# COMPARISON OF VARIOUS MEDIA IN TEACHING ENGINEERING PRINCIPLES: DESIGN OF A D.C. MOTOR TORQUE/SPEED CURVE DISPLAY MECHANISM

BY

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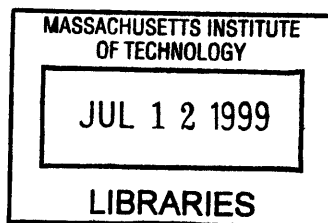PAPPALARDO PROFESSOR OF MECHANICAL ENGINEERING
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# COMPARISON OF VARIOUS MEDIA IN TEACHING ENGINEERING PRINCIPLES: DESIGN OF A D.C. MOTOR TORQUE/SPEED CURVE DISPLAY MECHANISM

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## ABSTRACT

Improving product development education depends on finding effective media with which to teach. In my thesis, I focused on a comparison between the physical intimacy with a mechanical system and a computer simulation of the same system – specifically DC motors and their torque/speed characteristics. I built a fully mechanical dynamometer that draws the torque/speed curve of a DC motor as a student grabs the motor shaft. I also designed an interactive dynamic computer simulation of the same device using a modeling and animation software package.

The design of the mechanical mechanism was a task that required engineering analysis, industrial design, human factors, and a focus on the education of students. There were a number of design challenges in this device that led me to build a fairly sophisticated mechanical mechanism that draws a torque/speed curve while being simple enough to understand. The design approach and analysis method was heavily stressed in creating this model. The computer simulation was modeled directly from the mechanical model.

In order to compare the teaching effectiveness of the models, I ran experiments with students comparing the mechanical device, the computer simulation, and a control, a written textbook explanation of DC motor torque/speed characteristics.

From the experiments, I found that the mechanical model was most effective in teaching students, followed by the computer simulations, and finally the control test. Students felt that the hand-on aspect of the mechanical model was the most important feature that distinguished it from the others. The results from this thesis can help to guide how media might be used more effectively in education.

Thesis Supervisor: Woodie C. Flowers
Title: Pappalardo Professor of Mechanical Engineering

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# 1 INTRODUCTION

## 1.1 Background

### 1.1.1 Product Development Education

Dispersal of new product development improvement in industry has traditionally been ineffective in transferring new information and processes. Large company wide teaching seminars seem to be the most widely used. These seminars, often lasting two or three days, require enormous time and resources to organize and run. In order for companies to capitalize on new product development improvements fully, they must incorporate effective ways of teaching this information in their company culture.

### 1.1.2 Center for Innovation in Product Development – Thrust 4

The Center for Innovation in Product Development (CIPD) was formed at MIT with the goal of becoming "the world leader in creation and deployment of breakthrough product development science, processes, and tools. The Center will lead in education and learning to increase product development knowledge and leadership skills. US industry, by applying the Center's output, will gain a privileged competitive position." Specifically in Thrust 4: Accelerating Capabilities Improvement, there is an emphasis on improving the speed and quality that an organization's product development capabilities are improved through the creation and implementation of new knowledge and processes. It is with this ultimate goal that my thesis addresses and attempts to answer some of these challenges.

For my thesis, I focused on various media that are available and are currently being used to teach. By comparing the pros and cons of these media in terms of teaching effectiveness for a given subject, much can be learned about how companies should focus their efforts in teaching product development. I decided to focus on an engineering concept that students were having difficulty grasping and applying. For this, I chose the characteristic torque/speed curves of DC Motors.

### 1.1.3 Torque/Speed Curves

The principles being taught through this thesis deal with DC motors. In many engineering classes, students must design and build machines that employ these motors as actuators driving their machines. The torque/speed characteristic exhibited by DC motors represents a linear inverse relationship. As seen in the graph, there is a tradeoff that occurs between the torque the motor can apply and the speed at which the motor runs. Often, motors characteristics are given as two points on the no-load speed and the stall torque. These two points represent the end points on the graph. As can be read from the curve, the no load speed represents the point where the motor is running at its maximum speed but applying zero torque. The stall torque represents the point where the motor is providing the maximum torque but is not spinning. These two endpoints are connected by a line, and the motor must run somewhere at or between these two points. Ignoring any hysterisis, there is a unique torque for every speed at which the motor runs and vice versa.

# Torque/Speed Curve of DC Motor

Stall Torque

Torque

No Load Speed
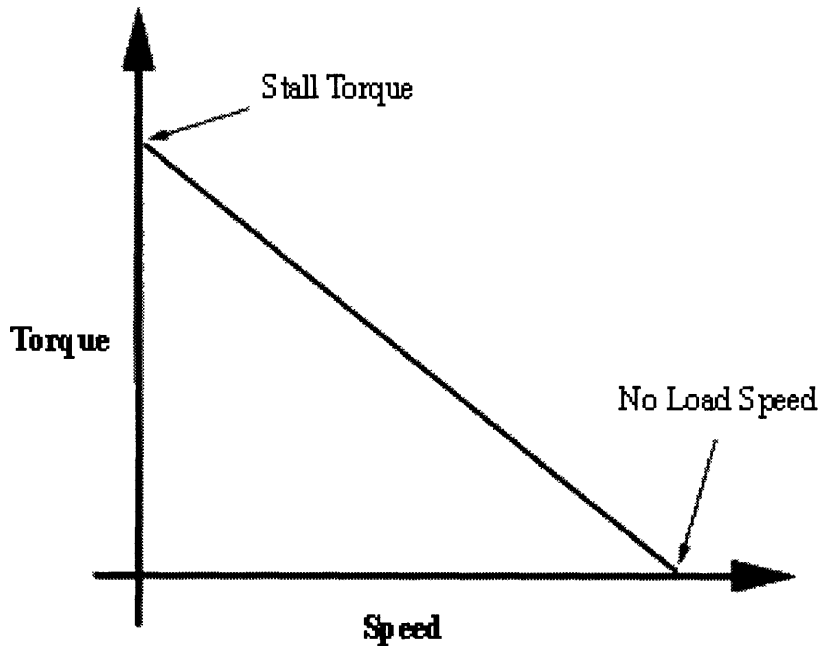
Speed

Figure 1.1: Torque/Speed Curve of a DC Motor

In terms of actually using this information in a design, a student must understand that when using DC motors, there is a tradeoff that occurs between torque and speed. Understanding this, a student would then design using this information to calculate the correct gearing and transmission for the motor.

## 1.1.4 MIT 2.70 (2.007) Students

The problems of understanding these concepts can be observed in the introductory design class at MIT, 2.007 (also known as the 2.70 Robot Building Contest). In this class, mostly sophomore mechanical engineering students are asked to put their understanding of engineering and physics to use and actually build a machine that competes against other machines. For many students, this is the first time that they are actually putting their theoretical knowledge of physics to concrete practice. It is here that numerous professors mentioned that many of the fundamental ideas of motors and their performance

characteristics were not well understood based on the mistakes that students made in designing and building their machines.

One scenario that often occurs involves a student misunderstanding the motor's performance characteristics that they are given. For example, a student may need to build a small vehicle using their motor to drive the wheels. The student would take the motor, connect it to power, and record the speed that the motor runs – not realizing that there is not any load on the motor. The student would then design their car's wheels and transmission to get their car to move at a specific speed based on the speed of their motor. The problem is that they do not take into account the loading of the motor caused by friction, inertia of their vehicle, and forces caused by inclines in the driving surface. Because of these loads, the motor has to provide a torque. This torque reduces the speed at which the motor runs based on the inverse relationship between torque and speed as described in the previous section. When the student actually drives their vehicle, it doesn't drive as fast as he originally thought. This scenario is very common and rests in the fact that students do not actively understand the torque/speed relationship in a concrete way.

## 1.2 Overall Project Goal

### 1.2.1 Purpose of the Device

This thesis attempts to bridge a gap that currently exists in many students' conception of torque and speed. MIT Mechanical Engineering students should all have had a course that teaches torque, speed, and electric motors by the time they graduate. Many of these students still only have a theoretical understanding of these concepts, which gets quickly forgotten unless supported by experienced phenomena in real life. It is reasonable to assume that most students have had enough exposure to "real" objects to have a fundamental understanding of torque and speed without the equations. The point of this thesis and the devices that I have built is to bridge the gap between what the students already know and what they learn in academic classroom settings. My device attempts to do exactly that. It creates a connection from actual, physical mechanisms in which the student has experienced and translates that into a graph that the student learned about in classes. This device hopefully gives the student a better overall understanding of the subject. The graphic below shows a spectrum of understanding and learning. My device attempts to bridge several blocks together to help students carry knowledge from one domain to another. In my device, I am trying to bridge the gap from what students learn about in classroom lectures to what they see in everyday life. The model uses hands-on learning tools with mechanisms that are similar to what students may see everyday. The contents of each block from left to right show the change of understanding from concrete to abstract.

⇐ Concrete                                    Abstract ⇒

| Everyday observations and objects that are familiar and "innately" understood and accepted. | Observations and objects that are similar to but slightly less common than things that are often seen everyday. | Classroom laboratory hands-on instruction. Physical interaction with devices. | Classroom lecture instruction. Theoretical or mathematical based. Graphical and auditory. | Book or instructional notes and other reading material. |
|---|---|---|---|---|

Figure 1.2: Spectrum of Learning and Understanding

The knowledge gained about how students learn engineering principles with various kinds of media can help us understand what forms of teaching are best of certain

kinds of subjects. This will eventually lead to improved product development education in industry by allowing companies to provide an optimal combination of live presentations, computer simulation, and reading – with cost and learning being the metrics.

## 1.2.2 Description of Models

In this thesis, I present two alternative forms for teaching students about DC motor torque/speed curves. The traditional method used at MIT and probably many engineering universities consists of a textbook explanation or a lecture describing the torque/speed characteristic for a motor. In my thesis, I built a completely mechanical model that allows a student to interact with the spinning motor shaft. In this device, there are several mechanisms that move as the student grabs the motor shaft. The device then draws the torque/speed curve of that motor on a Post-It Note as the student interacts with it. This device was built with the goal of making the mechanical movements representing torque and speed operationally transparent to the student so that by solely interacting with the model, the student could get an immediate understanding of the torque and speed tradeoff. My next model was a 3-D computer simulation of the mechanical device that I programmed using WorkingModel 3-D, a modeling and animation program. This computer simulation mirrors the mechanical model exactly except for the fact that the student's only interaction with the device is through the mouse. By comparing these two models with each other and with the control, I compared physical, computer, and traditional methods for explaining torque/speed curves.

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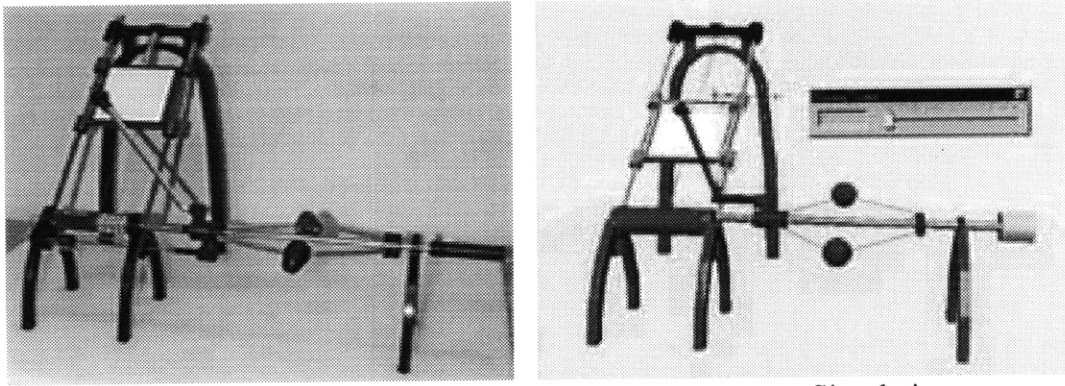
Figure 1.3: Mechanical Device and Computer Simulation

### 1.2.3 Matrix of Devices

In addition to these two basic models that I built, I helped to supervise three bachelor's thesis students in building some related models. These models would help fill in some of the gaps in the matrix and clarify the models and what student learn from them. The models can be broken down as follows. My physical model has both a physical input (the student grabbing the shaft of the motor) and a physical output (the mechanisms that display torque and speed). My computer model has both a computer input (the student using a mouse slider bar to simulate grabbing the motor shaft) and a computer output (the animation of the mechanisms). To fill in the matrix formed from the physical and computer versus input and output, a device that allows for physical input but computer output may be useful. This device consists of an actual motor that the student can interact with, but rather than the physical mechanisms as output, there is a torque sensor and an rpm sensor mounted on the motor. These sensors are hooked to a computer and actively display the torque and speed of the motor. The other node in the matrix consists of a computer input and a physical output. This is done by having an electromechanical brake controlled by a student through a computer. The brake is hooked up to the original device to simulate the student grabbing the shaft. With this matrix of devices, tradeoffs between how various inputs and outputs affect learning.

| INPUT | | Mechanical | Computer |
|---|---|---|---|
| **OUTPUT** | **Mechanical** | Mechanical Device - Motor with Mechanisms | Electromechanical Brake with Mechanical Device |
| | **Computer** | Motor with Torque and Speed Sensor | Computer Simulation with Mouse Slider Bar |

Figure 1.4: Matrix of Devices

There are many tradeoffs between all the modules in addition to how effective they are in teaching. These include cost and ease of widespread use. For the mechanical model, because the user needs to physically touch the device and also see the physical output, there is a necessity for having a model dedicated to a specific site. (Ignoring the possibility of haptic robotic feedback including the Phantom robot developed at the MIT Artificial Intelligence Laboratory.). The computer model represents the opposite extreme where one computer model could be distributed all over the world through the internet as a web site. This allows for low cost and high ease of distance learning and self paced learning. The physical input and computer output version of the model which uses sensors to read torque and speed, requires some hardware but also computer interaction. The computer input and physical output model incorporates an electromechanical brake in conjunction with the mechanical model. If videoconferencing capability was added, there could be one mechanical model in a remote site with a videocamera, and brake all controlled over the internet from remote computer site. This would reduce the number of models needed and also allow for distance learning.

## 1.3 Structure of Thesis Report

Chapter 2 describes the design and building of the mechanical device. I discuss the torque and the speed modules, perform a mathematical analysis of the device, discuss the industrial design and language of the device, and some detailed descriptions of various design features. I then go into some of the design issues and problems I faced in building and assembling the device.

Chapter 3 describes the design and modeling of the computer simulation of the mechanical system. I discuss some of my earlier methods of creating the simulation, both before deciding on using WorkingModel 3-D and once I started using this program. I end the chapter with some rendering and computational issues of computer simulations.

Chapter 4 describes my experimentation method to test the effectiveness of the devices that I designed. I then go into my experimental protocol.

Chapter 5 describes the results of my experiments.

Chapter 6 describes the work of three bachelor's thesis students that I supervised.

Chapter 7 gives an overall conclusion to the work done in the thesis.

Chapter 8 provides some recommendations for further work on the mechanical model, the computer simulation, and the experiments.

The thesis ends an appendix of detailed design drawings and engineering analysis.

# 2 DESIGN OF MECHANICAL SYSTEM

## 2.1 Overall Purpose

The design for this device, as compared to other products, has slightly different criteria in determining its performance and quality. Because this device is used in teaching an engineering principle, the main overriding criteria in the design is to be educationally transparent to the student. Also, because the students who will be using this device are mechanical engineers, there is an emphasis on design elements. Industrial design and human factors are also heavily considered. The aim of the device is to teach students about DC motor torque/speed curves in a way that bridges the gap that exists between the theory that the students learn in classes and the physical phenomena that they observe occurring in everyday products. Because this device is intended to be used in classroom demonstrations, the machine must be rugged enough to withstand abuse from students, constant use, and possible bumps and bangs.

As in Frank Lloyd Wright's philosophy in designing buildings, form follow function. This device uses aesthetics and industrial design elements to guide the student's understanding and approach to the device. The tradeoff between simplicity of design and the intrigue of interesting mechanisms was weighed to have a device that from first glance is straightforward in its function, but upon closer inspection contains many interesting mechanisms dealing with mechanical design. It was with this intent that I designed the device.

