37187688	319.3463158	468.9386186
	98.11646964	8.290061018	11.83543395	81.79944004	114.4334992
	-234.921069	23.17859358	-10.13525986	-280.542663	-189.2994751
	-29.27886008	2.276041433	-12.86393985	-33.75871075	-24.79900941

X Observed	Y Observed	Y Predicted	Y Residual	Y Residual%	First Deriv	Second Deriv
0.500000	0.102933	0.045655	0.057278	55.645742	-4.684841	0.901702
0.533330	-0.066209	-0.109649	0.043440	-65.610814	-4.624178	2.728357
0.566670	-0.227634	-0.261974	0.034339	-15.085248	-4.503743	4.482005
0.600000	-0.380132	-0.409282	0.029150	-7.668416	-4.326451	6.138829
0.633330	-0.513033	-0.549782	0.036749	-7.163152	-4.095805	7.680819
0.666670	-0.651972	-0.681799	0.029827	-4.574839	-3.815802	9.093275
0.700000	-0.778150	-0.803687	0.025537	-3.281761	-3.491152	10.363078
0.733330	-0.898836	-0.914077	0.015241	-1.695642	-3.126690	11.480755
0.766670	-0.994230	-1.011755	0.017525	-1.762653	-2.727499	12.438654
0.800000	-1.091715	-1.095599	0.003884	-0.355761	-2.299261	13.230024
0.833330	-1.161432	-1.164762	0.003330	-0.286707	-1.847484	13.850572
0.866670	-1.223050	-1.218569	-0.004482	0.366440	-1.377772	14.297270
0.900000	-1.267379	-1.256490	-0.010889	0.859177	-0.896241	14.568135
0.933330	-1.296453	-1.278244	-0.018208	1.404483	-0.408616	14.663028
0.966670	-1.313872	-1.283725	-0.030147	2.294551	0.079399	14.583037
1.000000	-1.322287	-1.273017	-0.049269	3.726064	0.561722	14.330818
1.033330	-1.314211	-1.246405	-0.067806	5.159453	1.032823	13.910500
1.066670	-1.302359	-1.204340	-0.098018	7.526215	1.487324	13.327565
1.100000	-1.231432	-1.147495	-0.083937	6.816241	1.919653	12.589627
1.133330	-1.077913	-1.076677	-0.001236	0.114645	2.324923	11.705396
1.166670	-0.988582	-0.992842	0.004259	-0.430854	2.698532	10.684988
1.200000	-0.885698	-0.897171	0.011472	-1.295304	3.035924	9.541008
1.233330	-0.756845	-0.790912	0.034066	-4.501106	3.333309	8.286637
1.266670	-0.635800	-0.675420	0.039620	-6.231452	3.587319	6.936314
1.300000	-0.493798	-0.552263	0.058465	-11.839882	3.794884	5.506968
1.333330	-0.379443	-0.422994	0.043551	-11.477584	3.953722	4.015429
1.366670	-0.231188	-0.289228	0.058040	-25.105081	4.062087	2.479380
1.400000	-0.088993	-0.152750	0.063757	-71.643163	4.118758	0.918615
1.433330	0.036893	-0.015252	0.052145	141.340167	4.123257	-0.647961
1.466670	0.157084	0.121569	0.035516	22.609331	4.075696	-2.201198
1.500000	0.236700	0.255906	-0.019205	-8.113744	3.976890	-3.720557
1.533330	0.338943	0.386115	-0.047171	-13.917111	3.828270	-5.187174
1.566670	0.471483	0.510604	-0.039121	-8.297326	3.631843	-6.582666
1.600000	0.598271	0.627751	-0.029480	-4.927518	3.390413	-7.888209
1.633330	0.721530	0.736144	-0.014614	-2.025486	3.107197	-9.087322
1.666670	0.829525	0.834482	-0.004957	-0.597548	2.785906	-10.164712
1.700000	0.922488	0.921510	0.000978	0.105989	2.431039	-11.105687
1.733330	0.996965	0.996214	0.000751	0.075297	2.047250	-11.898313
1.766670	1.057789	1.057731	0.000057	0.005427	1.639536	-12.532431
1.800000	1.098517	1.105322	-0.006805	-0.619426	1.213574	-12.999452
1.833330	1.128277	1.138487	-0.010210	-0.904898	0.774914	-13.293631

X Observed	Y Observed	Y Predicted	Y Residual	Y Residual%	First Deriv	Second Deriv
1.866670	1.147223	1.156904	-0.009682	-0.843934	0.329248	-13.411361
1.900000	1.153129	1.160432	-0.007303	-0.633343	-0.117246	-13.351365
1.933330	1.152515	1.149144	0.003371	0.292508	-0.558793	-13.114932
1.966670	1.150137	1.123293	0.026845	2.334039	-0.989694	-12.705572
2.000000	1.131345	1.083348	0.047997	4.242512	-1.404024	-12.129565
2.033330	1.031634	1.029943	0.001690	0.163840	-1.796490	-11.395150
2.066670	0.948336	0.963872	-0.015536	-1.638263	-2.162086	-10.512559
2.100000	0.871251	0.886153	-0.014902	-1.710427	-2.495867	-9.494875
2.133330	0.773073	0.797898	-0.024824	-3.211122	-2.793670	-8.356259
2.166670	0.661319	0.700338	-0.039019	-5.900175	-3.051800	-7.112376
2.200000	0.549872	0.594914	-0.045042	-8.191328	-3.266893	-5.781445
2.233330	0.425002	0.483074	-0.058071	-13.663747	-3.436427	-4.381738
2.266670	0.312865	0.366335	-0.053470	-17.090308	-3.558462	-2.932341
2.300000	0.233556	0.246375	-0.012819	-5.488746	-3.631617	-1.454266
2.333330	0.140747	0.124801	0.015946	11.329761	-3.655307	0.032453
2.366670	0.044410	0.003225	0.041185	92.737841	-3.629570	1.507764
2.400000	-0.082053	-0.116642	0.034589	-42.154658	-3.555156	2.950549
2.433330	-0.189031	-0.233236	0.044205	-23.385370	-3.433462	4.341577
2.466670	-0.306408	-0.345046	0.038639	-12.610167	-3.266474	5.662386
2.500000	-0.414210	-0.450540	0.036331	-8.771053	-3.056946	6.894429
2.533330	-0.519543	-0.548385	0.028842	-5.551488	-2.808056	8.021708
2.566670	-0.601235	-0.637355	0.036120	-6.007660	-2.523458	9.029668
2.600000	-0.694812	-0.716278	0.021466	-3.089399	-2.207533	9.904639
2.633330	-0.767155	-0.784211	0.017056	-2.223286	-1.864813	10.635828
2.666670	-0.831229	-0.840358	0.009129	-1.098243	-1.500135	11.214368
2.700000	-0.878392	-0.884044	0.005652	-0.643438	-1.118931	11.633102
2.733330	-0.919083	-0.914821	-0.004262	0.463732	-0.726497	11.887714
2.766670	-0.941802	-0.932412	-0.009391	0.997092	-0.328225	11.976033
2.800000	-0.954854	-0.936706	-0.018147	1.900532	0.070098	11.898191
2.833330	-0.960682	-0.927798	-0.032883	3.422923	0.463090	11.656759
2.866670	-0.954768	-0.905947	-0.048821	5.113364	0.845485	11.256399
2.900000	-0.942824	-0.871610	-0.071214	7.553243	1.211871	10.704352
2.933330	-0.890267	-0.825395	-0.064872	7.286756	1.557451	10.009602
2.966670	-0.773518	-0.768054	-0.005464	0.706395	1.877739	9.182899
3.000000	-0.689542	-0.700538	0.010997	-1.594769	2.168362	8.237517
3.033330	-0.612988	-0.623881	0.010893	-1.777007	2.425690	7.187569
3.066670	-0.520714	-0.539221	0.018507	-3.554230	2.646558	6.048392
3.100000	-0.417998	-0.447873	0.029875	-7.147187	2.828147	4.837474
3.133330	-0.314150	-0.351156	0.037006	-11.779880	2.968419	3.572154
3.166670	-0.208459	-0.250444	0.041985	-20.140459	3.065888	2.270307
3.200000	-0.104396	-0.147240	0.042844	-41.040291	3.119599	0.951330