In building this device, I went through several prototypes and breadboards of the subassemblies. A tremendous amount was learned from these prototypes – not only in terms of design elements, but also in terms of students' responses to the device and their interaction with it.
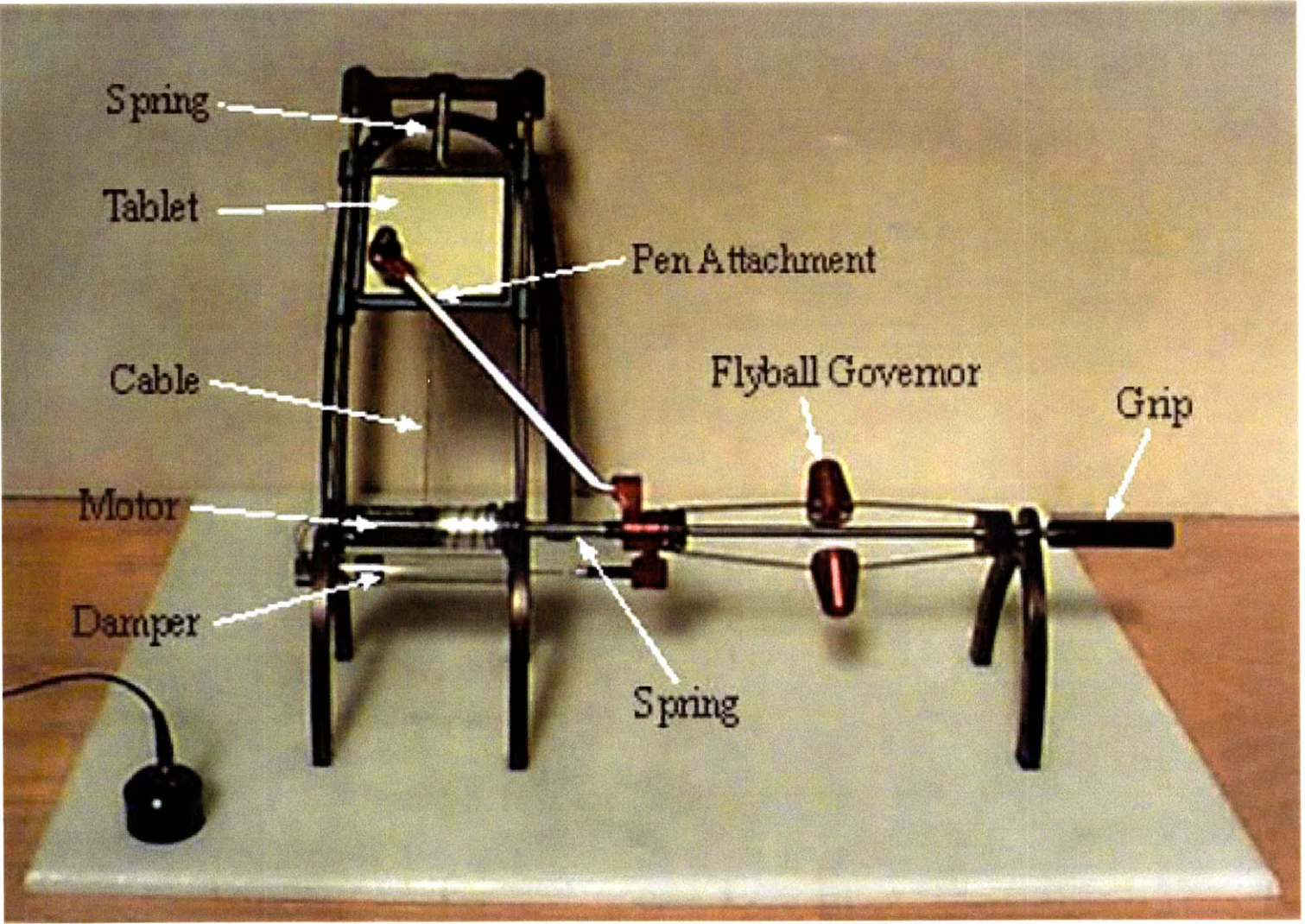
Figure 2.1: Mechanical Device

## 2.2 Overall Description

The device contains two main subsystems each with its own unique design considerations and language. Because the device is to teach about torque/speed curves, the first and most noticeable feature of the device is the layout of the machine. Mirroring the axes of the torque/speed curve that students learn about in classes, my device consists of a spatial separation of the torque and speed subsystems that align to form the axes of a graph. This architectural feature of separating subsystems according to function allows for more clarity in understanding of the overall device by allowing students to focus on each system independently, and then superimpose the motions to get the final motion. Coloring of the mechanism also further clarifies the separation between the systems and the base of the machine.

The first subsystem is the torque measuring mechanism that consists of a spring-loaded cable wrapped around the motor. The second subsystem is the speed measuring mechanism that consists of a spring-loaded flyball governor. There are several other interesting mechanisms and features that I will also highlight that affect the performance or aesthetics of the device.

In order for this device to effectively bridge the gap between what students learn in classes and what they already have an understanding of from interacting with everyday products, I had the mechanism draw a graph of the torque/speed curve on paper. The movement of the mechanism was the physical part of the machine that transparently demonstrates torque and speed. The graph on paper links this motion to the graph that the students learn about in classes. In this way, the torque/speed curve becomes less theoretical and more real to the students.
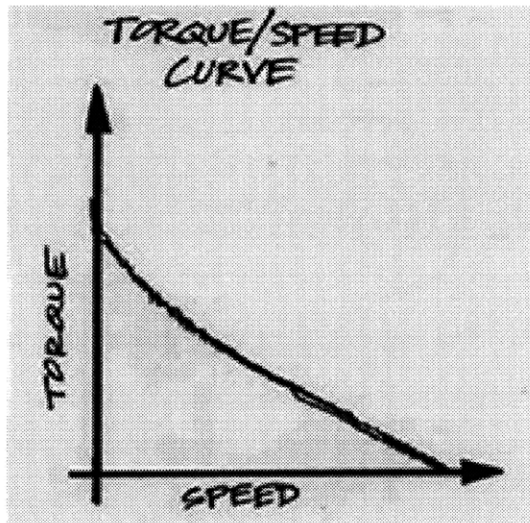
Figure 2.2: Actual Graph Drawn by Mechanical Device on Post-It Note

The layout of the tablet where the torque/speed curve is drawn is inclined at a 45° angle so that it is easily viewed by students. With the motor mounted at the bottom of the track that the tablet rides on, there is an even presentation of the tablet graph and the motor –the two main features of the entire device. This user-friendly view of the device is effective in presenting the graph to the student.

The student interacts with the device by squeezing a grip that is attached to the motor shaft. By allowing the student to adjust his gripping strength to range from zero grip (letting the motor shaft freely spin) to a full grip (stalling the motor shaft so that it stops spinning), the device actively maps out in real time the exact torque and speed state of the motor on the graph. This haptic input is a very visceral and intimate interaction between the student and the device. This device falls in the matrix category of physical input and physical output.

The DC motor being used in the device is one of the motors that is used in the 2.007 Introduction to Design (2.70) class at MIT

Figure 2.3: Maxon DC Motor

## 2.3 Torque Meter

### 2.3.1 Description of Mechanism

The torque measuring mechanism is the first subsystem of the overall device. The goal of this mechanism is to measure the torque output of the DC motor. Some of the criteria of in the design include linearity of the torque measurement, clarity in understanding how it works, an aesthetic design language that matches the rest of the device, and robustness of design so that it can last through class demonstrations, students, and accidental bumps.

The torque meter consists of a carriage connected to a cable that is wrapped around the body of the DC motor. The motor is mounted on bearings so that not only does the motor shaft spin but also the motor itself is allowed to spin. The carriage rides on two shafts through linear bearings and is connected to the motor by a steel cable. The carriage is connected to a back mounting piece with an extension spring.
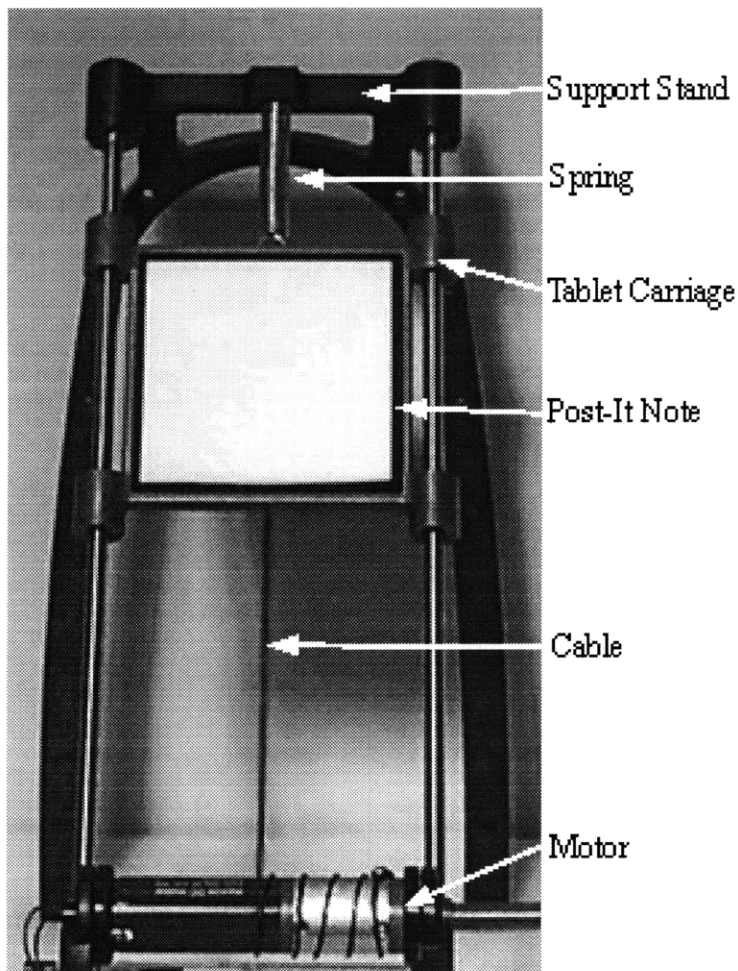
Figure 2.4: Torque Meter

## 2.3.1.1 Analytical Design

The torque meter uses the counter acting torque of the motor and the student's resisting grip to map out the torque that the motor is applying. As the student grips the knob, the motor wants to spin the opposite direction as the motor shaft in order to counteract the gripping torque that the student is applying. As the motor tries to spin on its bearings, the steel cable gets wrapped around the motor body. This wrapping of the cable pulls the carriage piece down the along the linear guides. There is an extension spring that is attached between the carriage and a grounded back mounting piece that resists this pulling.
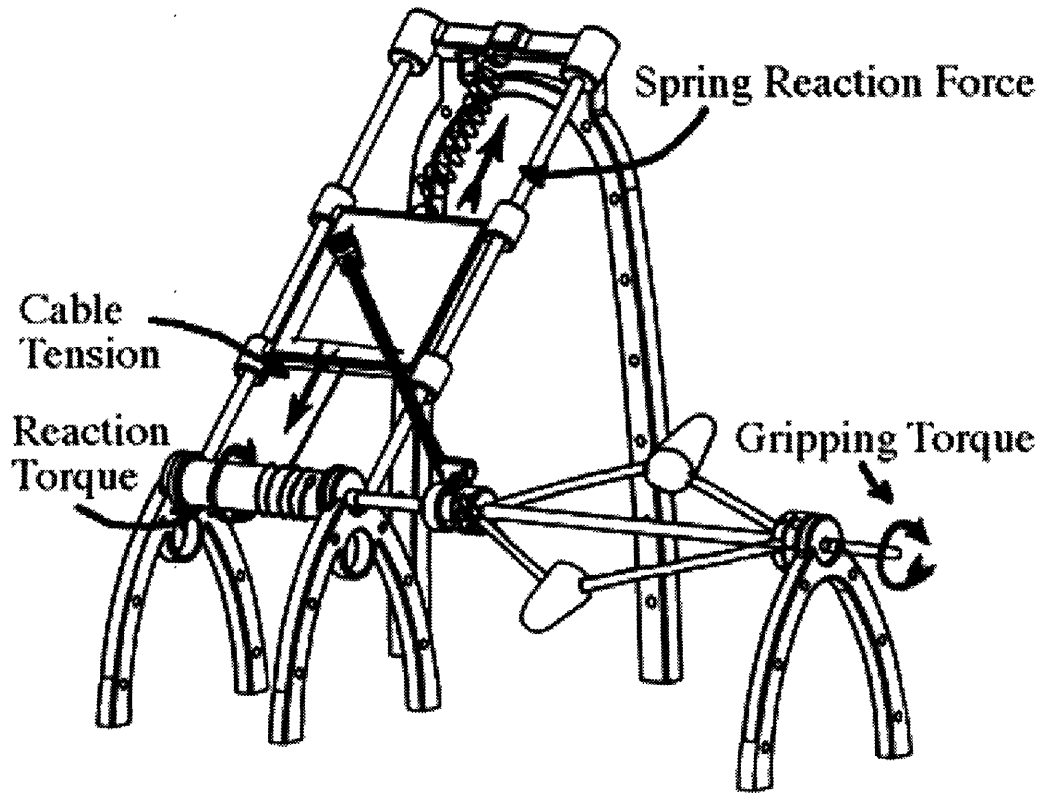
Figure 2.5: CAD Assembly of Mechanical Device with Forces

The extension of the spring is now related to the gripping torque that the student applies to the knob. This translates into the motion of the carriage. Assuming that we have a linear extension spring, the distance that the carriage travels will also be linear with the torque of the motor.

## 2.3.1.2  Qualitative Design

Once the concept design was finalized, the exact specifications for each component part were set. Because there are an infinite number of possibilities of components to choose from, I had to start with some assumptions. With the mechanical analysis confirmed, the design shifted towards a human factors and robustness decision. Once a few design criteria were set, the other specifications fell into place.

Considering that the motor must spin to wrap the cable, in a real life setting, there is the possibility of the motor spinning backwards or more than what was designed. Possible causes of this include dynamic effects, students who manually try to turn the

motor, or breaking of some components such as the spring, cable, or the interconnects. In order to do this, I designed a pin and track stop that limits the motor's turn to a little less than 360°. This set the maximum turn of the motor to be just under one revolution.
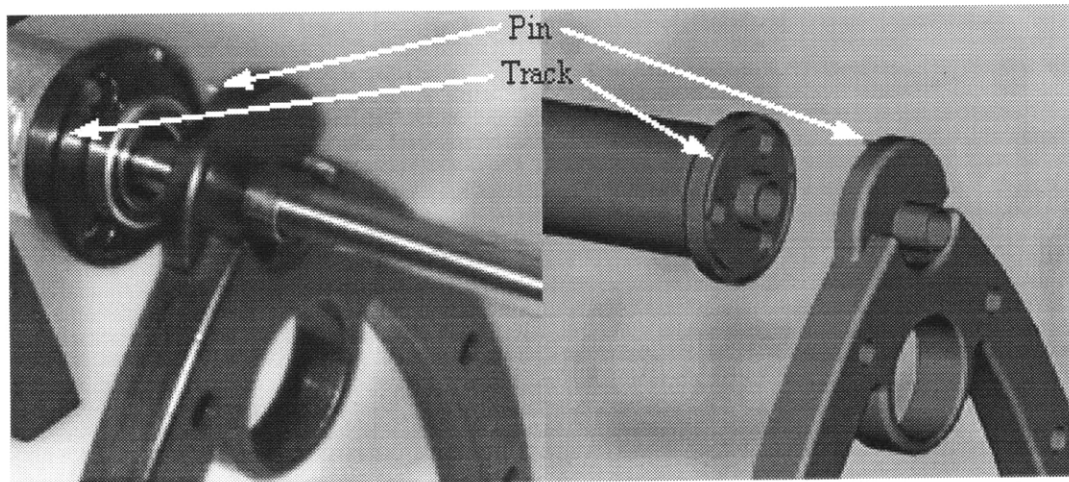


Figure 2.6: Pin in Track Feature on Actual Device and CAD Model

Once this specification was set, I decided that for aesthetics and clarity, the cable should wrap directly around the motor rather than having a collar piece. This led to a calculation of the maximum amount the motor could pull the cable equal to just less than the circumference of the motor body. Because the carriage is attached to the cable, the carriage could move this distance. In designing the spring, an extension spring was chosen to be large enough to stretch just under this amount based on the maximum stall torque.

Because the carriage piece acts as the board in which the torque/speed curve would be drawn, I wanted to ensure from a usability perspective that the graph would be large enough to see. From my previous calculations, it was confirmed that the carriage would move about 2." Also, because I wanted the student to be able to take the graph of the torque/speed curve with them, Post-It Notes were used as the graphing paper. This feature added convenience to the design of the device.

Once the basic design of the device was getting settled, I started creating the parts in ProEngineer, a three-dimensional computer aided design software package. The drawings of my parts are in Appendix 9.1.1. The CAD package allowed me to create and review

my parts before they were machined. Also, it has the capability of creating assemblies to ensure that my model would fit together once built.

## 2.3.1.3 Decision Flowchart

As can be seen, the design of mechanisms can often follow numerous paths that all satisfy analytical engineering. From there, the design must follow a decision path that satisfies other criteria such as cost, convenience, human factors, aesthetics, and usability. I felt that my decision flowchart was an optimal solution for this device given the criteria that I felt were most important. If these criteria changed so that maybe minimizing size was the main concern then the decision tree would have varying outcomes. The torque meter was a good example of qualitative criteria being the main deciding factors with the engineering analysis used to confirm its validity.

**Design Criteria**
1. Linearity of Torque Meter
2. Accuracy and Repeatability
3. Robust
4. Clarity of Meter
5. Aesthetics
6. Motor Torque Limit

**Criteria**

1. Linearity ⟶ Linear extension spring

2. Accuracy and Repeatability
3. Robust
⟶ Pin in track feature eliminates any overrotation of motor body ⟶ A little less than 360 degrees rotation of motor

4. Clarity of Meter ⟶ Cable rather than ribbon

5. Aesthetics ⟶ Wrap directly to motor (no collar piece) ⟶ Circumference of motor is travel distance of meter ⟶ Spring stretch distance is about circumference of motor ⟶ Spring constant for torque meter to get full travel on tablet

6. Motor Torque Limit

Figure 2.7: Design Flowchart for Torque Meter

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## 2.3.2 Screwdriver Example

In looking at the device from a student's perspective rather than a designer's perspective, I tried to come up with an example of this mechanism commonly seen in everyday life. By using a commonly occurring example, students can readily relate what they are learning about to what they already are familiar with. This led to the electric screwdriver example. When someone uses a handheld electric screwdriver (or a similar device such as a power drill), they hold the screwdriver in one hand. As they turn on power, the driver turns its bit and thereby screws the bolt into the material. Initially, if the bolt is easy to twist into the material, there is little torque resistance, but as the resistance to turning the bolt into the material increases, there is a counteracting torque that the person feels in their hand.