X Observed	Y Observed	Y Predicted	Y Residual	Y Residual%	First Deriv	Second Deriv
3.233330	-0.011812	-0.042980	0.031168	-263.868084	3.129316	-0.366481
3.266670	0.088820	0.060906	0.027914	31.428098	3.095371	-1.665022
3.300000	0.158312	0.162914	-0.004602	-2.907208	3.018741	-2.925479
3.333330	0.230334	0.261678	-0.031343	-13.607820	2.900970	-4.130923
3.366670	0.307956	0.355886	-0.047930	-15.564020	2.744115	-5.265306
3.400000	0.407131	0.444225	-0.037094	-9.111068	2.550906	-6.312743
3.433330	0.487667	0.525560	-0.037893	-7.770171	2.324424	-7.259761
3.466670	0.572806	0.598861	-0.026055	-4.548740	2.068142	-8.094327
3.500000	0.646823	0.663159	-0.016336	-2.525621	1.786153	-8.805395
3.533330	0.707570	0.717687	-0.010117	-1.429806	1.482641	-9.384544
3.566670	0.753975	0.761814	-0.007840	-1.039810	1.162022	-9.825152
3.600000	0.792939	0.795026	-0.002087	-0.263167	0.829196	-10.122258
3.633330	0.817253	0.817006	0.000248	0.030297	0.488895	-10.273403
3.666670	0.831596	0.827588	0.004008	0.482009	0.145896	-10.278051
3.700000	0.837502	0.826761	0.010741	1.282529	-0.194732	-10.137767
3.733330	0.837042	0.814685	0.022357	2.670916	-0.528317	-9.856187
3.766670	0.834281	0.791665	0.042616	5.108133	-0.850331	-9.438743
3.800000	0.811654	0.758176	0.053478	6.588798	-1.156176	-8.893135
3.833330	0.735029	0.714819	0.020211	2.749657	-1.441824	-8.228451
3.866670	0.658788	0.662313	-0.003525	-0.535113	-1.703556	-7.455229
3.900000	0.594743	0.601550	-0.006807	-1.144558	-1.937804	-6.586146
3.933330	0.521186	0.533477	-0.012291	-2.358323	-2.141670	-5.634432
3.966670	0.429604	0.459129	-0.029524	-6.872390	-2.312684	-4.614246
4.000000	0.338713	0.379680	-0.040967	-12.094898	-2.448724	-3.541493
4.033330	0.263546	0.296301	-0.032755	-12.428726	-2.548349	-2.431750
4.066670	0.195819	0.210197	-0.014378	-7.342590	-2.610607	-1.300904
4.100000	0.122876	0.122673	0.000203	0.164939	-2.635042	-0.165979
4.133330	0.051543	0.034964	0.016580	32.166520	-2.621803	0.957135
4.166670	-0.027529	-0.051711	0.024182	-87.844184	-2.571527	2.052884
4.200000	-0.106445	-0.136082	0.029637	-27.842301	-2.485426	3.105305
4.233330	-0.179502	-0.217010	0.037507	-20.895096	-2.365167	4.100213
4.266670	-0.259199	-0.293411	0.034212	-13.199177	-2.212845	5.024340
4.300000	-0.339625	-0.364214	0.024589	-7.240152	-2.031130	5.864768
4.333330	-0.409578	-0.428512	0.018933	-4.622579	-1.822949	6.610754
4.366670	-0.471509	-0.485491	0.013982	-2.965356	-1.591541	7.252926
4.400000	-0.530275	-0.534405	0.004130	-0.778767	-1.340648	7.782945
4.433330	-0.576334	-0.574684	-0.001651	0.286398	-1.074044	8.194766
4.466670	-0.614189	-0.605878	-0.008311	1.353166	-0.795663	8.483971
4.500000	-0.637310	-0.627649	-0.009661	1.515893	-0.509813	8.647715
4.533330	-0.653913	-0.639825	-0.014088	2.154376	-0.220609	8.685267
4.566670	-0.665030	-0.642364	-0.022666	3.408259	0.067841	8.597571

X Observed	Y Observed	Y Predicted	Y Residual	Y Residual%	First Deriv	Second Deriv
4.600000	-0.669459	-0.635361	-0.034098	5.093419	0.351231	8.387460
4.633330	-0.664339	-0.619051	-0.045289	6.817120	0.625638	8.059441
4.666670	-0.657177	-0.593789	-0.063388	9.645552	0.887307	7.619530
4.700000	-0.619351	-0.560079	-0.059272	9.569974	1.132480	7.075698
4.733330	-0.536288	-0.518517	-0.017770	3.313585	1.357918	6.436950
4.766670	-0.468102	-0.469797	0.001695	-0.362123	1.560685	5.713448
4.800000	-0.411902	-0.414750	0.002849	-0.691559	1.738030	4.917121
4.833330	-0.341663	-0.354247	0.012583	-3.683011	1.887787	4.060183
4.866670	-0.265779	-0.289217	0.023438	-8.818737	2.008185	3.155511
4.900000	-0.179841	-0.220704	0.040863	-22.722000	2.097798	2.217345
4.933330	-0.118623	-0.149729	0.031106	-26.222653	2.155774	1.259444
4.966670	-0.046999	-0.077335	0.030336	-64.545926	2.181694	0.295670
5.000000	0.024008	-0.004632	0.028640	119.293892	2.175591	-0.659326
5.033330	0.083144	0.067340	0.015804	19.008012	2.137991	-1.592051
5.066670	0.141744	0.137568	0.004176	2.946383	2.069835	-2.489466
5.100000	0.191217	0.205013	-0.013796	-7.215097	1.972563	-3.338402
5.133330	0.251274	0.268755	-0.017481	-6.957121	1.847964	-4.127354
5.166670	0.313325	0.327936	-0.014611	-4.663092	1.698172	-4.845761
5.200000	0.372309	0.381722	-0.009414	-2.528490	1.525798	-5.483579
5.233330	0.417332	0.429425	-0.012093	-2.897730	1.333622	-6.032715
5.266670	0.470793	0.470447	0.000346	0.073536	1.124655	-6.486365
5.300000	0.503545	0.504259	-0.000714	-0.141836	0.902304	-6.838810
5.333330	0.534532	0.530483	0.004049	0.757426	0.669946	-7.086306
5.366670	0.555778	0.548850	0.006928	1.246604	0.431051	-7.226567
5.400000	0.566286	0.559192	0.007094	1.252800	0.189353	-7.258804
5.433330	0.571425	0.561480	0.009945	1.740426	-0.051631	-7.183968
5.466670	0.571962	0.555794	0.016168	2.826713	-0.288438	-7.004451
5.500000	0.570428	0.542338	0.028091	4.924478	-0.517501	-6.724336
5.533330	0.564062	0.521419	0.042642	7.559892	-0.735624	-6.349003
5.566670	0.527859	0.493447	0.034412	6.519118	-0.939801	-5.885060
5.600000	0.456373	0.458952	-0.002579	-0.565060	-1.127091	-5.340781
5.633330	0.400305	0.418530	-0.018226	-4.553017	-1.295024	-4.725131
5.666670	0.352826	0.372851	-0.020025	-5.675509	-1.441427	-4.047945
5.700000	0.294226	0.322692	-0.028466	-9.674846	-1.564346	-3.320470
5.733330	0.238004	0.268849	-0.030844	-12.959607	-1.662336	-2.553974
5.766670	0.181015	0.212153	-0.031138	-17.201815	-1.734311	-1.760128
5.800000	0.134611	0.153520	-0.018909	-14.047368	-1.779526	-0.951585
5.833330	0.076625	0.093830	-0.017206	-22.454545	-1.797714	-0.140364
5.866670	0.028380	0.033966	-0.005586	-19.684567	-1.788981	0.661622
5.900000	-0.024354	-0.025148	0.000793	-3.257791	-1.753849	1.442024
5.933330	-0.077645	-0.082662	0.005017	-6.461531	-1.693220	2.189681

X Observed	Y Observed	Y Predicted	Y Residual	Y Residual%	First Deriv	Second Deriv
5.966670	-0.128751	-0.137765	0.009014	-7.000781	-1.608339	2.894018
6.000000	-0.177551	-0.189640	0.012089	-6.808871	-1.500878	3.544615
6.033330	-0.226453	-0.237583	0.011130	-4.914996	-1.372751	4.132619
6.066670	-0.272572	-0.280955	0.008383	-3.075355	-1.226136	4.650156
6.100000	-0.308372	-0.319154	0.010782	-3.496427	-1.063591	5.090058
6.133330	-0.346621	-0.351706	0.005085	-1.467073	-0.887756	5.446887
6.166670	-0.375407	-0.378222	0.002815	-0.749914	-0.701416	5.716436
6.200000	-0.400381	-0.398388	-0.001993	0.497804	-0.507647	5.895641
6.233330	-0.416288	-0.412013	-0.004275	1.027050	-0.309432	5.983104
6.266670	-0.425530	-0.419001	-0.006529	1.534434	-0.109774	5.978731
6.300000	-0.429678	-0.419352	-0.010326	2.403227	0.088164	5.883848
6.333330	-0.427619	-0.413175	-0.014444	3.377839	0.281467	5.701157
6.366670	-0.424002	-0.400668	-0.023334	5.503308	0.467326	5.434564
6.400000	-0.414878	-0.382134	-0.032744	7.892428	0.642919	5.089466
6.433330	-0.387520	-0.357953	-0.029567	7.629906	0.805787	4.672172
6.466670	-0.329431	-0.328577	-0.000854	0.259086	0.953688	4.189939
6.500000	-0.275593	-0.294561	0.018968	-6.882444	1.084508	3.651373
6.533330	-0.236382	-0.256493	0.020111	-8.507830	1.196561	3.065423
6.566670	-0.188739	-0.215010	0.026271	-13.919016	1.288454	2.441601
6.600000	-0.148659	-0.170829	0.022170	-14.913407	1.359043	1.790451
6.633330	-0.094808	-0.124661	0.029853	-31.488123	1.407616	1.122256
6.666670	-0.051264	-0.077232	0.025968	-50.654860	1.433786	0.447412
6.700000	-0.012042	-0.029320	0.017278	-143.477835	1.437498	-0.223109
6.733330	0.036203	0.018346	0.017857	49.325706	1.419074	-0.879144
6.766670	0.075167	0.065051	0.010117	13.458982	1.379151	-1.510873
6.800000	0.109760	0.110066	-0.000306	-0.279175	1.318729	-2.108422
6.833330	0.152176	0.152743	-0.000568	-0.373124	1.239080	-2.663151
6.866670	0.182626	0.192478	-0.009852	-5.394776	1.141737	-3.167159
6.900000	0.217679	0.228688	-0.011009	-5.057581	1.028575	-3.613008
6.933330	0.251427	0.260890	-0.009462	-3.763510	0.901607	-3.994735
6.966670	0.277352	0.288668	-0.011316	-4.079857	0.763012	-4.307400
7.000000	0.300439	0.311659	-0.011219	-3.734303	0.615247	-4.546959
7.033330	0.319538	0.329605	-0.010067	-3.150605	0.460752	-4.710878
7.066670	0.332194	0.342329	-0.010135	-3.051006	0.302028	-4.797778
7.100000	0.341014	0.349725	-0.008711	-2.554419	0.141743	-4.807466
7.133330	0.344849	0.351788	-0.006939	-2.012093	-0.017592	-4.741082
7.166670	0.345003	0.348589	-0.003586	-1.039528	-0.173523	-4.600888
7.200000	0.343852	0.340286	0.003566	1.037177	-0.323553	-4.390438
7.233330	0.341244	0.327111	0.014133	4.141599	-0.465459	-4.114263
7.266670	0.328359	0.309366	0.018993	5.784076	-0.597179	-3.777817
7.300000	0.292616	0.287434	0.005182	1.770969	-0.716733	-3.387766

X Observed	Y Observed	Y Predicted	Y Residual	Y Residual%	First Deriv	Second Deriv
7.333330	0.243220	0.261742	-0.018522	-7.615310	-0.822491	-2.951263
7.366670	0.213460	0.232766	-0.019306	-9.044518	-0.913061	-2.476061
7.400000	0.187075	0.201051	-0.013976	-7.471027	-0.987240	-1.970860
7.433330	0.151485	0.167148	-0.015663	-10.339699	-1.044201	-1.444308
7.466670	0.118427	0.131631	-0.013205	-11.149942	-1.083390	-0.905244
7.500000	0.086596	0.095120	-0.008524	-9.843254	-1.104522	-0.363060
7.533330	0.054611	0.058204	-0.003593	-6.578697	-1.107655	0.173426
7.566670	0.020172	0.021469	-0.001296	-6.426680	-1.093115	0.695627
7.600000	-0.011788	-0.014485	0.002696	-22.873423	-1.061536	1.194875
7.633330	-0.047285	-0.049114	0.001828	-3.866554	-1.013806	1.663493
7.666670	-0.072306	-0.081908	0.009601	-13.278477	-0.951047	2.094420
7.700000	-0.102045	-0.112369	0.010324	-10.116939	-0.874667	2.480973
7.733330	-0.126175	-0.140079	0.013903	-11.019127	-0.786219	2.817732
7.766670	-0.149835	-0.164670	0.014836	-9.901367	-0.687411	3.100164
7.800000	-0.171983	-0.185815	0.013833	-8.042967	-0.580178	3.324506
7.833330	-0.188800	-0.203273	0.014473	-7.665539	-0.466472	3.488326
7.866670	-0.202987	-0.216865	0.013878	-6.836667	-0.348299	3.590212
7.900000	-0.215028	-0.226469	0.011441	-5.320532	-0.227806	3.629777
7.933330	-0.223321	-0.232047	0.008726	-3.907539	-0.107022	3.607829
7.966670	-0.227110	-0.233622	0.006512	-2.867289	0.012064	3.526166
8.000000	-0.229602	-0.231285	0.001683	-0.733034	0.127436	3.387687
8.033330	-0.227637	-0.225189	-0.002449	1.075681	0.237298	3.196175
8.066670	-0.225157	-0.215543	-0.009614	4.269764	0.339985	2.956213
8.100000	-0.220513	-0.202620	-0.017893	8.114261	0.433914	2.673377
8.133330	-0.207841	-0.186730	-0.021110	10.157012	0.517783	2.353684
8.166670	-0.181811	-0.168223	-0.013588	7.473724	0.590494	2.003640
8.200000	-0.143806	-0.147497	0.003691	-2.566789	0.651111	1.630467
8.233330	-0.119389	-0.124961	0.005573	-4.667624	0.699004	1.241336
8.266670	-0.098846	-0.101040	0.002194	-2.219945	0.733772	0.843514
8.300000	-0.076619	-0.076189	-0.000430	0.560637	0.755231	0.444601
8.333330	-0.048007	-0.050843	0.002836	-5.907351	0.763475	0.051673
8.366670	-0.024105	-0.025432	0.001327	-5.505102	0.758816	-0.328495
8.400000	-0.000836	-0.000390	-0.000446	53.292616	0.741793	-0.689216
8.433330	0.022627	0.023887	-0.001260	-5.570109	0.713153	-1.024706
8.466670	0.042876	0.047036	-0.004160	-9.702736	0.673812	-1.329804
8.500000	0.065656	0.068704	-0.003048	-4.641846	0.624887	-1.599832
8.533330	0.083451	0.088598	-0.005147	-6.167821	0.567597	-1.831215
8.566670	0.101706	0.106467	-0.004761	-4.681092	0.503259	-2.021215
8.600000	0.116356	0.122089	-0.005733	-4.926903	0.433326	-2.167843
8.633330	0.129395	0.135306	-0.005911	-4.568280	0.359242	-2.270224
8.666670	0.140594	0.146009	-0.005415	-3.851751	0.282462	-2.328360

X Observed	Y Observed	Y Predicted	Y Residual	Y Residual%	First Deriv	Second Deriv
8.700000	0.149721	0.154125	-0.004404	-2.941678	0.204493	-2.343111
8.733330	0.155704	0.159643	-0.003939	-2.529794	0.126732	-2.316251
8.766670	0.159999	0.162591	-0.002592	-1.620080	0.050503	-2.250303
8.800000	0.162300	0.163042	-0.000742	-0.456990	-0.022898	-2.148560
8.833330	0.162454	0.161109	0.001345	0.827894	-0.092364	-2.014874
8.866670	0.162377	0.156938	0.005439	3.349484	-0.156921	-1.853559
8.900000	0.161380	0.150711	0.010668	6.610664	-0.215689	-1.669448
8.933330	0.158849	0.142632	0.016217	10.208870	-0.268008	-1.467477
8.966670	0.152636	0.132920	0.019716	12.916710	-0.313382	-1.252667
9.000000	0.133614	0.121820	0.011793	8.826504	-0.351440	-1.030198
9.033330	0.114592	0.109576	0.005016	4.376850	-0.382023	-0.804897
9.066670	0.094803	0.096434	-0.001631	-1.720452	-0.405120	-0.581286
9.100000	0.081073	0.082649	-0.001576	-1.943564	-0.420846	-0.363682
9.133330	0.066040	0.068459	-0.002419	-3.663551	-0.429470	-0.155680
9.166670	0.053307	0.054091	-0.000784	-1.470007	-0.431364	0.039713
9.200000	0.034592	0.039770	-0.005178	-14.967383	-0.426992	0.219979
9.233330	0.022627	0.025692	-0.003065	-13.544060	-0.416887	0.383485
9.266670	0.008974	0.012033	-0.003059	-34.091765	-0.401621	0.529292
9.300000	-0.006131	-0.001034	-0.005097	83.134056	-0.381801	0.657034
9.333330	-0.016790	-0.013373	-0.003417	20.348880	-0.358019	0.767134
9.366670	-0.029071	-0.024865	-0.004206	14.466866	-0.330841	0.860574
9.400000	-0.038823	-0.035399	-0.003424	8.819670	-0.300815	0.938729
9.433330	-0.048320	-0.044891	-0.003429	7.095722	-0.268415	1.003402
9.466670	-0.056698	-0.053272	-0.003425	6.041542	-0.234046	1.056561
9.500000	-0.063509	-0.060478	-0.003031	4.772688	-0.198081	1.100134
9.533330	-0.067345	-0.066462	-0.000883	1.311011	-0.160798	1.135902
9.566670	-0.071734	-0.071186	-0.000549	0.764691	-0.122421	1.165239
9.600000	-0.073362	-0.074614	0.001252	-1.707005	-0.083174	1.188881
9.633330	-0.074913	-0.076722	0.001809	-2.415146	-0.043234	1.206780
9.666670	-0.075328	-0.077491	0.002162	-2.870394	-0.002793	1.217878
9.700000	-0.074386	-0.076906	0.002520	-3.388097	0.037862	1.219948
9.733330	-0.072925	-0.074968	0.002044	-2.802231	0.078390	1.209487
9.766670	-0.071647	-0.071687	0.000039	-0.055124	0.118306	1.181629
9.800000	-0.068385	-0.067095	-0.001289	1.885207	0.156907	1.130180
9.833330	-0.062818	-0.061252	-0.001567	2.494145	0.193299	1.047659
9.866670	-0.053090	-0.054245	0.001156	-2.177024	0.226314	0.925459
9.900000	-0.040708	-0.046218	0.005509	-13.532926	0.254456	0.754297
9.933330	-0.030990	-0.037357	0.006367	-20.544254	0.275943	0.524436

Table B.2 Curve Fitting Data of 0.5 amp and 17.6cm^2 (2cm)

Fourier Series Polynomial 10x2

	Parameters	Std Error	T Value	95% Conf Lim	95% Conf Lim
6850	-35681.12461	7874.596624	-4.531168555	-51203.66344	-20158.58577
0.998352641	-1249.190888	514.1623159	-2.429565235	-2262.716392	-235.6653831
0.998188686	66861.13985	14751.99781	4.532344752	37781.7508	95940.52891
0.022504573	54907.76946	12105.48775	4.535775062	31045.22605	78770.31286
6423.943398	2068.226092	847.2048001	2.441235097	398.2015767	3738.250608
	2252.948931	915.5052954	2.460880284	448.2893172	4057.608545
	-39337.06462	8662.332955	-4.541162851	-56412.40271	-22261.72652
	-24376.46891	5359.893791	-4.547938795	-34941.98273	-13810.95508
	-1898.198562	762.6641319	-2.488904987	-3401.575074	-394.8220495
	-1287.855998	509.8409257	-2.525995723	-2292.863104	-282.8488908
	12889.16804	2829.590276	4.555135825	7311.431544	18466.90453
	5693.67392	1248.30179	4.561135749	3233.000194	8154.347646
	706.2825846	274.4345734	2.573591862	165.3124846	1247.252685
	307.40541	116.6458055	2.635374746	77.47121372	537.3396064
	-2031.979119	445.3346664	-4.562813705	-2909.83039	-1154.127848
	-553.1482052	121.5514698	-4.550732343	-792.7525305	-313.5438798
	-101.3332541	37.35822719	-2.712474915	-174.9744271	-27.69208112
	-22.51920204	8.157417536	-2.760579796	-38.59924227	-6.439161805
	103.2160069	22.81636477	4.523770895	58.24000048	148.1920133
	10.0799221	2.242686781	4.494574181	5.659099765	14.50074444
	2.827280292	0.930803952	3.03746056	0.992463707	4.662096878