Figure 2.8: Electric Screwdriver

By relating this to my device. The screwdriver is represented by the motor. The resistance of the bolt going into the material is represented by the student grabbing the shaft of the motor to slow it down. The person's hand is represented by the motor mounted on bearings with the spring-loaded cable wrapped around it to provide torsional

resistance. In having my device reflect this real life example, I was able to bridge another gap in the spectrum of learning which I described earlier.

With my device, I am able to map the space from the very mathematical and analytical information given in classes in the form of the torque/speed curve to a physical model. Then, by relating this physical model to something that the student probably has personally experienced in everyday life, a connection between what the student learned about in classes and what he experiences in normal activities is made.

### 2.3.3 Alternative Designs

In brainstorming for various mechanisms that would display the torque of the motor from a student grabbing the motor shaft, I went through several design concepts. These design alternatives were based on a user's perception and how effectively and clearly they demonstrated the torque measuring principle. The main criteria for this design were linearity of torque measurement and clarity in how the mechanism worked.

In order to display a torque measurement on a graph, there should be a spring element to satisfy the equation F=kx where F is the force, k is the spring constant, and x is the displacement. Because my device displays the torque/speed curve, the spring element is used to transform the torque to a distance that is then shown on the graph. For the spring element, both torsional and linear spring elements were considered.
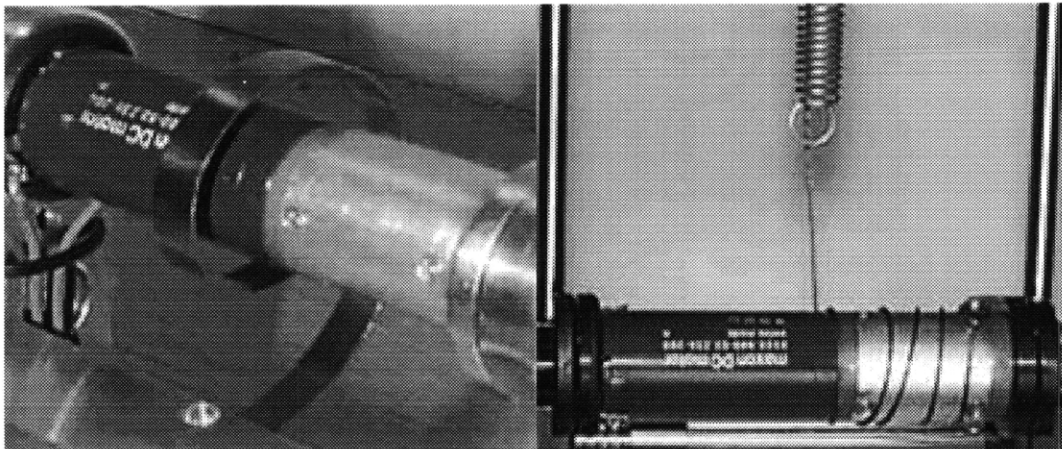


Figure 2.9: Comparison of Torsional and Linear Spring

In terms of performance, both springs would work, but looking at clarity of understanding, the linear spring is much more commonly used so would probably be more obvious to students.

In terms of the connection of the spring to the motor, I compared the use of a cable and a ribbon. In terms of performance in making the torque measurement linear, there was an issue of the ribbon wrapping over itself thereby changing the diameter of the moment arm around the motor. This could easily be solved by using a thin enough ribbon so that the error would be negligible. Also, because the motor rotation is limited to less than one rotation, there won't be an overlap of layers to change the diameter. The use of the cable was chosen from personal preference.
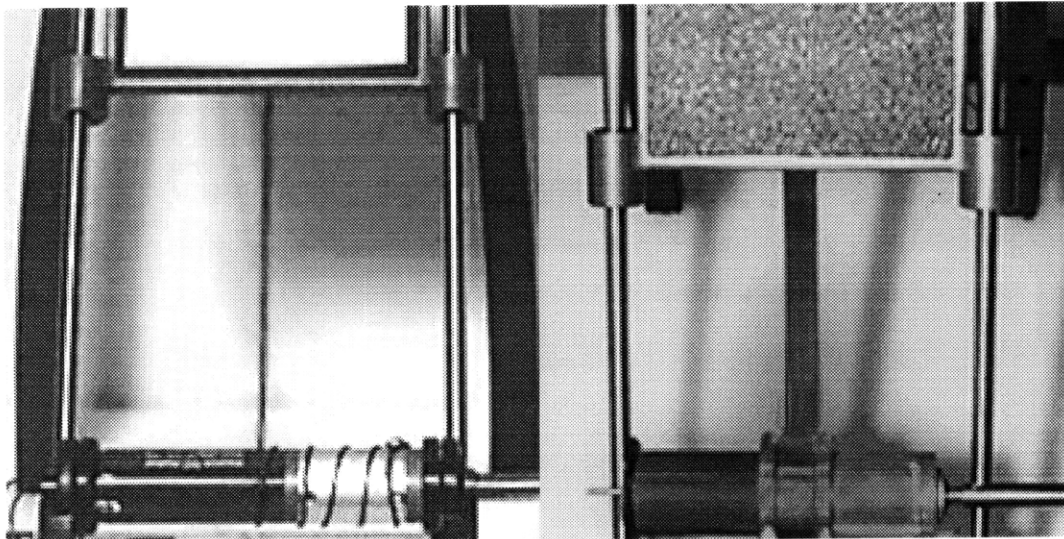

Figure 2.10: Comparison of Cable and Ribbon Wrap

## 2.4  Velocity Meter

### 2.4.1  Description of Mechanism

The velocity measuring mechanism is the second subsystem of the overall device. The goal of this mechanism is to measure the velocity output of the DC motor shaft. Along with the torque measuring mechanism, this subsystem will allow the torque/speed curve of the DC motor to be drawn. Similar to the torque measuring device, some of the major criteria of this design include linearity of the velocity measurement, clarity in understanding how it works, an aesthetic design language that matches the rest of the device, and robustness of design.

The velocity meter consists of a mechanism known as a flyball governor. The flyball governor works on the principle of the centripetal acceleration of a mass revolving around a center point. In my device, the flyball governor is attached to the output shaft of the DC motor. It consists of two masses connected by a linkage to the shaft in a way that allows the masses to spin with the motor shaft, but also move radially outwards as the centripetal force increases due to an increasing rotational velocity of the motor shaft. A linear extension spring is attached to one end of the linkage to provide a restoring force to the centripetal forces being transferred through the linkage. At the end of the moving linkage, a pen from a plotter is attached through an arm so that the velocity of the motor shaft is drawn on the tablet.
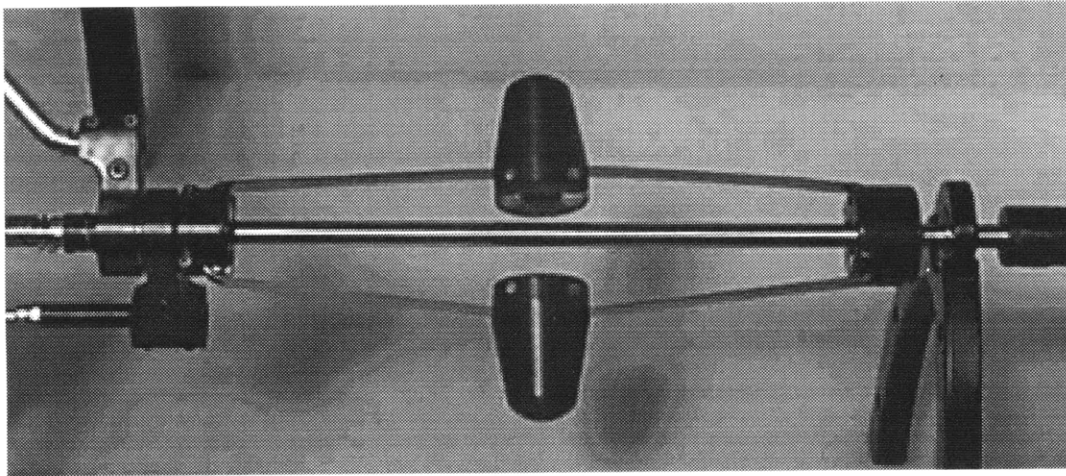
Figure 2.11: Velocity Meter – Flyball Governor

## 2.4.1.1 Analytical Design

The velocity meter uses the principle of centripetal acceleration to instantaneously map out the rotational velocity of the motor's output shaft. Because centripetal acceleration increases as the rotational velocity increases, I designed a device that takes advantage of this phenomena to measure the velocity of the motor. In order to design the device effectively so that the design criteria were satisfied, an analysis of the flyball governor was performed to determine its characteristics. In an Excel spreadsheet, the behavior of the device was mathematically mapped out.

The equation for centripetal acceleration is $a=r\omega^2$ where a is the centripetal acceleration, r is the radial distance from the center of rotation of the shaft, and $\omega$ is the rotational velocity of the shaft. Given that the principle of centripetal acceleration is used, a mass is needed to convert the acceleration to a force by $F=ma$ where F is the force, m is the mass, and a is the acceleration. From this force, a spring is needed to convert the force to a distance similar to the torque measuring device. From $F=kx$, where F is the force, k is the spring constant, and x is the displacement, the force would be converted to a distance. Putting this together, I as able to move from the motor shaft velocity to centripetal acceleration then to force and then to distance.

Going back to the first design criteria for the velocity meter, the movement of the pen in drawing the velocity of the device on the tablet should be linearly related with the velocity of the motor shaft. As can be seen from the above equation, the centripetal

acceleration is related to the square of the velocity. Because of this, unless there is some mechanism that can linearize this, the velocity meter will not be completely linear.

In order to compensate for this there were several approaches that were considered. The one chosen for my device was a linkage that would automatically adjust to compensate for the squared term to linearize the velocity meter. Some of the other approaches are discussed in the section on alternative designs. The linkage is a fairly simple system that helps to adjust for this squared term using a factor that includes a tangent function.
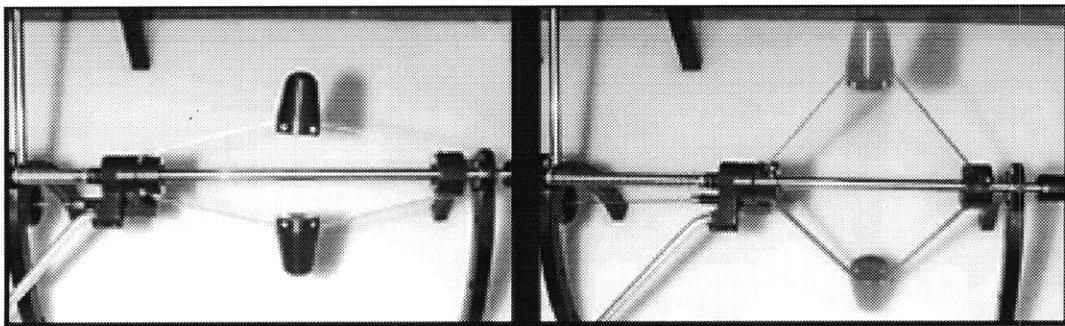


Figure 2.12: Governor in Slow Speed and Full Speed States

As can be seen from the picture, when the rotational velocity of the motor shaft is low, the masses are closer to the shaft. In this position, a small amount of force radially from the masses creates a large axial force at the sliding piece. Then, when the rotational velocity of the motor shaft is high, the masses are farther from the shaft. In this position, a force radially from the masses due to centripetal acceleration creates a small axial force at the sliding piece. This mechanism reacts this way due to the changing direction of the forces being transmitted through the linkages. From trigonometry, the changing angles of the linkages changes the magnitude of the forces. This characteristic of the mechanisms helps to linearize the squared term of the centripetal acceleration equation. I derived an equation of this mechanism and calculated its force characteristic on an Excel spreadsheet. Below is the graph comparing the velocity of the shaft and the pulling force at the sliding piece. See Appendix 9.2.1 for a complete derivation of the characteristic equation and discussion of the mechanism design.

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**Governor Analysis**
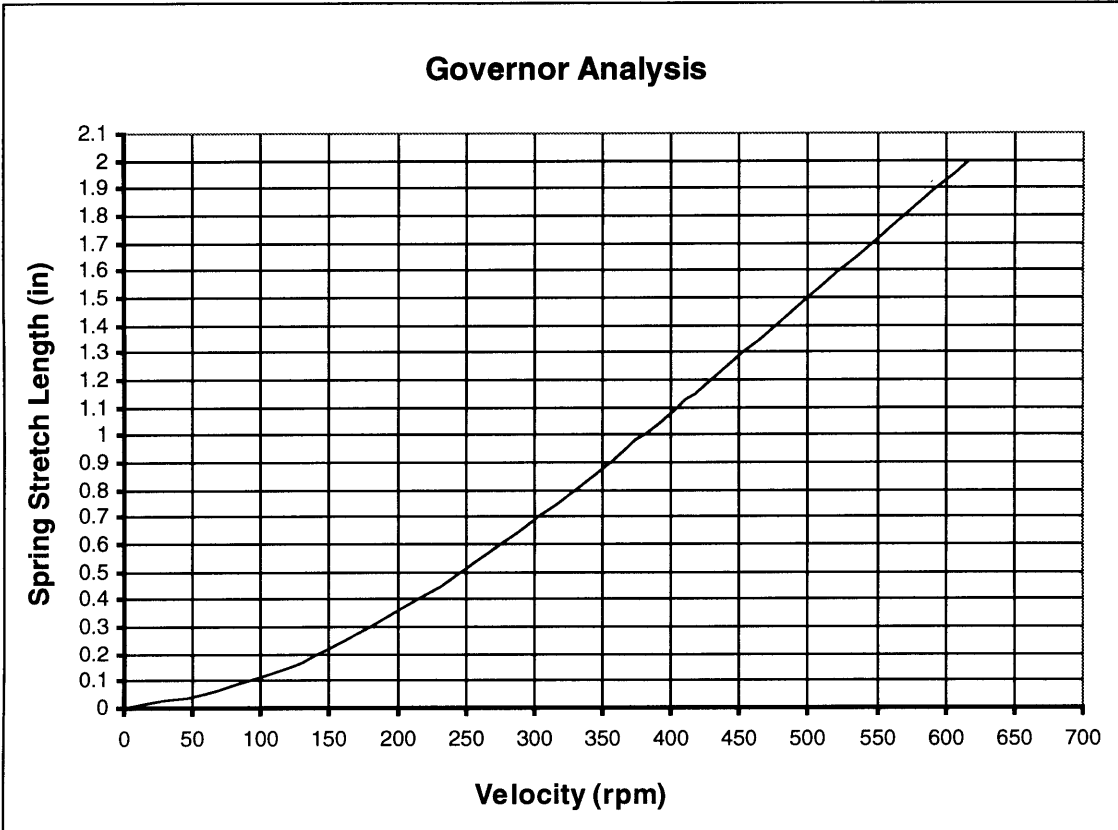
Figure 2.13: Analytical Graph of Governor Performance

Assuming the restoring spring is linear, the displacement of the sliding piece is linear with the force. As can be seen from the graph, the response of the mechanism is fairly accurate with some non-linearity at low speeds below about 150 rpm.

From the equation and spreadsheet, I designed the velocity meter around the motor characteristics of having a maximum no-load speed of about 600 rpm. By changing the masses, the linkage length, and the spring constant, I was able to design the device to move in a way to fit on a Post-In note.

2.4.1.2 Qualitative Design

In addition to the analytical design that went into designing the velocity meter, there were several design features and criteria that went into building the mechanism. In addition to having the device respond in a linear manner, the device had to be intuitively obvious, interesting to look at, and robust. These design features have some aspects of

analytical design, but fall more into human factors and how students respond emotionally to the device.

Not only does the linkage system compensate for most of the non-linearity of the centripetal acceleration equation, its symmetry is aesthetic and has a very balanced feel. The colors and shapes of the pieces help in making it fairly obvious what the device does. The spinning masses demand attention. Also, because the device has bearings and steel band linkages, the device is strong and sturdy to withstand bumps and continued use. The robust look of the device allows the student to feel comfortable with approaching the device and interacting with it.

The pen attachment is linked to the velocity meter through a bearing. This bearing allows the pen to move laterally with the sliding piece but not spin with it. The same mechanism is used to attach the sliding piece to a damper. When the motor shaft spins, the masses and linkages spin with it, but the pen does not so that it can write on the carriage tablet to plot out the velocity measurement of the motor.
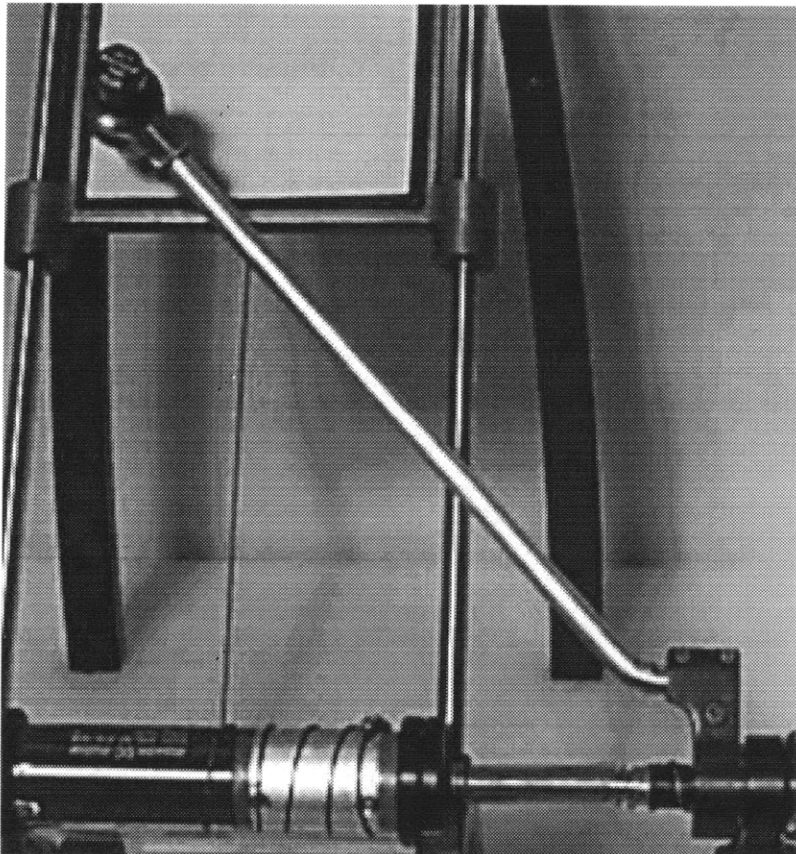


Figure 2.14: Pen Attachment on Velocity Meter

### 2.4.1.3 Decision Flowchart

The design of the velocity meter followed a series of decisions similar to the torque meter. Depending on the analytical and qualitative considerations that I set as criteria, the flow of design decisions were guided by the importance of the varying considerations. Once I had analyzed the mathematical model of the governor in Excel, various design parameters were manipulated to optimize the design.

Based on some of my initial architectural and human factors decisions, the width of the graphing area was set to be similar in dimension as the vertical height of the graph. Because the vertical graphing area of the torque is about 2", I set the horizontal dimension of the velocity meter to be similar. With this dimension set, I was able to manipulate variables in my mathematical model. The variables that determined the horizontal travel of the governor were the linkage length, the mass, and the spring constant. Also, because I wanted to have the governor fairly small, the smallest linkage length that was still in the linear region of the predicted model was chosen. This turned out to be about 3". Once this variable was set, the spring constant and the masses of the two spinning weights needed to be set. There was a direct tradeoff between the spring constant and the masses. Because I wanted the masses to be fairly visible to the student, I concentrated on the industrial design of the masses and then set the spring constant so that at the motor's maximum velocity of about 600rpm, the governor would move the pen about 2" as can be seen from the graph in Figure 2.13.

There were other considerations to take in to account such as the dynamic response of the system. This is essentially a second order system of a spring-mass system. In order to control for possible resonances, a damper was added which I discuss in a later section. The dynamic analysis of the governor is discussed in Chapter 2.5.3.

### 2.4.1.4 Fan/Mixer Examples

Similar to the screwdriver example for the torque meter, it is advantageous to the student to have a real life product with which he can compare the device. This allows the

student to bridge another gap in their understanding from a real product to a mechanical device to a theoretical topic that they learn in their classes.

In the mechanism that displays the velocity of the DC motor, I used the principle of centripetal acceleration in the form of a flyball governor. This device operates by having masses attached to a spinning shaft. When the velocity of the shaft increases, the masses have a tendency to pull further away from the shaft due to this centripetal acceleration. In looking at this principle, I looked around for products that I had seen that use this idea of centripetal acceleration on masses. Two products that immediately came into mind were small fans and mini-mixers. In the fans, the fan blades are attached to the shaft through hinges. These hinges allow the fan blades to lay flat when not in use to conserve space. When the fan is turned on, the fan blades flap out due to this centripetal acceleration on the blades. In the mini-mixer, there is a plastic rod that is split down its middle. This rod is attached to the shaft of the motor. When the motor is turned on, the two split halves of the rod spread apart and create a mixer. Both of these two real life products use principles similar to what I used in my device.

## 2.4.2 Alternative Designs

In designing for the velocity meter, there were several design alternatives that were considered. The criteria that eliminated most of them was the linearity requirement. There were several options that I had to make these devices linear, but I decided on my device based on ease of understanding, ease of manufacturing, and robustness.

Because the displacement of the pen is related to the velocity of the motor, even though there is a non-linear relationship between the centripetal acceleration and the rotational velocity, a non-linear spring with a varying spring constant could have been used. By manufacturing a spring that exactly compensates for the governor non-linearity, a linear device could have been made. Rather than have the spring constant k be a constant value, a spring constant would have been chosen that varied according to displacement. I chose not to follow this route because of the difficulty in manufacturing this spring exactly to specification.
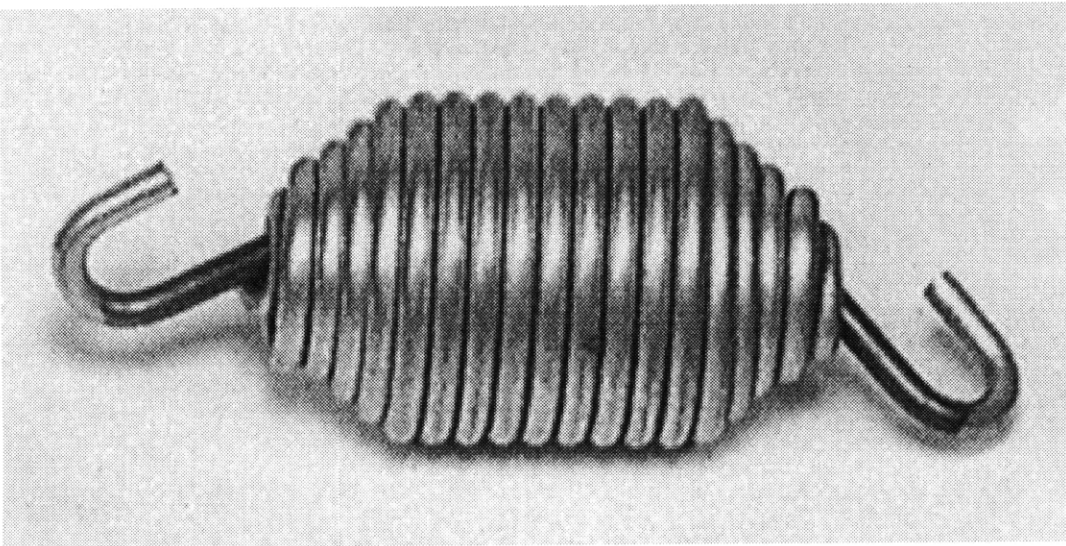
Figure 2.15: Nonlinear Spring

## 2.5 Mathematical Model of Mechanical System

### 2.5.1 Predicted Versus Actual Curve

In order to determine how my device would respond based on my initial designs, I derived a mathematical dynamic model of the system. By modeling the geometric relationships of the various forces and moving parts of the device, I was able to predict with a fair level of accuracy the resulting curve that my device drew on the Post-It note. After deriving an equation of the relationships between the components of my device, I modeled the dynamic states of the device in Excel. The resulting graph of my theoretical dynamic model is shown below.
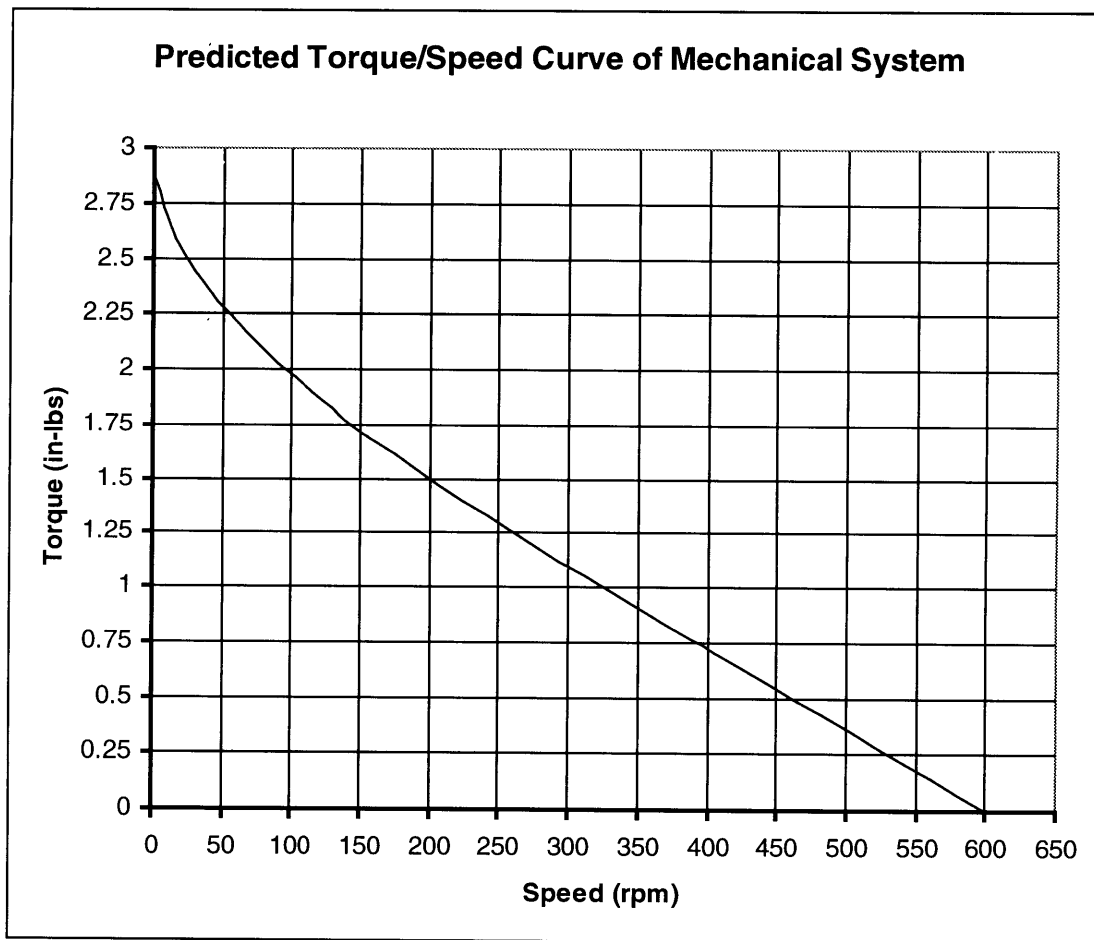


Figure 2.16: Predicted Torque/Speed Curve of Mechanical System

As can be seen from the graph, my model predicted extremely accurately the actual response of the mechanical system including the non-linearity of the torque/speed curve at low speeds. In the figure below, the predicted curve is overlaid with the plot from an actual Post-In note plot from the mechanical system. The curve in red is the predicted curve from my mathematical model in Excel. The black curve is a scanned in image of the actual curve from a Post-It note overlaid on the same graph. As can be seen, the two curves match up fairly well.

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**Predicted and Actual Torque/Speed Curves
of the Mechanical System**
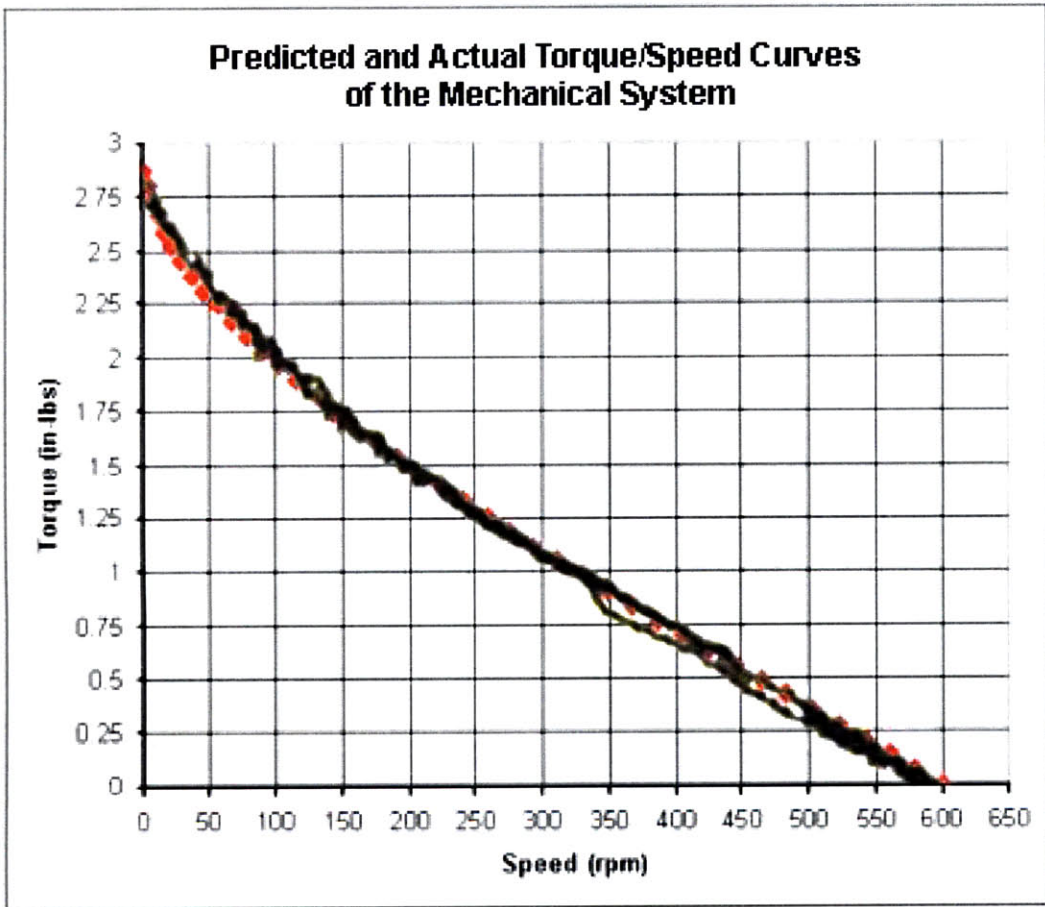
Figure 2.17:  Overlaid Predicted and Actual
Curves of Mechanical System

## 2.5.2 Explanation of Non-linearity

The non-linearity of the torque/speed curves in both the predicted and the actual models both derive from the governor's geometry. Essentially, the torque meter is completely linear assuming that the spring used to counteract the cable is linear. From the spring supplier specifications, given the stretch range that it is using in, it is linear. The governor performance is slightly non-linear at low speeds as was shown in the previous section on the governor analysis. This governor non-linearity translates to a slight upward sweep in the torque/speed curve at speeds below about 150 rpm. Further explanation can be found in the Appendix 9.2.1.

## 2.5.3 Dynamic Analysis of Frequency Response

For the design of the mechanical device, the dynamic response of the system was important in determining its frequency response to excitations. This analysis provided a description of how the device would perform given certain inputs. For the mechanical system, the two subassemblies of the torque meter and the velocity meter were both analyzed. The results of this analysis confirmed the design that was implemented. See Appendix 9.2.2 for a detailed discussion and derivation of the frequency response.

### 2.5.3.1 Torque Meter

The torque meter was a fairly simple second order system with one mass and one spring. Given this, the dynamic response of the system was calculated in terms of its natural resonant frequency. Given the system, the tablet with bearings was the inertial

$$\omega_n = \sqrt{\frac{k}{m}}$$

element and the linear spring was the spring element. From the equation, the natural

frequency of a second order spring/mass system can be calculated given the spring constant and the mass. In the torque meter, the mass of the tablet is 0.266 lbs, the spring constant of the linear extension spring is 1.87 lbs/in. Converting these to kg and N/m respectively, the natural frequency of the system $\omega_n$ is 23.67 hertz.

Given this frequency, it seems unlikely that a student could pulse his grip on the motor shaft 23 times a second. The highest frequency that a student could pulse the system at would probably be around 5 hertz. Because of this, the design of the torque meter was well out of the excitation range of a student. From actually running the device, the torque meter was not able to be excited to a resonant frequency. One consideration that must be made is a step input which is fairly common for this device when a student grabs very quickly and firmly to the motor shaft. This step input can excite resonances, but from my device, it can be seen that the damping in the linear bearing is high enough and the overshoot low enough not to be a problem. Hence, it was not necessary to put in a damping unit on the torque meter.

## 2.5.3.2 Velocity Meter

The velocity meter consists of a flyball governor and an extension spring. This second order system essentially has a mass element and a spring element, but unlike the torque meter, the velocity meter is extremely nonlinear. The reason for this rests mostly on the property of the governor in exhibiting behavior where the masses and forces are no longer constant values but are dependent upon the position of the governor. The derivation of the dynamic response of the system resulted in a nonlinear second order differential equation as follows.

$$\left(\frac{-m_s}{4}\right)x^2\ddot{x} + \left(lm_s\right)x\dot{x} + \left(\frac{m_b l^2}{2}\right)\ddot{x} + \left(\frac{k}{4} + \frac{m_b \omega^2}{8}\right)x^3 - \left(lk + \frac{3m_b l\omega^2}{4}\right)x^2 + \left(m_b l^2 \omega^2\right)x = 0$$

Where x is the displacement of the governor sliding mass, $m_s$ is the mass of the slider, $l$ is the linkage length, $m_b$ is the mass of the governor balls, k is the spring constant, and $\omega$ is the rotational velocity of the governor. See Appendix 9.2.2.3 for a full derivation.