X Observed	Y Observed	Y Predicted	Y Residual	Y Residual%	First Deriv	Second Deriv
0.500000	-0.055916	-0.087215	0.031299	-55.975226	-4.363719	0.854428
0.533330	-0.234642	-0.231883	-0.002759	1.175837	-4.308045	2.508463
0.566670	-0.372084	-0.373797	0.001713	-0.460293	-4.195328	4.264966
0.600000	-0.506129	-0.510926	0.004798	-0.947913	-4.023286	6.059826
0.633330	-0.636215	-0.641326	0.005111	-0.803377	-3.791642	7.831300
0.666670	-0.753573	-0.763069	0.009496	-1.260166	-3.502068	9.521431
0.700000	-0.875402	-0.874209	-0.001193	0.136245	-3.158359	11.076800
0.733330	-0.968140	-0.973061	0.004920	-0.508233	-2.765681	12.453118
0.766670	-1.056569	-1.058121	0.001552	-0.146912	-2.330494	13.614399
0.800000	-1.122479	-1.128053	0.005574	-0.496610	-1.860720	14.532572
0.833330	-1.180298	-1.181865	0.001566	-0.132704	-1.364657	15.189576
0.866670	-1.216970	-1.218836	0.001866	-0.153337	-0.851042	15.575626
0.900000	-1.244773	-1.238517	-0.006257	0.502638	-0.329269	15.688604
0.933330	-1.257915	-1.240793	-0.017122	1.361102	0.191785	15.533967
0.966670	-1.251786	-1.225830	-0.025956	2.073490	0.703530	15.123117
1.000000	-1.243278	-1.194091	-0.049187	3.956200	1.197388	14.473134
1.033330	-1.222167	-1.146295	-0.075873	6.208060	1.665884	13.605018
1.066670	-1.106954	-1.083381	-0.023573	2.129565	2.102270	12.542755
1.100000	-0.984759	-1.006566	0.021807	-2.214402	2.500263	11.313621
1.133330	-0.895739	-0.917196	0.021457	-2.395450	2.854890	9.945364
1.166670	-0.794761	-0.816756	0.021995	-2.767523	3.162078	8.466188
1.200000	-0.668167	-0.706947	0.038780	-5.803894	3.418437	6.905570
1.233330	-0.540239	-0.589472	0.049233	-9.113250	3.621804	5.290997
1.266670	-0.425617	-0.466084	0.040466	-9.507660	3.770869	3.648748
1.300000	-0.297259	-0.338679	0.041420	-13.933941	3.865062	2.005065
1.333330	-0.171388	-0.209044	0.037657	-21.971622	3.904767	0.382908
1.366670	-0.049523	-0.078942	0.029419	-59.404045	3.891053	-1.196728
1.400000	0.078619	0.049798	0.028821	36.658639	3.825690	-2.713528
1.433330	0.167669	0.175531	-0.007862	-4.688992	3.711054	-4.150757
1.466670	0.240842	0.296697	-0.055855	-23.191538	3.549998	-5.493720
1.500000	0.344389	0.411733	-0.067344	-19.554707	3.345998	-6.728606
1.533330	0.463967	0.519306	-0.055339	-11.927414	3.102789	-7.844835
1.566670	0.578789	0.618204	-0.039415	-6.809908	2.824393	-8.833581
1.600000	0.679344	0.707270	-0.027926	-4.110662	2.515365	-9.686942
1.633330	0.771002	0.785588	-0.014585	-1.891742	2.180225	-10.399602
1.666670	0.846400	0.852384	-0.005985	-0.707084	1.823626	-10.967658
1.700000	0.906994	0.906989	0.000005	0.000497	1.450655	-11.388196
1.733330	0.946265	0.948957	-0.002692	-0.284481	1.066140	-11.660241
1.766670	0.984002	0.977992	0.006010	0.610804	0.674913	-11.783981
1.800000	1.001260	0.993939	0.007321	0.731187	0.282135	-11.760807

X Observed	Y Observed	Y Predicted	Y Residual	Y Residual%	First Deriv	Second Deriv
1.833330	1.009313	0.996834	0.012479	1.236411	-0.107460	-11.593508
1.866670	1.010157	0.986859	0.023299	2.306425	-0.489244	-11.285938
1.900000	1.008086	0.964359	0.043727	4.337624	-0.858397	-10.843482
1.933330	0.999342	0.929826	0.069516	6.956219	-1.210642	-10.272492
1.966670	0.918039	0.883877	0.034162	3.721215	-1.541914	-9.580382
2.000000	0.823313	0.827307	-0.003995	-0.485179	-1.848127	-8.776416
2.033330	0.761721	0.760998	0.000724	0.095035	-2.125816	-7.870440
2.066670	0.677043	0.685929	-0.008886	-1.312513	-2.371830	-6.873328
2.100000	0.576718	0.603254	-0.026537	-4.601311	-2.583198	-5.797967
2.133330	0.474475	0.514144	-0.039670	-8.360731	-2.757598	-4.657389
2.166670	0.378905	0.419836	-0.040931	-10.802571	-2.893127	-3.465476
2.200000	0.277352	0.321709	-0.044357	-15.993101	-2.988254	-2.238005
2.233330	0.204332	0.221098	-0.016766	-8.205138	-3.042088	-0.990347
2.266670	0.128168	0.119357	0.008811	6.874796	-3.054223	0.261660
2.300000	0.034132	0.017935	0.016197	47.453759	-3.024795	1.500750
2.333330	-0.059337	-0.081822	0.022485	-37.893768	-2.954507	2.710708
2.366670	-0.146933	-0.178600	0.031667	-21.552305	-2.844567	3.875437
2.400000	-0.247021	-0.271050	0.024029	-9.727296	-2.696828	4.978192
2.433330	-0.340041	-0.357976	0.017935	-5.274448	-2.513577	6.003942
2.466670	-0.419277	-0.438264	0.018988	-4.528706	-2.297553	6.938471
2.500000	-0.500569	-0.510829	0.010261	-2.049803	-2.052163	7.767896
2.533330	-0.570183	-0.574776	0.004593	-0.805507	-1.781042	8.480595
2.566670	-0.628628	-0.629328	0.000700	-0.111285	-1.488168	9.066434
2.600000	-0.679916	-0.673803	-0.006114	0.899196	-1.178095	9.516608
2.633330	-0.718471	-0.707719	-0.010752	1.496499	-0.855368	9.824871
2.666670	-0.743512	-0.730739	-0.012773	1.717940	-0.524694	9.986965
2.700000	-0.759775	-0.742671	-0.017104	2.251230	-0.191186	10.000773
2.733330	-0.767572	-0.743506	-0.024066	3.135338	0.140313	9.866678
2.766670	-0.764090	-0.733390	-0.030700	4.017847	0.465008	9.587247
2.800000	-0.758460	-0.712637	-0.045823	6.041586	0.777939	9.167656
2.833330	-0.745239	-0.681713	-0.063527	8.524313	1.074646	8.615126
2.866670	-0.672680	-0.641216	-0.031464	4.677416	1.350930	7.938882
2.900000	-0.572096	-0.591920	0.019824	-3.465151	1.602693	7.150790
2.933330	-0.513063	-0.534691	0.021628	-4.215375	1.826504	6.263942
2.966670	-0.449084	-0.470490	0.021406	-4.766635	2.019368	5.292903
3.000000	-0.362927	-0.400434	0.037507	-10.334578	2.178639	4.254455
3.033330	-0.283700	-0.325657	0.041956	-14.788936	2.302409	3.165558
3.066670	-0.201544	-0.247342	0.045798	-22.723650	2.389314	2.043841
3.100000	-0.122527	-0.166781	0.044254	-36.117829	2.438526	0.908362
3.133330	-0.043579	-0.085210	0.041631	-95.527985	2.449914	-0.222755

X Observed	Y Observed	Y Predicted	Y Residual	Y Residual%	First Deriv	Second Deriv
3.166670	0.022090	-0.003860	0.025950	117.476149	2.423915	-1.331631
3.200000	0.091121	0.075989	0.015132	16.606781	2.361593	-2.399974
3.233330	0.140977	0.153178	-0.012200	-8.654160	2.264566	-3.411385
3.266670	0.203949	0.226605	-0.022656	-11.108433	2.134952	-4.350585
3.300000	0.260938	0.295184	-0.034246	-13.124089	1.975484	-5.202912
3.333330	0.326364	0.357993	-0.031628	-9.691050	1.789226	-5.956252
3.366670	0.384888	0.414210	-0.029323	-7.618549	1.579592	-6.600266
3.400000	0.436354	0.463089	-0.026735	-6.126897	1.350504	-7.126107
3.433330	0.486210	0.504063	-0.017853	-3.671874	1.105947	-7.527700
3.466670	0.524791	0.536695	-0.011904	-2.268354	0.850056	-7.801076
3.500000	0.551253	0.560662	-0.009409	-1.706819	0.587297	-7.944324
3.533330	0.566900	0.575815	-0.008915	-1.572640	0.321927	-7.958071
3.566670	0.576948	0.582140	-0.005193	-0.900030	0.058143	-7.845008
3.600000	0.580706	0.579759	0.000947	0.163119	-0.199746	-7.610066
3.633330	0.580016	0.568934	0.011082	1.910601	-0.447865	-7.260076
3.666670	0.578252	0.550047	0.028205	4.877567	-0.682588	-6.803543
3.700000	0.567207	0.523616	0.043591	7.685235	-0.900394	-6.251012
3.733330	0.512902	0.490248	0.022655	4.416926	-1.098342	-5.614015
3.766670	0.435741	0.450637	-0.014897	-3.418670	-1.273876	-4.905115
3.800000	0.393938	0.405594	-0.011656	-2.958723	-1.424728	-4.138401
3.833330	0.340554	0.355957	-0.015403	-4.522984	-1.549256	-3.327932
3.866670	0.281954	0.302610	-0.020656	-7.325958	-1.646269	-2.488041
3.900000	0.224812	0.246516	-0.021704	-9.654329	-1.714981	-1.633875
3.933330	0.174879	0.188606	-0.013727	-7.849596	-1.755182	-0.779621
3.966670	0.120421	0.129812	-0.009391	-7.798373	-1.767104	0.061002
4.000000	0.075781	0.071100	0.004681	6.176354	-1.751426	0.874207
4.033330	0.022780	0.013356	0.009424	41.368901	-1.709269	1.647877
4.066670	-0.027916	-0.042578	0.014662	-52.521612	-1.642119	2.370942
4.100000	-0.073651	-0.095868	0.022217	-30.165454	-1.551882	3.032936
4.133330	-0.123567	-0.145794	0.022227	-17.987485	-1.440717	3.625432
4.166670	-0.168144	-0.191713	0.023569	-14.017402	-1.311022	4.141399
4.200000	-0.212363	-0.233025	0.020662	-9.729640	-1.165530	4.574893
4.233330	-0.253841	-0.269263	0.015422	-6.075311	-1.007019	4.922023
4.266670	-0.292110	-0.300049	0.007939	-2.717846	-0.838363	5.180376
4.300000	-0.318997	-0.325079	0.006082	-1.906630	-0.662644	5.348872
4.333330	-0.343536	-0.344175	0.000639	-0.186057	-0.482799	5.428183
4.366670	-0.359394	-0.357253	-0.002141	0.595812	-0.301716	5.420295
4.400000	-0.371565	-0.364311	-0.007254	1.952266	-0.122360	5.328544
4.433330	-0.378259	-0.365458	-0.012801	3.384095	0.052603	5.157483
4.466670	-0.380974	-0.360880	-0.020094	5.274465	0.220668	4.912646

X Observed	Y Observed	Y Predicted	Y Residual	Y Residual%	First Deriv	Second Deriv
4.500000	-0.377910	-0.350851	-0.027059	7.160240	0.379385	4.600738
4.533330	-0.373905	-0.335717	-0.038188	10.213403	0.526689	4.229037
4.566670	-0.360861	-0.315883	-0.044978	12.464032	0.660755	3.805381
4.600000	-0.322489	-0.291831	-0.030658	9.506799	0.779916	3.338474
4.633330	-0.260073	-0.264074	0.004001	-1.538416	0.882913	2.836962
4.666670	-0.225106	-0.233157	0.008051	-3.576488	0.968765	2.309621
4.700000	-0.187987	-0.199685	0.011699	-6.223221	1.036715	1.765733
4.733330	-0.149253	-0.164253	0.015000	-10.049868	1.086382	1.214000
4.766670	-0.106833	-0.127461	0.020628	-19.308533	1.117656	0.662880
4.800000	-0.072987	-0.089942	0.016955	-23.230409	1.130683	0.120986
4.833330	-0.032706	-0.052287	0.019581	-59.870885	1.125909	-0.404013
4.866670	-0.000746	-0.015068	0.014322	-1921.0855	1.104011	-0.904963
4.900000	0.030527	0.021138	0.009390	30.758328	1.065923	-1.374869
4.933330	0.063969	0.055819	0.008150	12.740367	1.012773	-1.807867
4.966670	0.091121	0.088506	0.002616	2.870439	0.945858	-2.198771
5.000000	0.118657	0.118744	-0.000087	-0.073178	0.866704	-2.542814
5.033330	0.143585	0.146162	-0.002577	-1.794744	0.776915	-2.836384
5.066670	0.166442	0.170441	-0.003999	-2.402572	0.678194	-3.076622
5.100000	0.187458	0.191299	-0.003841	-2.049104	0.572416	-3.261287
5.133330	0.205099	0.208540	-0.003441	-1.677592	0.461427	-3.389195
5.166670	0.216451	0.222025	-0.005574	-2.574950	0.347093	-3.459919
5.200000	0.227343	0.231666	-0.004324	-1.901784	0.231386	-3.473795
5.233330	0.233479	0.237454	-0.003975	-1.702622	0.116149	-3.432030
5.266670	0.236470	0.239434	-0.002964	-1.253483	0.003171	-3.336545
5.300000	0.236547	0.237712	-0.001165	-0.492353	-0.105733	-3.190100
5.333330	0.235780	0.232449	0.003331	1.412563	-0.208953	-2.996091
5.366670	0.233939	0.223860	0.010079	4.308495	-0.304997	-2.758527
5.400000	0.227496	0.212212	0.015285	6.718630	-0.392435	-2.482261
5.433330	0.205867	0.197809	0.008058	3.913965	-0.470092	-2.172498
5.466670	0.177257	0.180990	-0.003733	-2.106078	-0.536964	-1.834904
5.500000	0.148187	0.162139	-0.013952	-9.415403	-0.592189	-1.475877
5.533330	0.128628	0.141651	-0.013023	-10.124164	-0.635179	-1.101856
5.566670	0.108609	0.119932	-0.011323	-10.425388	-0.665555	-0.719509
5.600000	0.089587	0.097421	-0.007833	-8.743858	-0.683139	-0.336000
5.633330	0.066653	0.074535	-0.007882	-11.825062	-0.688016	0.041817
5.666670	0.045100	0.051689	-0.006588	-14.607653	-0.680487	0.407159
5.700000	0.024775	0.029299	-0.004525	-18.263078	-0.661088	0.753118
5.733330	0.007057	0.007744	-0.000687	-9.742360	-0.630569	1.073453
5.766670	-0.010631	-0.012627	0.001997	-18.781682	-0.589869	1.362353
5.800000	-0.028308	-0.031483	0.003174	-11.213790	-0.540153	1.614346

X Observed	Y Observed	Y Predicted	Y Residual	Y Residual%	First Deriv	Second Deriv
5.833330	-0.044783	-0.048548	0.003765	-8.408030	-0.482717	1.824944
5.866670	-0.058326	-0.063595	0.005269	-9.033487	-0.418984	1.990454
5.900000	-0.069755	-0.076430	0.006675	-9.568790	-0.350547	2.107986
5.933330	-0.078782	-0.086928	0.008146	-10.340094	-0.279018	2.175853
5.966670	-0.085719	-0.095016	0.009296	-10.845234	-0.206042	2.193430
6.000000	-0.092366	-0.100668	0.008302	-8.987966	-0.133335	2.161257
6.033330	-0.096009	-0.103925	0.007916	-8.245064	-0.062507	2.081097
6.066670	-0.098538	-0.104873	0.006336	-6.429694	0.004910	1.955854
6.100000	-0.099321	-0.103652	0.004332	-4.361139	0.067436	1.789714
6.133330	-0.098274	-0.100446	0.002172	-2.210351	0.123815	1.587850
6.166670	-0.096883	-0.095477	-0.001406	1.450847	0.172968	1.356375
6.200000	-0.094369	-0.089005	-0.005364	5.683683	0.213996	1.102463
6.233330	-0.090833	-0.081310	-0.009523	10.484423	0.246293	0.833747
6.266670	-0.084477	-0.072686	-0.011791	13.958036	0.269505	0.558305
6.300000	-0.071989	-0.063444	-0.008545	11.869882	0.283537	0.284686
6.333330	-0.054478	-0.053885	-0.000593	1.087928	0.288595	0.021153
6.366670	-0.042569	-0.044298	0.001729	-4.060620	0.285147	-0.224331
6.400000	-0.032461	-0.034961	0.002499	-7.699559	0.273925	-0.444179
6.433330	-0.026830	-0.026114	-0.000716	2.670300	0.255895	-0.631908
6.466670	-0.020997	-0.017963	-0.003034	14.449557	0.232212	-0.782141
6.500000	-0.013628	-0.010680	-0.002948	21.629726	0.204213	-0.890765
6.533330	-0.006658	-0.004382	-0.002275	34.176646	0.173323	-0.955412
6.566670	-0.001822	0.000860	-0.002682	147.163299	0.141013	-0.975426
6.600000	0.003221	0.005020	-0.001799	-55.831490	0.108775	-0.952009
6.633330	0.007210	0.008127	-0.000917	-12.716005	0.078000	-0.888290
6.666670	0.009971	0.010250	-0.000279	-2.800515	0.049946	-0.789207
6.700000	0.012349	0.011499	0.000850	6.880477	0.025701	-0.661516
6.733330	0.013960	0.012015	0.001945	13.929621	0.006077	-0.513381
6.766670	0.014650	0.011962	0.002688	18.350475	-0.008401	-0.354120
6.800000	0.014957	0.011515	0.003442	23.013025	-0.017523	-0.193962
6.833330	0.015033	0.010852	0.004182	27.817361	-0.021435	-0.043256
6.866670	0.014497	0.010138	0.004358	30.064248	-0.020623	0.087944
6.900000	0.013653	0.009520	0.004133	30.269152	-0.015893	0.190402
6.933330	0.013039	0.009110	0.003929	30.131161	-0.008334	0.256598
6.966670	0.012272	0.008982	0.003291	26.812960	0.000752	0.281232
7.000000	0.011275	0.009161	0.002114	18.746575	0.009925	0.261873

Table B.3 Curve Fitting Data of 0.75 amp and 17.6cm^2 (2cm)

Fourier Series Polynomial 10x2

	Parameters	Std Error	T Value	95% Conf Lim	95% Conf Lim
6850	3251.128291	8750.403921	0.371540368	-14023.78955	20526.04613
0.998407205	-1871.03906	570.6601645	-3.2787273	-2997.627907	-744.450214
0.998206913	-6194.197226	16393.21956	-0.377851172	-38557.44853	26169.05408
0.022764786	-5341.546755	13453.54614	-0.397036343	-31901.33833	21218.24482
5265.347177	3074.91149	940.4019509	3.269784253	1218.383885	4931.439096
	3307.469276	1016.404053	3.254089026	1300.899445	5314.039106
	4138.935805	9628.494031	0.429863257	-14869.49453	23147.36614
	2846.596232	5959.057212	0.477692382	-8917.686272	14610.87874
	-2735.938731	846.9408469	-3.230377589	-4407.956809	-1063.920652
	-1810.476536	566.3753654	-3.196601842	-2928.606396	-692.3466771
	-1707.396245	3146.828534	-0.542576828	-7919.818537	4505.026048
	-871.2253705	1388.76774	-0.627336988	-3612.910078	1870.459337
	960.8735522	304.9978812	3.150426974	358.7512515	1562.995853
	400.8905902	129.7053795	3.090778437	144.8281506	656.9530297
	365.4084122	495.6697411	0.73720137	-613.1354507	1343.952275
	119.0637358	135.3636075	0.879584535	-148.1690936	386.2965651
	-124.5824241	41.56758382	-2.997105259	-206.6445325	-42.52031564
	-26.07849737	9.08364189	-2.87092971	-44.01128868	-8.145706066
	-26.89592128	25.42559472	-1.057828601	-77.09075387	23.2989113
	-3.228383383	2.501130664	-1.290769583	-8.166078501	1.709311736
	2.767596867	1.037488287	2.667593362	0.719402854	4.81579088