With this differential equation, Simulink – a Matlab program that specializes in modeling, simulating, and prototyping dynamic systems was used. With this program, I

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made a block diagram for the system and recorded the step response of the system at different speeds and positions. From this data, I was able to get the natural frequency of the governor at different states and for different pairs of governor masses and springs that would work in my design.
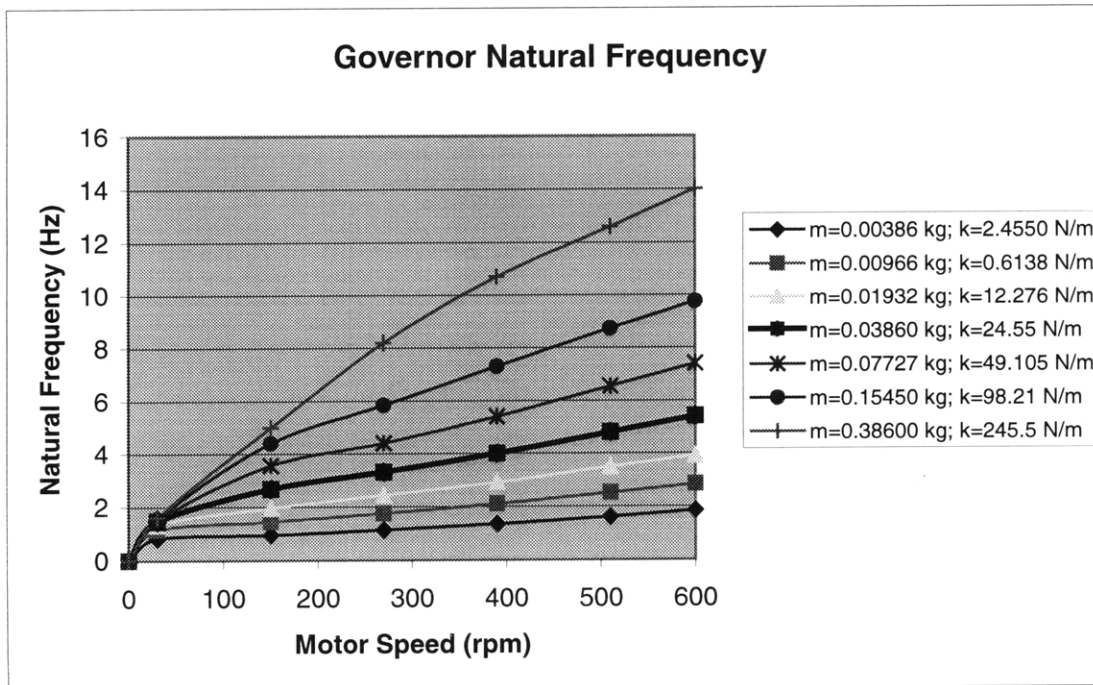


Figure 2.18: Governor Natural Frequency at Various Speeds and Spring/Mass pairs

As can be seen from the graph, for a given spring/mass system that satisfies the governor performance requirement, the natural frequency increases as the speed of the motor increases. For my device, a governor ball mass of 0.0386 kg and a spring constant of 24.55 N/m was used. As can be from the figure, when the governor is spinning at full speed and the x displacement is at its maximum displacement of about 2", the natural frequency is around 5.5 hertz. In all the cases, the natural frequency tends towards zero as the motor speed approaches zero. Also, in the graph, the natural frequency of the entire system increases as the masses and spring constants increase.

With respect to my design, I did not want my device to have an oscillatory response when a student grabs the motor shaft. From my analysis, it can be seen that my

governor design falls within a range of natural frequencies that students are probably capable of producing with their hands. When this occurs, the governor exhibits resonant behavior and will overshoot its steady state response. In order to compensate for this, I added an adjustable Airpot damper. This allowed me to create a damped second order system to control for this overshoot. The tradeoff that exists is in the time response of the governor which is slightly slowed down.

In order to eliminate resonant behavior, it is desired to have the natural frequency of my device to be higher than what a student is capable of producing with his fingers. This turns out to be around 5 hertz. In order to do this, a large spring and mass pair could have been used so that at least at higher speeds, there would be a higher natural frequency and less chance of overshoot. Of course, for all the spring/mass pairs, at low motor speeds, the natural frequency drops to a region where resonant behavior becomes very possible. Given this I could have chosen the mass to be similar to the line of the 0.386 kg mass and the 245.5 N/m spring constant. Of course, this turns out to be a mass ten times larger than the one presently used. This in itself could have caused other adverse affects such as acceleration problems of the motor being able to spin the governor up to speed. This in itself could have caused a large slow down in the time response of the system.

Looking at the graph and the actual governor system, it makes sense that this varying natural frequency occurs. For a given spring/mass pair when the governor's speed is high, the x displacement is large and the masses of the governor balls become less dominant from geometry. Because the spring constant stays constant, and the effective mass decreases, there is an increase in natural frequency. At low speeds, the governor geometry tends to drive the effective mass towards infinity thereby making the natural frequency tend towards zero. In terms of the natural frequency increasing as the spring/mass pairs increase, because the spring constant is fixed while governor mass becomes less dominant at high speeds, the spring constant is large relative to the effective mass of the system. This drives the natural frequency higher. No matter the spring/mass pair used, there is a region that the governor enters which it is possible for a student to excite the natural frequency of the governor thereby requiring a damper.

In using the device, the damper can be adjusted while driving an oscillating input. This results in oscillatory behavior at low damping. As the damping is increased the

oscillations decrease and then disappear all together. If the damping is increased further, there is an obvious time response delay for the velocity meter. For my system, the damper can be adjusted so that there is negligible overshoot and time response lag.

## 2.6 Industrial Design

The industrial design of the components of this device was a crucial area of its effectiveness. I spend a large amount of time and effort into creating a machine whose aesthetics matched its functionality to enhance its overall impression. There were several areas in which I focused my efforts. These included the shapes of the machined parts as well as the overall architectural design and layout of the device. Human factors also had a large affect on how the device ended up looking. By studying how and in what situations students would be using the device, I designed its layout and feel to create an interesting as well as educational model. Coloring of the components and subassemblies also had a great deal to do with the design language of the device. An effective functional design without good industrial design would have been a failure. Because of the situation in which this device was being used, aesthetics and human factors became a major contributor to its final appearance.

### 2.6.1 Aesthetic Shapes

The shapes of the components in my device were designed with the intention of grabbing attention. There were several functional aspects of the design, but once the functional elements of the parts were satisfied, the rest of the design depended on creating a design language and creating a specific impression. There were several areas that each had specific requirements and functions. These included the supports, the carriage tablet, the velocity masses, and the pen.

The supports of the device include four pieces that hold the rest of the machine up. The basic design language I wanted to convey was that of stability yet gracefulness. I decided to use an arch as the basic design element to build upon. I design the parts with this common design language in mind yet added elements specific to each piece. The circular endplates on the motor were designed to be the same diameter as the motor endplate. When the motor was mounted on the supports, it had the appearance of resting on the supports. This helped to make the motor stand out rather than be hidden in the design.

The carriage tablet was designed to be very elegant yet sturdy. The tablet holds a board to which I can attach Post-It Notes. This makes it very simple to draw a graph to show people. Then the student could take off the Post-It Note to keep for future reference. The cylindrical shapes on the carriage that hold the linear bearings are similar to the top mounting bracket that hold the two steel shafts.

The masses on the velocity meter were designed to be sleek but also large enough to grab the attention of a student. These masses must stand out so that the velocity mechanism is easily seen. The image of spinning masses is very real for most students, and this device is effective in that. By having the steel linkages not colored and very thin, the masses tend to feel like they are almost floating and are not attached to anything.

The pen is attached to the velocity meter through a bearing so that the pen moves laterally with the velocity meter, but does not rotate with it. The angular linkage is used to set it apart from the rest of the device which is laid out orthogonally. In this way, the shaft of the motor and the linear shaft guides for the carriage are perpendicular. The pen was also built so that it can rotate on its bearing down off the tablet in case the student does not want the device to draw.

## 2.6.2  Coloring of Modules

In order to effectively design the device to be educationally clear to the students, color was incorporated as a crucial design element in the device. An anodizing process was used to color the aluminum pieces. Because the torque meter and the velocity meter are the main elements of the device, I felt that they should have very different colors to separate visually. The carriage piece of the torque meter was anodized blue and the velocity meter pieces were anodized red. The support structure pieces were colored black. This anodizing not only made the model look nice, but also served an important function of separating functional elements in the design.

## 2.6.3  Human Factors

The human factors design had some affect on the layout of the device. Because of many of the other design decisions already made, I designed with the philosophy of form follows function. With the layout of the device shaped similar to the axes of a graph, the grip of the motor shaft was placed at the right end of the model. This was more convenient for right handed users, but due to the simplicity of the act of grabbing the shaft, would not be awkward for left handed students. Also, because this device would be used in front of a classroom as a demonstration device as well as a device that an individual student could use, the tablet was angled at a 45° so that it was easy to see. The motor was positioned below the carriage with the governor to the right as these were the parts of the model on which the student should focus most.

The other area of the model that the human factors affect most was the gripping mechanism. The way the student physically interacts with the device was important so that it was completely obvious what the student should do. Also, the tactile feedback of being able to intimately interact with the device was important to how the student learns. In my device I decided on a long thin grip so that a student could use their entire hand to grab the piece. I did not want the student to be able to stop the motor too easily, so the gripping piece was designed thin enough to require a fair gripping force to stall the motor.
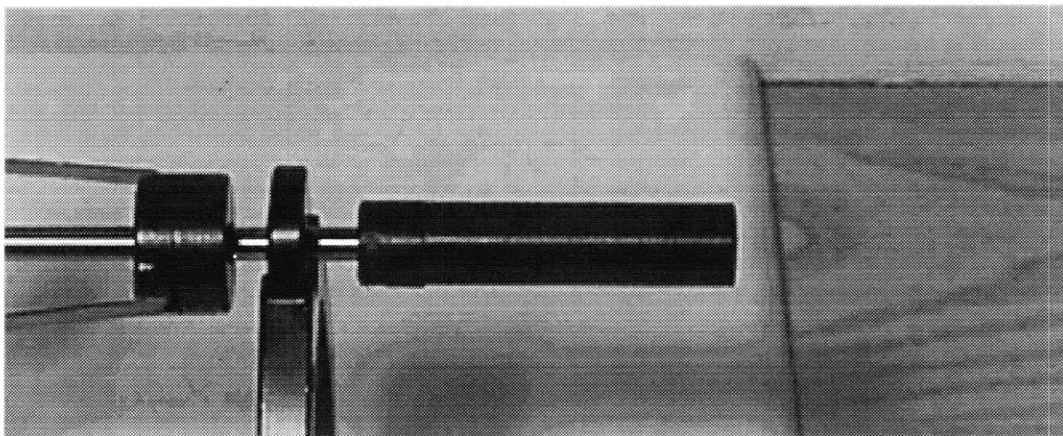


Figure 2.19: Gripping Piece

## 2.7 Further Features

There were several design features in my mechanism that I want to highlight as interesting elements of mechanical design. While they were not central to the theme of the device, they were essential to the working and performance of the mechanisms. While there are a number of interesting design features that came out of this device, I focus on the most interesting of them.

### 2.7.1 Damper

The device is a dynamic model with several moving parts. The mechanisms involved moving masses, springs, and structural elements. Because of this, the model, on a first order glance, contains two major second order systems. This requires that attention be given to dynamic responses of the system so that there isn't any instability when it runs. In order to control for the second order system response and behavior, a damper was added to the velocity meter. This damper is in the form of an Airpot, a dashpot made from a glass cylinder housing a graphite plug. The damping occurs by resistance to airflow controlled by a screw adjustment. This damper was mounted right below the motor on the motor mount structures and was connected to the sliding piece on the velocity meter. By having this damper on the mechanism, a student can adjust the response of the mechanism to take care of any resonances while still allowing for a fast response time.
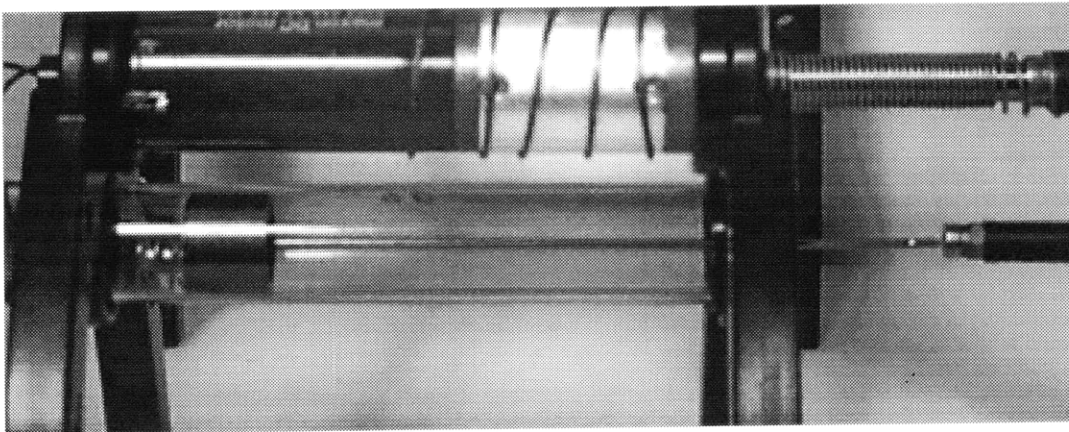


Figure 2.20: Airpot Adjustable Damper

### 2.7.2 Rotation Limiter

The rotation limiter was a mechanism that I conceived of to improve the response of the torque meter mechanism. This limiter negated any possibility of overshoot in the dynamic response of the torque meter. By limiting the rotation of the motor, there was no possibility of overshooting so that the cable would unwind. Also, depending on the torque of the motor and the strength of the spring, it limited the winding of the cable. This limiter also acted as a safety feature for the device to ensure that over curious students would not start turning the motor with their hands and over stretch the spring or unwind the cable. See Figure 2.6.

### 2.7.3 Safety Shield

Because of the high speed at which the governor spins, it was necessary to build a safety shield around the governor. This was to ensure that in case one of the linkages or one of the joints failed, the governor pieces would not fly out and injure a student. Also, the shield keeps students from sticking objects into the spinning governor. The safety shield consisted of a plexiglass cover bolted down to the base.

## 2.8 Other Design Issues

In this device, the DC motor is run in the entire range of states from no-load free running to stall. Because of this, there are issues with overheating due to drawing too much current at stall. Because machines are generally designed to run the motor near peak efficiency which is about half the no-load speed and half the stall torque for this DC motor, this device has some additional problems that could occur. In the device, it was advised not to stall the motor out of too long so that the motor would not burn out.

## 2.9 Design Revisions

This design, as in any design, had several areas of revisions in order to improve performance or in response to students' input. I was able to implement some of the revisions, but there are several that I did not have time to address. These are mentioned as recommendation.

### 2.9.1 Shaking of Velocity Meter

Initially when I built the device, there was a fair amount of shaking of the velocity meter that eventually translated to wobbling of the pen as it drew the curve on the tablet. The wobbling of the pen was a result of several things. I analyzed the device to determine the causes of this. Some of the areas that could have caused error were

1. Masses being slightly different weights
2. Linkages being slightly different lengths
3. Hinges between the masses and linkages being wobbly
4. The motor shaft being bent
5. The motor shaft not being centered accurately
6. Misalignment of the sliding piece

The masses were every close so probably wasn't the cause of the large amount of wobble. The linkages were rechecked and adjusted to ensure that they were very close in length to each other. I replaced some of the bearings in the hinges from bushings to ball bearings. The sliding piece had a fair bit of angular wobble because it was a linear bearing. This piece was lengthen by adding a bushing so that the angular wobble was less. I rechecked the motor shaft to ensure that is was straight and centered properly. Once I had done this and reran my device, it came out to be much better in terms of shaking and drew a much straighter curve.
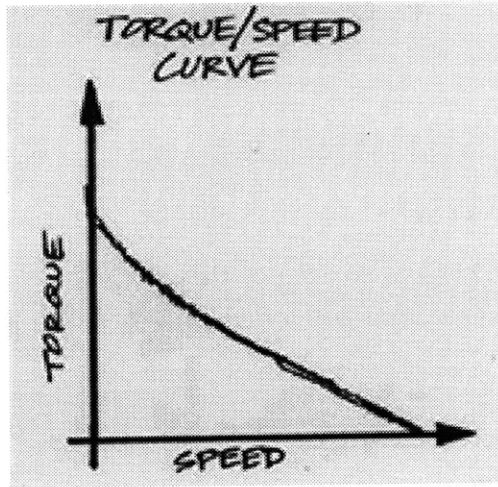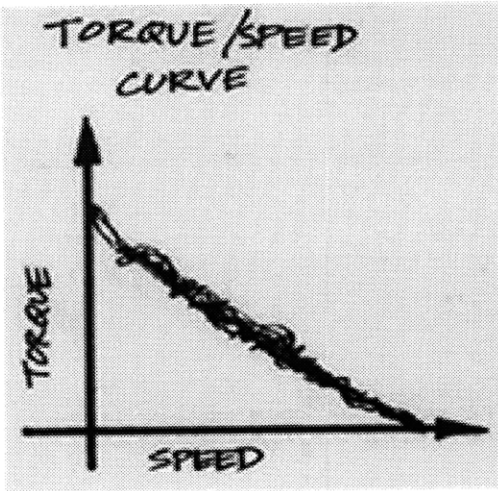
Figure 2.21: Before and After Curves of mechanical Device

# 3 DESIGN OF COMPUTER SIMULATION

## 3.1 Overall Purpose

In order to compare the effectiveness of various media in teaching engineering principles, I also created a computer simulation of the mechanical device that I had designed. By comparing how students learn and react to a computer simulation of a physical model, a better idea of how the use of computers and the internet could affect learning and teaching can be studied.