X Observed	Y Observed	Y Predicted	Y Residual	Y Residual%	First Deriv	Second Deriv
0.533330	-0.067002	-0.083543	0.016541	-24.687185	-4.282632	0.534074
0.566670	-0.209844	-0.225716	0.015871	-7.563427	-4.236375	2.273471
0.600000	-0.376414	-0.365306	-0.011108	2.950886	-4.129360	4.166753
0.633330	-0.496362	-0.500261	0.003899	-0.785513	-3.957856	6.128742
0.666670	-0.625496	-0.628447	0.002951	-0.471775	-3.720922	8.074795
0.700000	-0.733360	-0.747632	0.014271	-1.946024	-3.420603	9.923885
0.733330	-0.859423	-0.855808	-0.003616	0.420698	-3.061257	11.605875
0.766670	-0.937039	-0.951138	0.014099	-1.504636	-2.649342	13.062130
0.800000	-1.029861	-1.031953	0.002092	-0.203137	-2.193446	14.245986
0.833330	-1.084765	-1.096970	0.012206	-1.125184	-1.703085	15.126042
0.866670	-1.137921	-1.145226	0.007305	-0.641944	-1.188568	15.684304
0.900000	-1.167930	-1.176071	0.008141	-0.697025	-0.661056	15.915322
0.933330	-1.188243	-1.189266	0.001023	-0.086081	-0.131216	15.825928
0.966670	-1.199499	-1.184904	-0.014595	1.216739	0.390678	15.432680
1.000000	-1.191835	-1.163423	-0.028412	2.383881	0.894586	14.760803
1.033330	-1.182915	-1.125567	-0.057347	4.847975	1.371883	13.841514
1.066670	-1.153431	-1.072337	-0.081095	7.030724	1.815034	12.710092
1.100000	-0.996343	-1.005016	0.008673	-0.870467	2.217347	11.405371
1.133330	-0.905979	-0.925038	0.019059	-2.103726	2.573821	9.965986
1.166670	-0.815478	-0.833969	0.018491	-2.267448	2.880693	8.429729
1.200000	-0.719446	-0.733567	0.014121	-1.962767	3.135180	6.833889
1.233330	-0.582927	-0.625575	0.042648	-7.316103	3.335947	5.211514
1.266670	-0.487056	-0.511759	0.024703	-5.071938	3.482655	3.592085
1.300000	-0.353806	-0.393983	0.040177	-11.355685	3.575776	2.002599
1.333330	-0.246041	-0.273978	0.027936	-11.354347	3.616721	0.464491
1.366670	-0.109191	-0.153414	0.044223	-40.500837	3.607500	-1.004782
1.400000	-0.010681	-0.033994	0.023313	-218.256736	3.550674	-2.390248
1.433330	0.093729	0.082778	0.010951	11.683478	3.449212	-3.681683
1.466670	0.170507	0.195503	-0.024996	-14.659985	3.306336	-4.871681
1.500000	0.249893	0.302792	-0.052899	-21.168713	3.125620	-5.954178
1.533330	0.340861	0.403477	-0.062616	-18.369923	2.910660	-6.926037
1.566670	0.438809	0.496504	-0.057696	-13.148296	2.665106	-7.785300
1.600000	0.555088	0.580865	-0.025777	-4.643777	2.392892	-8.530084
1.633330	0.625500	0.655760	-0.030260	-4.837786	2.097770	-9.159727
1.666670	0.719612	0.720508	-0.000896	-0.124518	1.783496	-9.673550
1.700000	0.772536	0.774500	-0.001964	-0.254227	1.454138	-10.070346
1.733330	0.828758	0.817316	0.011442	1.380660	1.113517	-10.349218
1.766670	0.861280	0.848654	0.012626	1.465968	0.765478	-10.508964
1.800000	0.886438	0.868317	0.018121	2.044225	0.414224	-10.548207
1.833330	0.895412	0.876274	0.019138	2.137353	0.063685	-10.465872

X Observed	Y Observed	Y Predicted	Y Residual	Y Residual%	First Deriv	Second Deriv
1.866670	0.898480	0.872613	0.025867	2.879014	-0.282175	-10.261141
1.900000	0.897023	0.857563	0.039460	4.398942	-0.619067	-9.934098
1.933330	0.894108	0.831489	0.062619	7.003491	-0.943033	-9.485683
1.966670	0.854760	0.794876	0.059884	7.005930	-1.250149	-8.918035
2.000000	0.748529	0.748377	0.000152	0.020342	-1.536325	-8.235456
2.033330	0.681338	0.692738	-0.011400	-1.673149	-1.797910	-7.443639
2.066670	0.609699	0.628820	-0.019121	-3.136067	-2.031457	-6.550216
2.100000	0.522797	0.557651	-0.034855	-6.666991	-2.233608	-5.565817
2.133330	0.447706	0.480307	-0.032601	-7.281860	-2.401596	-4.502474
2.166670	0.340324	0.397942	-0.057618	-16.930344	-2.533059	-3.374247
2.200000	0.262012	0.311857	-0.049845	-19.023938	-2.626032	-2.198171
2.233330	0.188455	0.223333	-0.034877	-18.506949	-2.679253	-0.991964
2.266670	0.130316	0.133680	-0.003365	-2.582047	-2.692035	0.225348
2.300000	0.043106	0.044305	-0.001198	-2.780012	-2.664348	1.432711
2.333330	-0.025852	-0.043483	0.017630	-68.196963	-2.596868	2.609714
2.366670	-0.111230	-0.128400	0.017170	-15.436314	-2.490915	3.735967
2.400000	-0.180669	-0.209148	0.028480	-15.763562	-2.348594	4.790662
2.433330	-0.255239	-0.284583	0.029344	-11.496729	-2.172572	5.755139
2.466670	-0.332077	-0.353654	0.021577	-6.497488	-1.966086	6.612267
2.500000	-0.392140	-0.415369	0.023229	-5.923585	-1.733107	7.346271
2.533330	-0.454088	-0.468935	0.014848	-3.269842	-1.477891	7.944690
2.566670	-0.502597	-0.513702	0.011105	-2.209465	-1.205047	8.397779
2.600000	-0.542332	-0.549139	0.006806	-1.255029	-0.919707	8.698539
2.633330	-0.569833	-0.574927	0.005094	-0.893897	-0.626932	8.843704
2.666670	-0.593951	-0.590909	-0.003042	0.512218	-0.331828	8.833199
2.700000	-0.604196	-0.597085	-0.007111	1.176874	-0.039716	8.670321
2.733330	-0.609915	-0.593644	-0.016271	2.667755	0.244514	8.361599
2.766670	-0.606439	-0.580921	-0.025519	4.207934	0.516231	7.916385
2.800000	-0.600308	-0.559418	-0.040890	6.811542	0.770924	7.347148
2.833330	-0.587280	-0.529763	-0.057517	9.793794	1.004774	6.668298
2.866670	-0.516110	-0.492697	-0.023413	4.536445	1.214456	5.896011
2.900000	-0.431827	-0.449098	0.017271	-3.999516	1.397031	5.048598
2.933330	-0.386337	-0.399896	0.013559	-3.509515	1.550367	4.144622
2.966670	-0.326377	-0.346076	0.019699	-6.035573	1.672929	3.203014
3.000000	-0.268705	-0.288716	0.020011	-7.447088	1.763719	2.243505
3.033330	-0.199814	-0.228863	0.029049	-14.538060	1.822486	1.284466
3.066670	-0.132706	-0.167563	0.034857	-26.266385	1.849548	0.343328
3.100000	-0.083196	-0.105896	0.022700	-27.285158	1.845770	-0.562941
3.133330	-0.037917	-0.044851	0.006934	-18.287759	1.812571	-1.419851
3.166670	0.028149	0.014641	0.013508	47.988385	1.751793	-2.214716