In order to create this simulation, I wanted to create, as accurately as possible, a computer replica of the mechanical device that I had designed. I wanted to have an interactive simulation where a student would be able to simulate grabbing the motor shaft to slow it down. A mouse slider bar was incorporated that would allow the student to adjust the grabbing torque of the motor shaft.

The design criteria was to create a realistic model replica of the mechanical device. While this approach may not prove whether there is a better way to teach torque/speed curves to students on a computer, I was just measuring how effective computer simulations where in modeling.
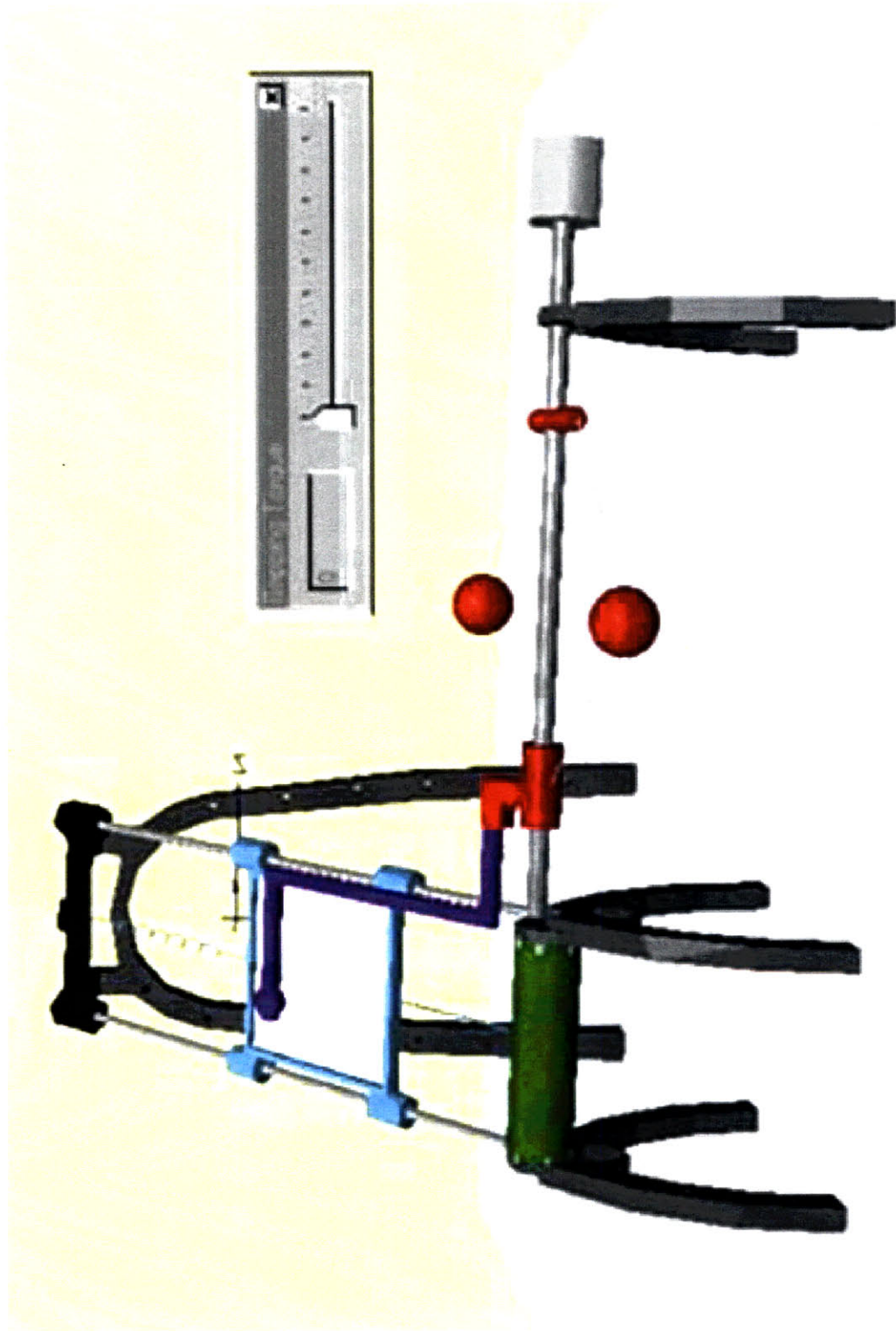
Figure 3.1: Computer Simulation

## 3.2 Initial Approach

In creating this simulation, I brainstormed through various criteria and methods of how to most effectively design the system. I first had to decide what tool I would be using to create the simulation. Initially, I wanted the simulation to be on the internet. I considered making a flip book of various images of a drawing of my device. I would then flip through the different pictures depending on what image was needed. I started drawing some two-dimensional pictures on Adobe Illustrator, By changing each drawing just slightly, a semblance of a choppy video of the different states that the devices runs through as the student grabs the motor shaft was created. After starting on this, I realized that this method would be fairly poor in quality as compared to the mechanical model. This not only had to do with image quality and realism because it was just a two-dimensional image, but also because the simulation was just a flip book of various images. I felt that if I continued to follow this style of simulation, I would not be doing justice to computer media.

In order to ensure that some reasonable data was gathered to compare the two different media done equally well rather than one done poorly. Because of this, more realistic animation and modeling programs where looked into to build my device. Because my mechanical model was built fairly well, I wanted to find a computer simulation program that was equivalent in quality. I decided to find the best software package for computer simulation for normal desktop PCs. After some looking around, I found Working Model 3D from Knowledge Revolution.

The computer simulation was run on a Dell PC with an Intel Pentium II processor running at 366 megahertz. This computer has 128 megabytes of RAM. When the computer was purchased, it was one of the fastest desktop personal computers on the market.

## 3.3 Working Model 3D

Working Model 3D is a three-dimensional dynamic simulation program with advanced motion simulation technology and animation and rendering capabilities. In this software, a user is able to create different sets of rigid bodies and constraints between them to build a mechanical model. From there, actuators can be implemented to create a dynamic simulation of a mechanical model with realistic physical properties in effect. This software also has the ability to import CAD models of parts to use in the simulation. Because of this I was able to import my ProEngineer models so that my simulation mirrored my actual device as realistically as possible. From the demonstration models that were included in the software, I concluded that this software was as advanced as any simulation and animation package on the PC market.

Using this software package, I designed the computer simulation to be as close to the physical model as possible. a similar coloring scheme was followed. In the computer model, I had to address the issue of how a student would interact with the device to simulate grabbing the shaft of the motor in the mechanical model. I decided to have a mouse slider input bar that the student could control. This slider bar controlled a resisting torque to the motor shaft, which is essentially what the student does in the physical model.
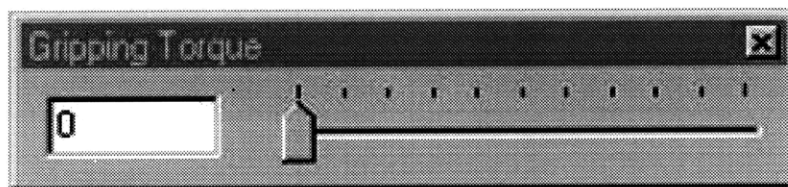


Figure 3.2: Mouse Slider Bar from Computer Simulation

The modeling of the computer simulation was fairly simple because it was just a copy of my mechanical model. This eliminated the need to redesign an entirely new simulation. I ran through several tests on the simulation until I was able to get an interactive animation of the model that performed fairly well. In the final version, there was an input mouse slider bar that allowed a student to control the simulated gripping of the motor shaft. As was discussed earlier in the matrix of devices, this computer

simulation has computer input and computer output.

## 3.4 Rendering/Computational Issues

In designing the computer simulation, there were several issues that needed to be resolved in order for the animation to be accurate. All of these were due to the limitation of the computer or the software package themselves. While there were no absolute limitations in creating a dynamic model of my device, there were user issues that dealt with how fast the simulation ran. These included difficulty in creating a non-rigid body such as the cable, collision detection and simulation computational time, and the software refresh rate.

The physical model has a flexible cable wraps around the motor body. In Working Model 3D, there are no flexible elements that can be created. Because of this, I initially made the cable from many small elements connected to each other with a hinge element. Upon doing this, the numerous small elements became a large computational sink for the computer and eventually, the computer ran extremely slow. It was so slow that it became intrusive to the user running the simulation. In order to solve this problem, I eventually had to mimic the motion of the cable wrapping around motor without actually simulating the cable. This mimic was implemented by having the motor rotate independently from the motion of the carriage. Visually, the effect was exactly the same, but computationally, there were fewer elements for the computer to simulate. This helped to make the simulation run faster.

Collision detection and simulation was a similar problem to the non-rigid body problem. In this, there were other areas where the computer was calculating numerous collisions and interactions between moving parts on the model. In order to reduce this, I created relationships between the motions and degrees of freedom of bodies without actually simulating the exact physical model interactions. Again, visually, the simulation looked exactly the same, but the computation time was reduced allowing for a faster simulation and animation in real-time.

Finally, because the software refresh rate was somewhat slow, the motion of the governor became very choppy if run at high speeds. Because of this, the governor speed was slowed down in the simulation to make the governor's spinning clearly visible in the

simulation. By doing this, the computer model was somewhat different from the mechanical device. While the speed was slower, the relationship between speed and torque was still preserved.

# 4 DESIGN OF EXPERIMENT

With the mechanical model and computer simulation running, I had to design an experiment to determine how each model compared as an educational tool. Because I was trying to determine different factors that affect how various media perform as teaching aids, I needed to come up with an experiment to judge how students reacted to each model.

In addition to these models, I wanted to compare both to a control. For the control, I found some old lecture notes from an MIT class 2.671: Measurement and Instrumentation in which we covered torque/speed curves in lecture and as part of a laboratory experiment. I decided to use the physical model, the computer simulation, and the control to compare how effective each was in teaching the principle of torque/speed curves.

In order to run these experiments effectively, some pilot studies were run of different students of varying background and expertise to get a feel of how the students should be run through the varying devices. high school students taking some form of advanced physics were mainly used.

Once I had determined my student group, I devised a protocol to keep the experiment consistent between the various devices. In this way, the experiment could be kept fairly accurate in terms of how the students were addressed.

# 4.1 Background of Testers

In getting people to run through my experiment, I decided to get students who had not ever learned about torque/speed curves, but have some technical aptitude. I chose some advanced high school students as my main group.

## 4.1.1 Local High School Students

I decided that for a first test, it would be interesting to get the response from students who what not yet learned about torque/speed curves, but may be interested and aiming towards a technical field. To do this, I contacted John Samp, a physics teacher at the Cambridge Rindge and Latin High School. Mr. Samp teaches A.P. Physics and an Intensive Physics class which had students who had not learned about DC motors and torque/speed curves, but were more advanced in the sciences.

## 4.1.2 MITES Students

MITES (Minority Introduction to Engineering and Science) is an MIT sponsored summer program where minority high school seniors from around the country come to study and do research in the engineering and sciences. I contacted Mr. Karl Reid, the coordinator of the MITES program to do a demonstration of my device for the students. The students all had to apply to be admitted to the program and are of high academic caliber. Part of the MITES curriculum consists of a three week long design contest in which students participate in a "mini-2.70" contest. In this, they will be using motors to drive vehicles in a contest. I worked with Diane Brancazio to set up this experiment with the students.

# 4.2 Protocol

The protocol that I decided upon was a result of various pilot studies on students and from feedback from colleagues. From talking with professors who taught 2.007: Introduction to Design, there were many students who reportedly didn't understand torque/speed curves well enough to use motors effectively in their designs. In order to help address this problem, I decided to create an experiment using a real life example. After thinking about multiple choice tests and other experimental protocols, I decided on a scenario format.

## 4.2.1 Scenario

Initially, I asked whether the student understood what torque was. This gave me an initial starting point so that I would have a better understanding of each student's background knowledge. From here, I started my scripted scenario. In the scenario, I read them a script of a situation and give them this information

Pretend that you are in the 2.007 class and are supposed to build a robot car using a motor to drive the wheels of the car. The car that you build may have different devices on it that add weight to the car. The track that the car drives on my also have some inclines and hills on it. You are to connect the wheel directly to the axis of the motor. Upon getting your kit of parts, you hook your motor up to electrical power and record the motor speed as 1 revolution per second. You decide that you want your car to drive at approximately 1 foot per second. Can you tell me how you would go about designing the wheels of the car?

In my experiment, I gave them this scenario to answer. Then I let them run through one of the models – either the mechanical, computer, or the control. I then asked them to recheck their answer to see if there was anything that they should add or would need to take into account. From this scenario, I hoped to be able to record the students'

before and after understanding based on each model, and also a comparison of learning between models.

In the scenario test, I purposely led them to an easy calculation answer that resulted in them answering that they would design the circumference of the wheel to be equal to 1 foot. I did not ask them to necessarily give me a numeric answer, but more of an explanation of what factors they should consider in the design of the wheel. I made sure I emphasized that the vehicle had weight, the course might have inclines, and that there would be friction or rubbing of the wheels on the ground.

For this initial question, the answer that I looked for would be to first calculate the circumference of the wheel to be related to the linear speed of the vehicle and the rotational speed of the motor. Then by stating that this would be a starting point to design from, and from there, take into account other factors such as mass of the vehicle and friction. This would affect the wheel size design because initially, when the motor was tested, it wasn't applying any torque.

The initial starting point calculation of understanding that the circumference of a wheel spinning at 1 revolution per second on a vehicle that travels at 1 foot per second would equal 1 foot was used to start to classify students. I used this initial understanding of relating linear motion to angular motion to give an initial rating of analytic or problem solving aptitude. I rated the students' performance in solving this first problem on a scale of 1-5.

| 1 | Student guessed and made no calculation. Then even with help with pictures and suggestions, they could not get the correct answer or even understand the answer. |
| 2 | Student needed lots of help and suggestions to get the answer, but after a fair amount of time, was able to understand the answer. |
| 3 | Student needed a some help, but was then able to get it on their own given the initial suggestions. |
| 4 | Student took some time to get the answer, but needed very little help. Needed to write the calculations and figures out. |
| 5 | Student was able to answer the question immediately with little time. Did not need to write calculations or drawings to get the answer. |

Figure 4.1: Table of Student Initial Performance Rating

Once I had gotten the answer from the student, I ran them through one of the models.

### 4.2.2 Models

#### 4.2.2.1 Control

The control model for my experiment was given to the student after answering the initial scenario test. This model consisted of a text description of DC motor torque/speed characteristics and a picture of the curve. See Appendix 9.3.1. the description was written based on some text books and lecture notes from the MIT mechanical engineering class 2.671: Measurement and Instrumentation. I modeled the control description after what I remembered being given as an undergraduate student. In this control, students are given a verbal or written explanation of the torque/speed curve relationship, but are not given any real model that relates what they just learned.

For the students who were given the control model, I allowed them to ask me questions based on what they read and would explain in scientific terms anything that they did not understand. This control group is essentially modeling students who are presently learning about torque/speed curves in their classes. There were 21 students in the control group.

#### 4.2.2.2 Mechanical Device

The mechanical device was presented to the student after giving them the scenario test. For the mechanical device, I initially explained some of the component parts of the mechanism including the motor and shaft. Then, I immediately turned on the device without any explanation of how the device works or even what is does. The only other information that I gave the student was to allow them to grab the shaft grip to slow down or stall the motor. If they had any questions about the workings of the mechanisms, I would answer them as long as it didn't give away when the device was measuring. After the student had played with the device and drawn the torque/speed curve several times, I then stopped the motor and drew the x and y axes on the graph. I then asked them what they thought the axes represented or measured. If this was done successfully, I then asked them to explain to me what they thought the graph showed and what it described about

70

the motor as it ran in different positions. There were 44 students who tested the mechanical device.

### 4.2.2.3  Computer Simulation

The computer simulation was also given to the student after they were given the scenario test. When I showed the computer screen to the students, I showed them the mechanical model, but did not turn it on for them. This was just to allow them to see the motor and some specific pieces on the device a little more clearly. This is because the computer simulation was not very detailed. I explained to the student that in the real model, the student is generally allowed to grab the motor shaft to slow or stop the motor. I did not demonstrate this but just explained the idea to them. I then showed the student the mouse slider bar shown in Figure 3.2 and explained that this performed the same function as grabbing the motor shaft. Once this was explained, I turned the simulation on and let the student manipulate the mouse slider bar to see the effects of grabbing the motor shaft. Once the student had simulated the device drawing the curve several times, I showed them a picture of the torque/speed curve – without labeling the axes – and asked them if they could tell me what the axes were measuring. I followed the same procedure as I did with the mechanical model for the simulation to keep the experiment consistent. There were 23 students who tested the computer simulation.