X Observed	Y Observed	Y Predicted	Y Residual	Y Residual%	First Deriv	Second Deriv
3.200000	0.063125	0.071661	-0.008536	-13.521811	1.665737	-2.936180
3.233330	0.119424	0.125427	-0.006003	-5.026321	1.556978	-3.575752
3.266670	0.154477	0.175243	-0.020766	-13.442876	1.428320	-4.127010
3.300000	0.196202	0.220467	-0.024265	-12.367314	1.282869	-4.585184
3.333330	0.238695	0.260607	-0.021912	-9.179908	1.123731	-4.948059
3.366670	0.273824	0.295268	-0.021444	-7.831302	0.954044	-5.215204
3.400000	0.308800	0.324133	-0.015333	-4.965491	0.777087	-5.387690
3.433330	0.340477	0.347022	-0.006544	-1.922125	0.595921	-5.468353
3.466670	0.359346	0.363848	-0.004502	-1.252847	0.413488	-5.461216
3.500000	0.372078	0.374609	-0.002531	-0.680153	0.232741	-5.371386
3.533330	0.383584	0.379410	0.004173	1.087985	0.056284	-5.204817
3.566670	0.386191	0.378435	0.007757	2.008488	-0.113482	-4.968002
3.600000	0.385501	0.371946	0.013555	3.516294	-0.274233	-4.668105
3.633330	0.384504	0.360276	0.024228	6.301068	-0.424038	-4.312370
3.666670	0.379902	0.343815	0.036087	9.499055	-0.561197	-3.908124
3.700000	0.359883	0.323020	0.036863	10.243006	-0.684142	-3.463124
3.733330	0.296451	0.298381	-0.001930	-0.651160	-0.791678	-2.984753
3.766670	0.258560	0.270420	-0.011860	-4.586879	-0.882843	-2.480301
3.800000	0.229567	0.239713	-0.010146	-4.419734	-0.956839	-1.957444
3.833330	0.197046	0.206833	-0.009787	-4.967107	-1.013201	-1.423333
3.866670	0.159922	0.172362	-0.012439	-7.778437	-1.051683	-0.885044
3.900000	0.123643	0.136917	-0.013274	-10.736095	-1.072247	-0.350085
3.933330	0.085445	0.101082	-0.015637	-18.300581	-1.075134	0.174564
3.966670	0.056299	0.065429	-0.009131	-16.217976	-1.060797	0.681964
4.000000	0.027689	0.030542	-0.002853	-10.304488	-1.029944	1.164794
4.033330	-0.009987	-0.003053	-0.006933	69.424606	-0.983500	1.616319
4.066670	-0.033275	-0.034866	0.001592	-4.784040	-0.922602	2.029961
4.100000	-0.062319	-0.064419	0.002100	-3.369144	-0.848660	2.399073
4.133330	-0.086312	-0.091311	0.004998	-5.791175	-0.763239	2.717814
4.166670	-0.109758	-0.115195	0.005437	-4.953880	-0.668081	2.980857
4.200000	-0.128133	-0.135766	0.007633	-5.956739	-0.565180	3.183389
4.233330	-0.146841	-0.152807	0.005965	-4.062429	-0.456589	3.321767
4.266670	-0.158410	-0.166167	0.007757	-4.896768	-0.344460	3.393370
4.300000	-0.170335	-0.175759	0.005424	-3.184556	-0.231112	3.396791
4.333330	-0.177765	-0.181584	0.003819	-2.148129	-0.118787	3.332120
4.366670	-0.180032	-0.183714	0.003682	-2.045089	-0.009700	3.200903
4.400000	-0.181612	-0.182292	0.000680	-0.374591	0.093915	3.006426
4.433330	-0.180119	-0.177536	-0.002583	1.433804	0.190059	2.753511
4.466670	-0.177505	-0.169724	-0.007782	4.383867	0.276911	2.448516
4.500000	-0.174131	-0.159197	-0.014934	8.576399	0.352815	2.099596

X Observed	Y Observed	Y Predicted	Y Residual	Y Residual%	First Deriv	Second Deriv
4.533330	-0.161417	-0.146341	-0.015075	9.339381	0.416484	1.715985
4.566670	-0.136237	-0.131577	-0.004660	3.420499	0.466946	1.307998
4.600000	-0.109573	-0.115364	0.005791	-5.285129	0.503548	0.887158
4.633330	-0.088654	-0.098167	0.009513	-10.730447	0.526070	0.465109
4.666670	-0.070788	-0.080446	0.009658	-13.644034	0.534671	0.053602
4.700000	-0.058792	-0.062669	0.003877	-6.595082	0.529895	-0.335550
4.733330	-0.039712	-0.045262	0.005549	-13.974255	0.512671	-0.691639
4.766670	-0.026880	-0.028614	0.001733	-6.448599	0.484256	-1.005071
4.800000	-0.011763	-0.013083	0.001320	-11.221472	0.446232	-1.267517
4.833330	0.001764	0.001045	0.000719	40.751492	0.400399	-1.472824
4.866670	0.010661	0.013546	-0.002885	-27.058801	0.348719	-1.616940
4.900000	0.020939	0.024253	-0.003314	-15.824795	0.293299	-1.698050
4.933330	0.028993	0.033079	-0.004086	-14.093507	0.236219	-1.716938
4.966670	0.035359	0.040005	-0.004646	-13.139531	0.179488	-1.676760
5.000000	0.040728	0.045071	-0.004343	-10.663237	0.125025	-1.583034
5.033330	0.044870	0.048383	-0.003513	-7.828784	0.074475	-1.443323
5.066670	0.047018	0.050095	-0.003077	-6.544727	0.029208	-1.266852
5.100000	0.048859	0.050402	-0.001543	-3.157557	-0.009697	-1.064282
5.133330	0.049012	0.049527	-0.000515	-1.050350	-0.041572	-0.846845
5.166670	0.048782	0.047711	0.001071	2.194921	-0.066116	-0.625900
5.200000	0.048092	0.045200	0.002892	6.012757	-0.083386	-0.412527
5.233330	0.047171	0.042229	0.004942	10.477411	-0.093809	-0.216521
5.266670	0.045407	0.039014	0.006393	14.079716	-0.098105	-0.046041
5.300000	0.043183	0.035746	0.007437	17.222141	-0.097232	0.092743
5.333330	0.038811	0.032577	0.006233	16.061032	-0.092315	0.196331
5.366670	0.032445	0.029623	0.002822	8.696964	-0.084544	0.263904
5.400000	0.026462	0.026959	-0.000497	-1.879841	-0.075101	0.297347
5.433330	0.020709	0.024623	-0.003914	-18.899889	-0.065052	0.301203
5.466670	0.017948	0.022619	-0.004671	-26.026300	-0.055274	0.282194
5.500000	0.015800	0.020928	-0.005128	-32.452168	-0.046399	0.248687

Table B.4 Curve Fitting Data of 0.1 amp and 17.6cm^2 (2cm)

Fourier Series Polynomial 10x2

	Parameters	Std Error	T Value	95% Conf Lim	95% Conf Lim
6850	30706.03543	9472.668098	3.241540304	11961.33474	49450.73611
0.998830794	2230.690498	616.1779844	3.620204801	1011.385465	3449.99553
0.998635927	-57488.96776	17746.97861	-3.239366488	-92607.03573	-22370.8998
0.022051898	-47087.41568	14566.15574	-3.232659086	-75911.20921	-18263.62216
5424.687061	-3682.530351	1015.550888	-3.626140643	-5692.122289	-1672.938414
	-3991.848982	1097.879334	-3.635963315	-6164.354055	-1819.343909
	33582.54209	10426.70501	3.220820198	12949.97453	54215.10966
	20672.97365	6454.761733	3.202747755	7900.165038	33445.78226
	3339.857102	915.1307517	3.649595532	1528.978493	5150.735711
	2245.107962	612.2377069	3.667052743	1033.600028	3456.615897
	-10831.0521	3409.76456	-3.176480931	-17578.36082	-4083.743382
	-4725.542877	1505.449664	-3.138957742	-7704.55608	-1746.529673
	-1215.279296	329.8716269	-3.684097681	-1868.035715	-562.5228762
	-519.6157638	140.3749924	-3.7016263	-797.3925412	-241.8389865
	1659.184587	537.5932834	3.086319412	595.3844953	2722.984678
	442.1414635	146.9034331	3.00974221	151.4460802	732.8368467
	167.1323896	45.02234882	3.71220947	78.04128628	256.223493
	36.45414895	9.847913366	3.701713002	16.9669056	55.9413923
	-79.97291919	27.61343336	-2.896159928	-134.6149206	-25.33091781
	-7.40116477	2.718742102	-2.72227541	-12.78106475	-2.021264788
	-4.082270196	1.126079737	-3.62520527	-6.310578778	-1.853961615

X Observed	Y Observed	Y Predicted	Y Residual	Y Residual%	First Deriv	Second Deriv
0.633330	-0.274654	-0.257632	-0.017022	6.197570	-4.138850	0.785223
0.666670	-0.418992	-0.394791	-0.024201	5.776070	-4.076627	3.010729
0.700000	-0.532365	-0.528536	-0.003828	0.719116	-3.934934	5.524242
0.733330	-0.658051	-0.656136	-0.001915	0.291016	-3.707274	8.137544
0.766670	-0.769582	-0.774738	0.005156	-0.669916	-3.393341	10.665642
0.800000	-0.880332	-0.881477	0.001145	-0.130067	-2.999031	12.941107
0.833330	-0.960274	-0.973877	0.013603	-1.416523	-2.534988	14.830786
0.866670	-1.031283	-1.049866	0.018583	-1.801920	-2.015602	16.240296
0.900000	-1.083650	-1.107838	0.024188	-2.232106	-1.458202	17.115972
0.933330	-1.125706	-1.146847	0.021140	-1.877972	-0.880726	17.446145
0.966670	-1.150837	-1.166526	0.015689	-1.363275	-0.300874	17.254668
1.000000	-1.165833	-1.167072	0.001240	-0.106331	0.264436	16.595032
1.033330	-1.159897	-1.149220	-0.010678	0.920590	0.800973	15.541855
1.066670	-1.151564	-1.114117	-0.037447	3.251825	1.297193	14.181907
1.100000	-1.136246	-1.063288	-0.072958	6.420970	1.744110	12.607534
1.133330	-1.042777	-0.998465	-0.044312	4.249427	2.136211	10.906783
1.166670	-0.906794	-0.921505	0.014711	-1.622303	2.470730	9.158450
1.200000	-0.831397	-0.834391	0.002994	-0.360092	2.747038	7.429511
1.233330	-0.729940	-0.739017	0.009077	-1.243511	2.966752	5.769396
1.266670	-0.621265	-0.637193	0.015928	-2.563734	3.132807	4.210844
1.300000	-0.498827	-0.530709	0.031883	-6.391547	3.248834	2.771950
1.333330	-0.403004	-0.421135	0.018131	-4.498973	3.318948	1.455354
1.366670	-0.285786	-0.309901	0.024115	-8.438205	3.347123	0.252728
1.400000	-0.163320	-0.198409	0.035089	-21.484739	3.336907	-0.850836
1.433330	-0.058815	-0.087856	0.029041	-49.377045	3.291285	-1.875336
1.466670	0.035359	0.020652	0.014707	41.592888	3.212523	-2.841191
1.500000	0.126327	0.125975	0.000352	0.278842	3.102329	-3.765437
1.533330	0.195435	0.227117	-0.031682	-16.211001	2.961834	-4.661086
1.566670	0.274668	0.323111	-0.048444	-17.637191	2.791812	-5.534629
1.600000	0.374073	0.412930	-0.038857	-10.387558	2.593106	-6.384553
1.633330	0.466038	0.495658	-0.029621	-6.355873	2.366565	-7.203000
1.666670	0.553017	0.570411	-0.017394	-3.145243	2.113382	-7.975760
1.700000	0.626727	0.636285	-0.009558	-1.525098	1.835552	-8.683032
1.733330	0.693304	0.692522	0.000782	0.112774	1.535545	-9.302650
1.766670	0.744464	0.738447	0.006017	0.808194	1.216574	-9.811325
1.800000	0.782277	0.773470	0.008808	1.125917	0.882913	-10.186376
1.833330	0.806592	0.797191	0.009401	1.165546	0.539250	-10.408576
1.866670	0.819401	0.809366	0.010035	1.224639	0.190837	-10.463103