### 4.2.3  Questions

After the student had gone through their model, I asked them if they could tell me how the information they just learned affected their previous design of the wheel on the vehicle. This was done to try to find out what they had learned from going through the models. For the control, after the student finished reading the sheet, I asked if the student had any questions about the sheet. I then probed their understanding of the graph by asking them to describe to me what the torque/speed curve represented – using their own words. For the computer simulation and mechanical device, I again asked them if they had any questions and probed them about the torque/speed curve that the models had

drawn. This was done to get them to actively explain what they were observing in the models – not just see the model and not think about it.

Then, I brought up the question about the wheel design and asked if what they just saw in the models affect how they might approach the problem again. When doing this, I reiterated that the motor was tested with nothing attached to the shaft and was freely spinning. Also, I reminded them that the vehicle may have mass and the wheels would have to be driving on the ground – which may have different slopes or surfaces. After this, I waited to see how they responded.

The answer that I was looking for was an explanation that because the motor was initially spinning without any load attached to it, it was supplying zero torque, and therefore was operating at its maximum speed. Then, by explaining that the motor, when attached to the car, would be applying some torque to drive the car and overcome any friction or forces, the speed of the motor would decrease from the initial 1 revolution per second. It was this understanding of the tradeoff between torque and speed in the motor as shown in the torque/speed curve, for which I was looking.

I again rated the students on their understanding after this discussion on a scale of 1-5.

| | |
|---|---|
| 1 | Little or no understanding of the motor torque/speed tradeoff and how it would affect the vehicle – even with hints and suggestions. |
| 2 | Some understanding of the tradeoff, but with many hints and suggestions but not completely grasping the concept and its effects. |
| 3 | Concept fairly well understood. Need some guidance but generally understanding the concept. |
| 4 | Understand the concept, but need some time to figure out. Maybe some hints, but was partially thinking through the concepts themselves. |
| 5 | Well understood. Quickly seeing the effects of this tradeoff in the wheel design. Often with zero or very little guidance. Sometimes, students would actively catch their own mistake on the initial problem without me asking. |

Figure 4.2: Table of Final Understanding of Concepts

## 4.3 Evaluation

Using the rating from the initial aptitude test, the rating from the final understanding test, and the classification of which model the student used, some correlations between the factors were found. The initial aptitude test was done to get a basic understanding of the skill level and knowledge of the students. Also, this served as a check to ensure that the student groups for each of the three models were approximately equivalent in term of average initial skill.

# 5 RESULTS OF EXPERIMENT

From the data that was collected from the students there were several interesting trends and advantages and disadvantages between the various models. Using this, a better understanding of education and learning can start to be formed in how media can assist in teaching students about engineering principles.

Given the fairly small sample size, the qualitative comparison between the students' performance, and the difficulty in assessing all the information into useful deductions, I propose these experimental results to be only basic trends in the data that suggest the usefulness of further research. In no way are my results a final judgement on media education comparison, but are a first step towards formulating some initial hypotheses regarding how engineering might be taught better.

## 5.1 Initial Analytical Aptitude Test

In my experiments, each student was rated on a 1-5 scale based on how they answered and approached my initial question on wheel sizing based on linear speed and rotational speed. A histogram of how the students faired is below.

**Histogram of Initial Peformance**
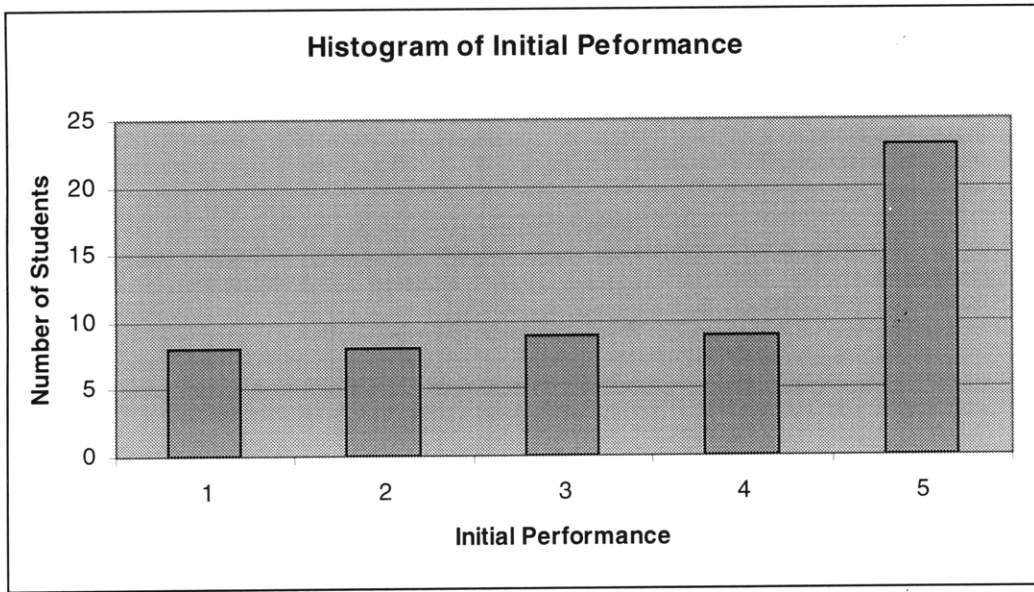
Figure 5.1: Histogram of Students' Initial Performance

From the graph, many of the students were able to get the answer immediately with a score of 5 with a smaller number of students performing at each of the other levels.

In order to insure that there was not any bias in the initial level of students being tested with certain devices, I made a graph of the average performance of students that went through each device – the control, the computer simulation, and the mechanical device.

**Student Group Comparison**

| | Control | Computer Simulation | Mechanical Device | All Groups |
|---|---|---|---|---|
| Series1 | 3.714285714 | 3.409090909 | 3.384615385 | 3.553571429 |

Figure 5.2: Student Group Comparison

As can be seen from the graph, the performance, when I randomly assigned which students would study which model, was fairly equal between the models. From this, it can be seen that at least initially, there was no bias towards aptitude level of students from one model to another.

## 5.2 Comparison of Media in Understanding

For the first order comparison of how students performed on the scenario question, a graph was made simply comparing the average score that students got after going through either the control, the computer simulation, or the mechanical device. This gave an initial impression of how effective each model was at teaching the student about DC motors and torque/speed curves.

**Comparison of Understanding**

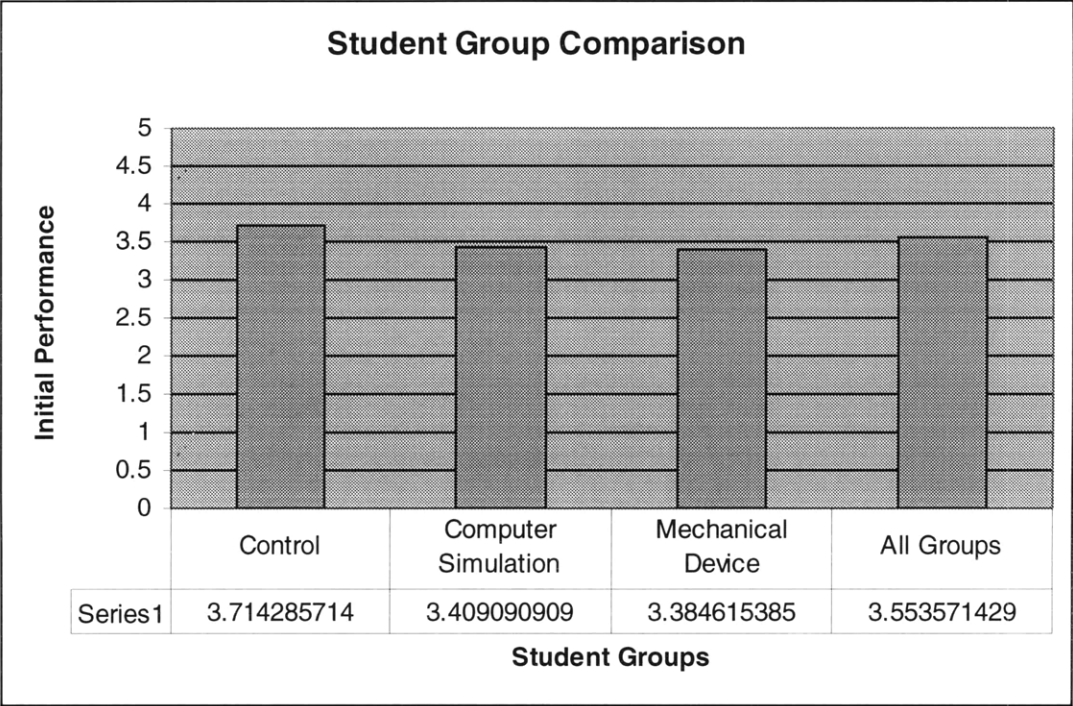| | Control | Computer Simulation | Mechanical Device |
|---|---|---|---|
| Series1 | 2.095238095 | 2.434782609 | 3.615384615 |
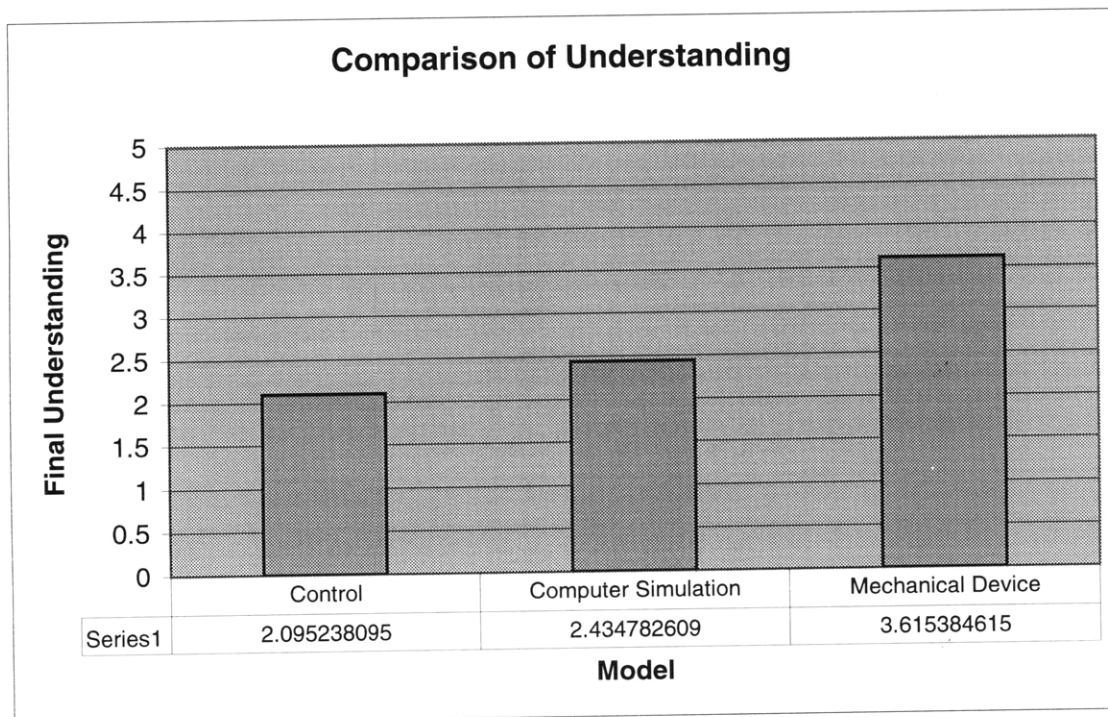
Figure 5.3: Final Comparison of Understanding Between Three Models

As can be seen from the graph, in the control experiment in which a student was given a written description of the torque/speed curves – similar to present classroom instruction style, the students had an average understanding of a little over 2. The computer simulation was an improvement over the control with a score of about 2.4. The mechanical device had the highest understanding average of over 3.6. This brief overview shows that the two teaching devices were both more effective than the control with the mechanical device being significantly higher. While this experiment is not a final

judgement on how students should be educated, it is a good indicator that something can be improved in the way we are presently teaching engineering principles.

To get a more detailed view of how specific aptitude students performed on the test based on which model they used, I plotted another graph that showed the students' final understanding of motors and torque/speed curves as related to type of model and initial performance aptitude.

# Comparison of Understanding for Student Groups



| | Initial Performance 5 | Initial Performance 4 | Initial Performance 3 | Initial Performance 2 | Initial Performance 1 |
|---|---|---|---|---|---|
| ▦ Control | 2.5 | 2.25 | 2.5 | 1 | 1 |
| ■ Computer Simulation | 3.8 | 2.25 | 1.5 | 1.667 | 1 |
| ☐ Mechanical Device | 5 | 4 | 3 | 2.667 | 2 |
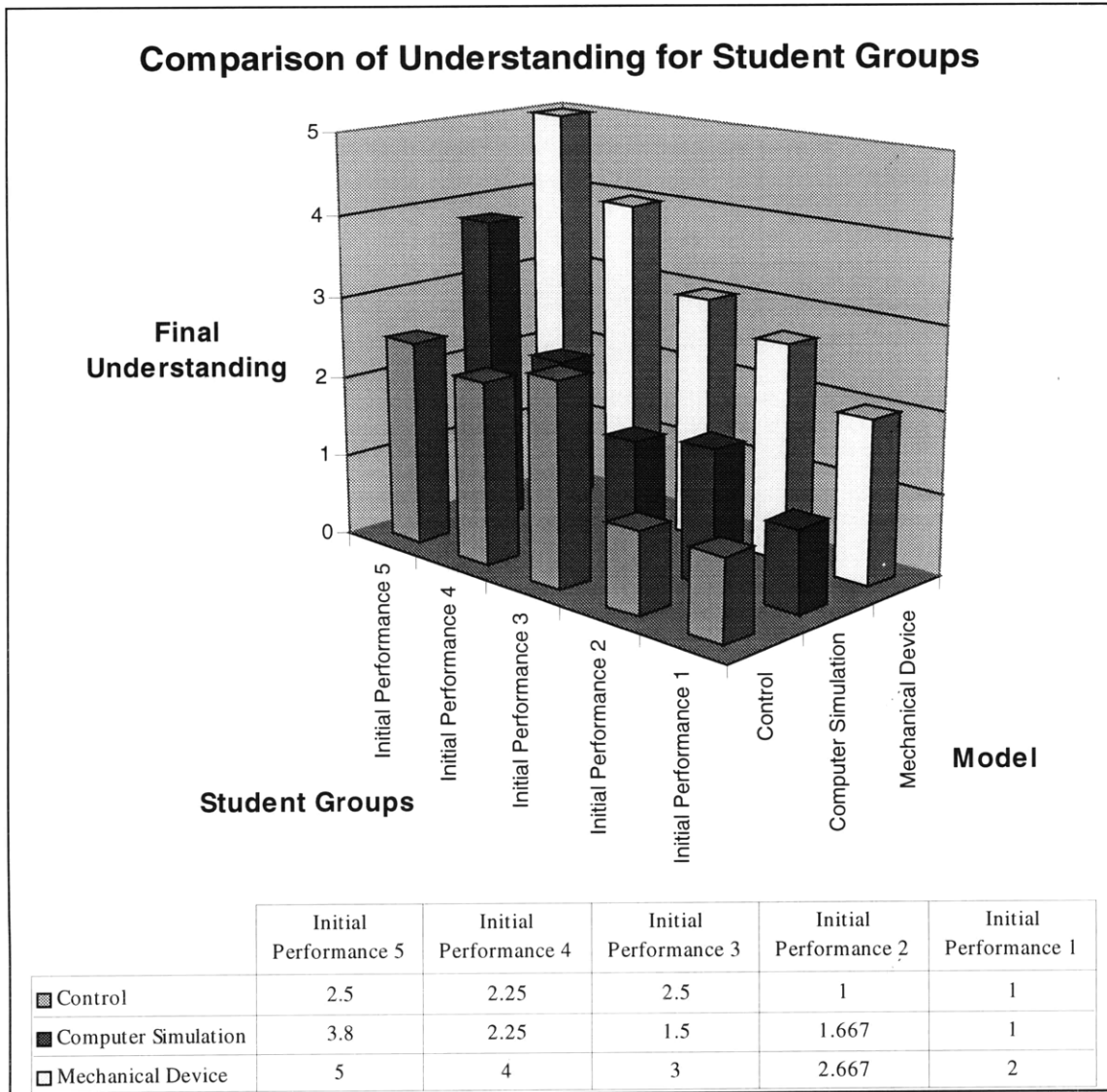
Figure 5.4: Comparison of Understanding for Student Groups

As can be seen from the graph, general trend lines can be seen based on the figure. This shows an increase in understanding as the initial performance aptitude increased as well as the model effectiveness that the previous graph showed. Due to the small number of samples that I was able to test in the experiment, the error in this graph would be fairly high. I made this to just get a feel of any trends that might come out from the experiments.

## 5.3 Discussion of Results

The results of the experiment revealed a number of interesting observations on how students learn. Also, in addition to comparing the various media in teaching effectiveness, I also was able to get feedback on how to improve each model in terms of aesthetics, human factors, and functionality. Methods to improve the effectiveness of the devices will help in planning future educational methods.

The first and most important observation from this experiment was the greater effectiveness of the models when compared to the control in terms of the students' understanding the principles involved in the torque/speed tradeoff. As was seen in Figure 5.3, the students' level of understanding was greatest after using the mechanical model. The computer simulation was next, followed by the control. While the experiment didn't have a large number of samples and the criteria for judging understanding was qualitative, I feel fairly confident that there was some level of improvement when the students used either the mechanical or computer models.