X Observed	Y Observed	Y Predicted	Y Residual	Y Residual%	First Deriv	Second Deriv
1.900000	0.825384	0.809929	0.015454	1.872359	-0.156359	-10.340888
1.933330	0.825307	0.799022	0.026285	3.184890	-0.496492	-10.039419
1.966670	0.822315	0.776969	0.045346	5.514442	-0.823734	-9.562643
2.000000	0.803754	0.744314	0.059440	7.395241	-1.132207	-8.921336
2.033330	0.707110	0.701762	0.005348	0.756288	-1.416779	-8.131511
2.066670	0.633860	0.650172	-0.016312	-2.573429	-1.672905	-7.213578
2.100000	0.574187	0.590592	-0.016406	-2.857232	-1.896563	-6.192076
2.133330	0.506919	0.524141	-0.017222	-3.397320	-2.084802	-5.092609
2.166670	0.407898	0.452015	-0.044117	-10.815694	-2.235503	-3.941185
2.200000	0.335799	0.375534	-0.039735	-11.833027	-2.347284	-2.764102
2.233330	0.253805	0.295982	-0.042177	-16.618026	-2.419734	-1.584823
2.266670	0.186691	0.214644	-0.027953	-14.972661	-2.453145	-0.424244
2.300000	0.125330	0.132855	-0.007525	-6.003944	-2.448445	0.698702
2.333330	0.059290	0.051837	0.007453	12.570445	-2.407153	1.769276
2.366670	-0.009361	-0.027244	0.017884	-191.052463	-2.331195	2.775671
2.400000	-0.082805	-0.103225	0.020420	-24.660737	-2.222932	3.707780
2.433330	-0.146642	-0.175095	0.028452	-19.402527	-2.084940	4.558465
2.466670	-0.217025	-0.241927	0.024902	-11.474424	-1.919983	5.321912
2.500000	-0.282898	-0.302836	0.019938	-7.047834	-1.731165	5.992427
2.533330	-0.340122	-0.357096	0.016975	-4.990719	-1.521613	6.565279
2.566670	-0.387806	-0.404086	0.016280	-4.198020	-1.294595	7.035497
2.600000	-0.436248	-0.443255	0.007007	-1.606232	-1.053762	7.397414
2.633330	-0.471020	-0.474217	0.003197	-0.678671	-0.802747	7.645566
2.666670	-0.498578	-0.496702	-0.001877	0.376375	-0.545357	7.774409
2.700000	-0.514575	-0.510553	-0.004022	0.781527	-0.285810	7.778849
2.733330	-0.525819	-0.515776	-0.010043	1.909961	-0.028244	7.655128
2.766670	-0.529709	-0.512504	-0.017205	3.248038	0.223109	7.401274
2.800000	-0.526602	-0.501022	-0.025581	4.857666	0.463765	7.018247
2.833330	-0.520815	-0.481754	-0.039061	7.499959	0.689554	6.510148
2.866670	-0.505222	-0.455257	-0.049965	9.889745	0.896488	5.884788
2.900000	-0.438204	-0.422239	-0.015965	3.643274	1.080732	5.154688
2.933330	-0.368087	-0.383503	0.015416	-4.188225	1.239113	4.335942
2.966670	-0.318078	-0.339943	0.021865	-6.874260	1.369037	3.448334
3.000000	-0.273335	-0.292569	0.019234	-7.036727	1.468518	2.515614
3.033330	-0.220125	-0.242402	0.022277	-10.119941	1.536506	1.562960
3.066670	-0.166044	-0.190482	0.024438	-14.717742	1.572784	0.616585
3.100000	-0.115123	-0.137890	0.022767	-19.775873	1.577988	-0.296698
3.133330	-0.068491	-0.085622	0.017131	-25.012445	1.553645	-1.152572

X Observed	Y Observed	Y Predicted	Y Residual	Y Residual%	First Deriv	Second Deriv
3.166670	-0.020792	-0.034612	0.013820	-66.467233	1.502018	-1.929608
3.200000	0.019099	0.014248	0.004851	25.400235	1.426081	-2.609809
3.233330	0.052694	0.060218	-0.007524	-14.279425	1.329263	-3.180917
3.266670	0.090047	0.102678	-0.012631	-14.026783	1.215295	-3.636137
3.300000	0.120958	0.141096	-0.020138	-16.648981	1.088150	-3.974025
3.333330	0.159999	0.175110	-0.015111	-9.444583	0.951643	-4.199049
3.366670	0.188225	0.204477	-0.016252	-8.634410	0.809352	-4.320344
3.400000	0.217525	0.229044	-0.011519	-5.295338	0.664617	-4.350714
3.433330	0.237084	0.248784	-0.011700	-4.935029	0.520173	-4.305516
3.466670	0.258254	0.263751	-0.005497	-2.128618	0.378228	-4.200951

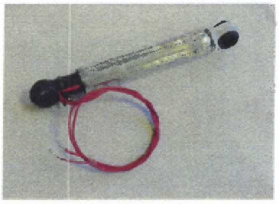
APPENDIX C

MR FRICTION DAMPER PRODUCT BULLETIN

Data sheet of MR fluid friction damper which is used the experiment system.

LORD Rheonetic™
Magnetically Responsive Technology

MR Controllable Friction Damper
RD-1097-01 Product Bulletin



General

RD-1097-01 is a controllable friction magnetically responsive (MR) fluid damper providing controllability and responsiveness in a light-weight package. As a magnetic field is applied to the MR fluid inside the housing, the damping characteristics of the fluid increase in under 25-millisecond response time. Featuring straightforward controls, simple design, and quiet operation, this MR damper is especially well suited for suspension and isolation applications.

Benefits

- Turn friction damping on and off when needed
- Low voltage and current requirements
- Industrial durability
- Real-time control
- Simple electronics

Special Instructions

- Do not apply more than 0.5A for more than 30 seconds at a time or heat damage may result. Housing temperature must not exceed 70° C.
- Recommended for experimental use only.

Recommended Accessories

Wonder Box™ Device Controller Kit (Lord part number RD-3002-03), which includes a DC power supply and solderless banana plugs.

Typical Data*

Compressed Length	7.68 inches (195 mm)
Extended Length	9.96 inches (253 mm)
Body Diameter	1.26 inches (32 mm)
Weight	1.1 pound (.48 kg)
For Installation on Pin	0.31 inches (8.0 mm)
Electrical Characteristics: Input Current (continuous) Input Current (intermittent) Resistance (25° C)	 0.5 amps maximum 1.0 amps maximum 20 ohms
Damper Forces: (Peak to Peak) 2 in/sec at 1 amp 8 in/sec at 0 amp	 > 22 pounds (100 N) < 2 pounds (9 N)
Mechanical Characteristics: Maximum Operating Temperature Storage Temperature Limits	 160°F (70°C) - 40° F to 212°F (-40°C to 100°C)
Durability	2 million cycles @ ± 0.5 inches (± 13 mm), 2 hertz with input current varying between 0 and 0.5 amps
Response Time (amplifier and power supply dependent)	< 25 msec – time to reach 90% of max level during a 0 to 1 amp step input @ 2 in/sec (51 mm/sec)

* Data is typical and not to be used for specification purposes.

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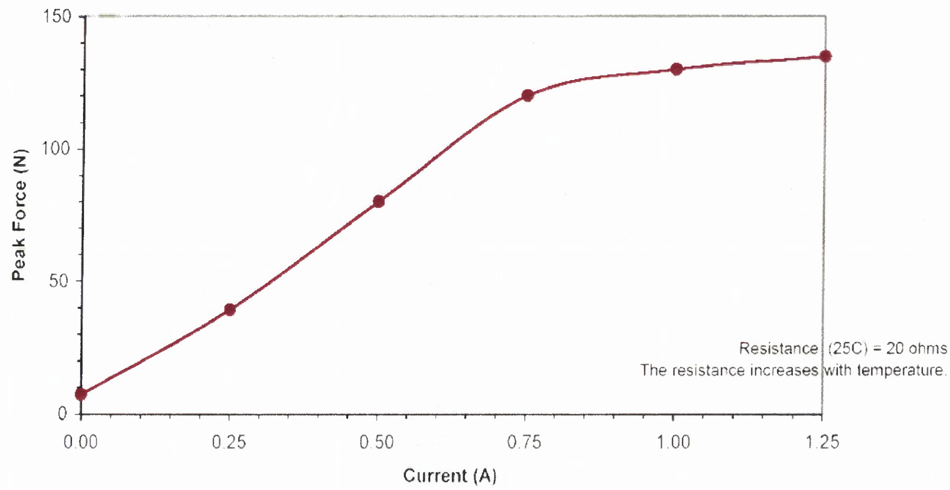
Typical Force vs. Current Graph
RD-1097-01 Controllable MR Dampers



Data measured at 2 Hz, 50 mm total stroke length.

Do not apply more than 0.5 A for longer than 30 seconds at a time, or heat buildup may melt the plastic shaft.

Housing temperature should not exceed 70C.

For additional information, please contact us at:
Lord Corporation, Materials Division, Customer Service Department
406 Gregson Drive, P.O. Box 8012, Cary, NC 27511
Telephone: 888-811-5673, ext. 2124 Telephone Outside the U.S.: 919-469-2500, ext. 2124 Fax: 919-481-0349
E-mail: mrfluid@lord.com or visit us at our website at www.mrfluid.com

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