Next, one can also observe a correlation between analytical skill and performance. As can be seen from Figure 5.4, as the initial performance of the student in answering the aptitude calculation increased, their understanding of the torque/speed scenario also improved. In this graph, because of the larger number of groupings, the small number of samples greatly affected the validity of the graph. Even with this, I feel that the trend shown is somewhat accurate. Also, aside from one performance group, there was an increase in understanding when going from the control to the computer and mechanical devices. Given a large sample size for the experiment, a more accurate trend graph could be modeled.

Finally, more qualitative results were found just by observing the students and their interaction with the devices and their feedback. Seeing their reactions to various models and the different functions gave me some valuable insights on how to go about improving my devices.

## 5.4 Input on Mechanical Device

The mechanical device received the most optimistic reviews and comments from the students. There were several things that could definitely improve its performance in terms of helping students learn. The most commonly heard praise for the device had to do with the hands-on aspect of the model. Many students mentioned that just being able to feel the motor in their hand allowed them to gain a better understanding of the physical characteristics of DC motors. Some mentioned that even without the mechanisms that drew the graph, just having a motor to play with is in itself helpful. One student also mentioned that the sound of the motor also helped her feel more in tuned to the motor. Other comment heard involved how the device was "cool." The bright colors and interesting shapes seemed to draw many observers who just wanted to see what the device was. Several of the students who seemed more inclined towards design and mechanical engineering were also very complementary about the mechanisms that made the machine work.

There were several improvements that I received directly from the students or that I came up with by observing students' interaction with the model. One improvement was a switch that would allow only the torque sensor or the velocity sensor to work at a time. By decoupling the motions, many students felt that the machine would be easier to understand. After the student understood each mechanism, they could then superimpose the motions to get the entire torque/speed curve. Another improvement that was discovered after presenting my device to an audience was to create a different model for different settings. For example, one version could be used primarily for students to use individually. Another version could be used in a large lecture hall where the lecturer might be able to project the drawn torque/speed curve through an overhead projector. Another could be used as a permanent display. These improvements would help to improve the teaching effectiveness of the mechanical device.

## 5.5 Input on Computer Simulation

The computer simulation also received positive comments from students, but usually with some suggestions along with it. Most students liked the computer simulation, but thought that it ran too slowly. Also, the detail in the animation limited their understanding of exactly what was going on with the mechanisms. Most students said that they could definitely see how the computer simulation could be very effective if there were improvements. The mouse interface limited how well the students felt they could interact with the model. Also, adding sound to the animation would help and make it more realistic and enjoyable. While most of the negatives had to do with limitations with the computer's computational speed, most students said that they could definitely see a more realistic animation – like in movies such as Toy Story – could probably be almost as effective as the mechanical model without the haptic feedback.

One aspect of the computer simulation that was not addressed in this thesis was to design an educational model completely around the computer's advantages. In my thesis, I just modeled the computer simulation after my mechanical model. Further research would most definitely find a better simulation to explain torque/speed curves that did not follow a mechanical device, but took advantage of a computer's capabilities.

# 6 BACHELOR'S THESES

In order to fill out the matrix of devices that I wrote of earlier in the introduction, I helped to oversee three bachelor's degree thesis students in mechanical engineering. My thesis involved devices that had physical input and output, or computer input and output. I was also interested in combinations of these to study how a device's input and output changed the way students learned. In order to do this, I decided to have a device that had physical input but computer output. I wanted to allow a student to be able to physically grab the spinning shaft of the motor. But instead of having a mechanical mechanism drawing the torque/speed curve, a torque sensor and velocity sensor would electronically read the values and plot these on the computer screen. The other combination consisted of computer input but physical output. This was accomplished by allowing a student to use a mouse slider bar to control the grabbing force on the motor shaft. This slider control would then be connected to an electromechanical brake that was physically connected to my original mechanical device. This could be done in a way that a student could be seeing a video of a remote mechanical device and control the device through the computer.

In order to accomplish this, I helped three bachelor's degree students to get these other modules built. One student was in charge of building the torque and speed sensor module. The second student was in charge of building the electromechanical brake. The third student was in charge of the computer interface between the sensors and the brake using an A/D board and Lab View as the software.

## 6.1 Torque and Speed Sensors

The student that I helped in building the torque and speed sensor module was Fabio Brunet. In his thesis, he built a motor module stand that housed a torque sensor using strain gauges and an rpm sensor using an infrared transmitter/receiver unit. In his device, he designed and built the module using basic sensor elements rather than prepackaged components. This allowed for a cheaper design, customizable sensor values, and much more engineering learning and experience for him.

For the torque sensor, semiconductor strain gauges were mounted on a thin aluminum cantilever beam. This beam was mounted on the DC motor which was itself mounted on bearings. In this setup, as in my mechanical device, when the student grabs the motor shaft, the counteracting torque tends to make the motor body spin in the opposite direction. Because the cantilever is constrained from rotating, the torque reaction of the motor body is translated to bending of the cantilever beam. With the strain gauges mounted on each side of the beam, the stain on the beam can be measured through a Wheatstone bridge by measuring changes in resistance though the gauges. Knowing the geometry of the aluminum beam allows us to convert the resistance to stain to deflection of the beam to reaction torque. This allows us to measure the torque that the motor is applying.
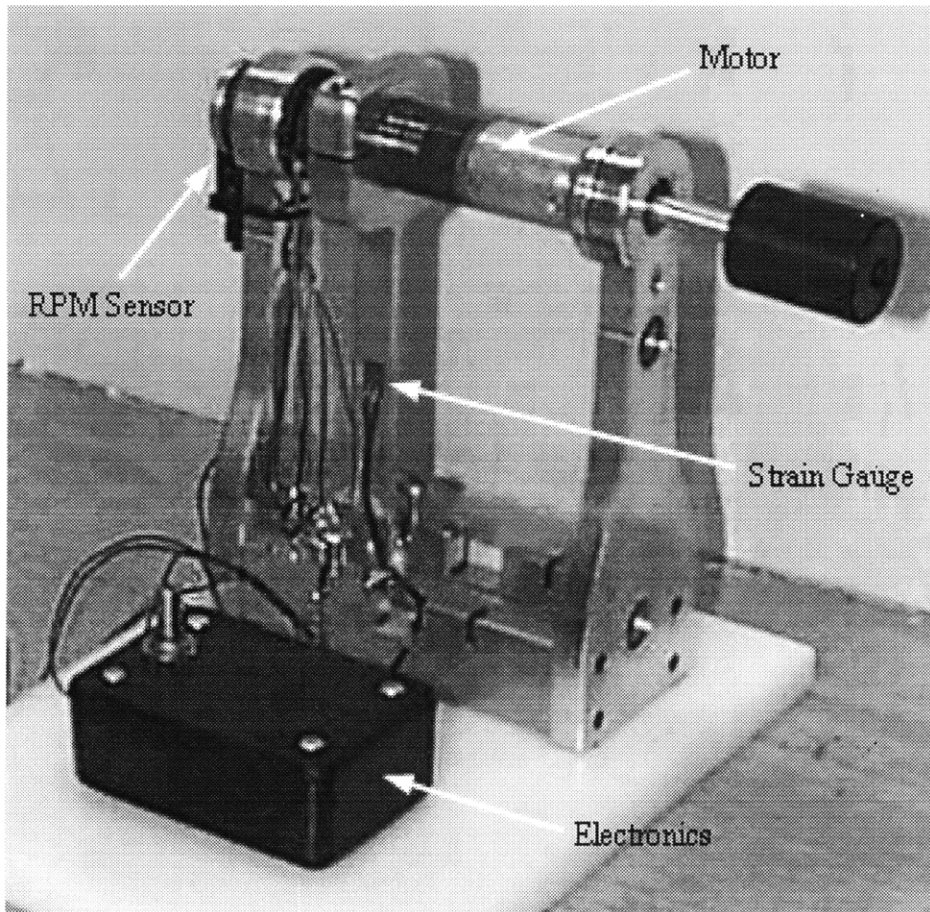
Figure 6.1: Torque and Speed Sensor Model

For the velocity sensor, an optical sensor was used as an interferometer. By mounting a disc with slits cut into it onto the motor shaft, reading could be taken by counting the number of slits per unit time as the motor shaft spins. By knowing this and the number of slits in the disc, the rotational velocity of the motor shaft can be calculated. For this module, the infrared unit was mounted to the supports and with the disc passing between the sensor's emitter and receiver. This allowed the rotational velocity of the spinning motor shaft to be measured by just counting interruptions of the sensor by the disc per unit time. From this, the instantaneous velocity of the motor shaft could be read.

These two sensors were attached to a motor mount as a stand alone module with which a student could interact. The signals from the sensors, both of which are analog, were then sent to an A/D board in a computer and read with Lab View software. This computer interface was set up by Indran Ratnathicam. With this setup, a student could

then grab the shaft of the motor to slow it down or stall it and see the torque/speed curve being plotted in real time on the computer screen.

## 6.2 Electromechanical Brake

The fourth and final module of the matrix of devices involved having a computer input and a physical output. In order to do this, there must be a computer interface that the student uses to control the physical device. This was done by building an electromechanical brake connected to my original mechanical model. Ania Mierzejewska was the undergraduate student working on this device. In this device, a motor was used to drive a gripping device. By controlling this device through a computer so that the brake is attached to the mechanical model, the student is given a computer input and a physical output.

The actual design of the electromechanical brake uses the principle of a lead screw to draw two rubber brake pads together to form a frictional interface. The rubber brake pads are spring loaded to allow for a greater range of braking forces over a large distance making it easier to control. The brake would be acting on a disc attached to the motor shaft on the mechanical model. There was an adjustment capability on the brake to change the radial distance that the brake was acting. This allows for adjustment of the braking torque while keeping the squeezing force the same.
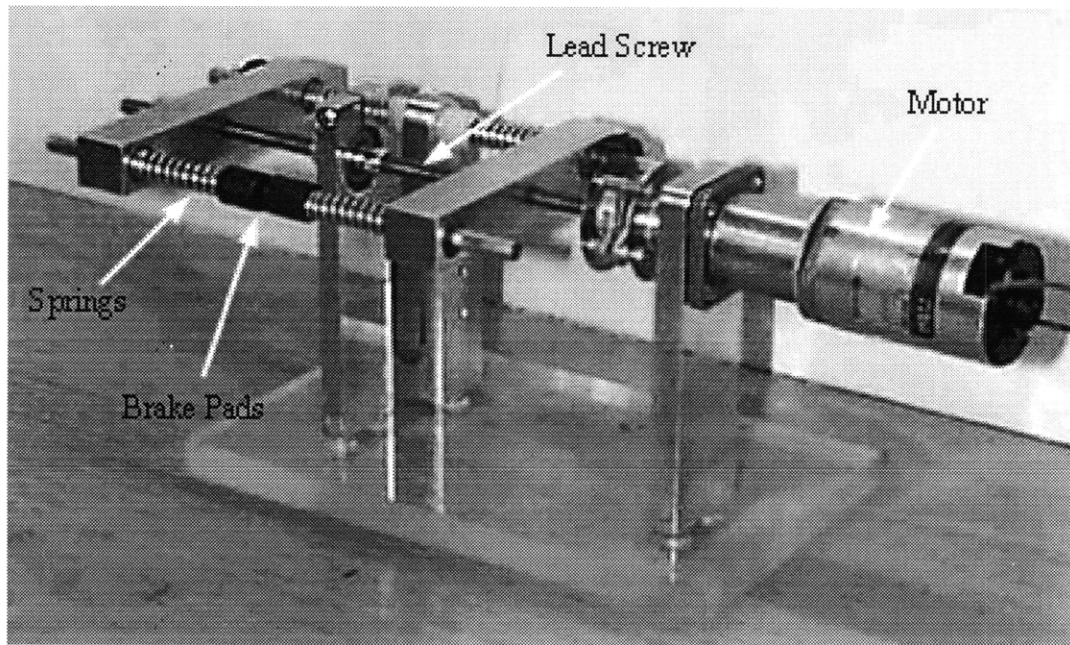
Figure 6.2: Electromechanical Brake

## 6.3 Videoconferencing

The possibilities of videoconferencing allow for a number of opportunities for distance learning and self paced learning. By incorporating this with the computer input and physical output model, a student could use a computer mouse slider bar to control the electromechanical brake. This brake attached to the mechanical model could be located at a distance site with videoconferencing capabilities. The student would then be able to turn on the mechanical model and then control the electromechanical brake through the computer. The feedback would be a video of the mechanical model.

# 7 CONCLUSIONS

In my research, I designed several models to compare effectiveness in teaching engineering principles. Specifically, a fully mechanical dynamometer and a computer simulation of the same device were compared with a control to determine the tradeoffs in teaching and understanding between these various media. The results of this will be used to help guide how new product development will be disseminated in industry. The educational aspect of product development practice is the focus of Thrust 4 of the CIPD.

I built the fully mechanical model with mechanisms that draw out the torque/speed curve of a motor when a student grabs the motor's shaft. The computer simulation was modeled completely from the mechanical device, but involved a mouse slider bar as the interactive element. The control was a description taken from lectures and textbooks describing the torque/speed curve. After running around 60 high school students through the device, the results were rather promising.

The first and most important result from the experiments was the direct comparison between how well the devices helped the students understand the subject of motor torque/speed behavior. On a scale of 1 to 5 where 1 represented little or no understanding and 5 which represented full understanding, the mechanical model scored a 3.62, the computer model scored a 2.43, and the control scored a 2.10. From this first order test, there was fairly strong evidence that both the mechanical and computer models were better than the control with the mechanical model being substantially higher. In the experiments, I also gathered data on the students' aptitude in analytical problems. From this, there was a correlation between how high their aptitude was and how well they learned the material from the models.

In the thesis, as part of the creation of the mechanical model, I performed a detailed analysis of how the model was designed and optimized. Mathematical models of both the steady state and the dynamic response of the models were made.

In conclusion, the results of this thesis will help to guide how material could be better taught. Given that there are other considerations such as cost, ease of access, and longevity of various media, a better understanding of the tradeoffs between various media in teaching engineering principles can be made.

# 8 RECOMMENDATIONS

After building the various models for teaching about DC motor torque/speed curves, there are several recommendations that I would suggest for future research into this area. These involve both additions to the existing models and also possibilities for future models. Also, given the models that I present in this thesis, there are additional possibilities for further experimentation and study.

# 8.1 Further Mechanical Design Revisions

In terms of the mechanical model that I built, there are several ideas that I have for slightly altering my model to increase its capability. Also, depending on the format that the device will be used in, there are several architectural changes that I would recommend that might be more fitting for those situations. Given that I concentrated on motor torque/speed curves, most of the recommendations are for improving this model. There are also several other subjects that might be interesting to develop similar teaching tools.

## 8.1.1 Existing Device

### 8.1.1.1 Toggle to Separate Torque and Velocity Meters

For the existing model, one interesting suggestion that I received from several student subjects was to give the device the capability to run the torque meter and the velocity meter separately. As the device is right now, the student must grab either the carriage or the sliding piece to run only the velocity meter or the torque meter, respectively. While this works fairly well, it is not good design practice to require a student to have to manually stop something on the device. It would be a fairly easy adjustment to create some locks to allow for this separation of functions.

A simple lock on the carriage piece sliding motion or on the rotation of the motor body would both achieve a locking of the torque meter so that only the velocity meter would run. In order to stop the velocity sensor, an opposite approach would be taken. If there were a way to unlock the endpieces on the motor shaft that are attached to the linkages, this would keep the governor from rotating. This could be accomplished by making a lock on this endpiece. When the student wants the velocity meter to measure, he would lock the endpiece to the shaft. When the velocity meter is to be suppressed, the student merely has to unlock this piece from the shaft.

### 8.1.1.2 Cable Versus Ribbon

In the mechanical device, I decided to use a cable wrap around the motor body to pull the carriage piece down. I also had the thought of using a ribbon rather than a cable. While I have gotten varying feedback from students, it would probably be worthwhile to build both devices, one with the cable and one with the ribbon, and then test students. By gathering feedback from students in comparing how obvious each element was in making the torque meter most easily understandable, the design could be altered for future use.

## 8.1.1.3  Damper on Tablet

In my mechanical model, I mounted a damper on the sliding piece of the velocity meter. I did not do this on the carriage of the torque meter. In the dynamic analysis of the mechanisms, I found that the natural frequency of the sliding piece of the velocity meter varied according to governor speed as seen in Figure 2.18. It is realistic for a student to excite the motor shaft at these frequencies causing oscillations. The natural frequency of the carriage of the torque meter was about 24 hertz. It would be very difficult for student to excite the motor shaft at this frequency. Given this, it became unnecessary to mount a damper to the carriage piece.

If the damper on the velocity meter is removed and the shaft excited at a fairly high frequency (for a human hand) of about 5 hertz, then resonant behavior can be detected on the graph in the direction of the velocity, but not in the direction of the carriage. This proves the need for the damper for the velocity meter.

If this mechanical device was used to demonstrate second order system response, it might be good to try to increase the mass of the carriage to the point that the natural frequency reduces to a value similar to the natural frequency of the velocity meter. In this case, a damper would be attached to both meters, and the device could also be used to demonstrate not only torque/speed curves but also second order system dynamics.

## 8.1.1.4  Adjustable Masses and Spring Constants for Governor

Because of the resonant behavior exhibited by the governor device, it would be interesting to have adjustable masses and spring constants so that the changing natural frequencies could be studied. With the damper on the velocity meter, the governor would be an interesting model of nonlinear second order system dynamics.

### 8.1.2 Overhead Projector Version

One possible version of the mechanical model would be a smaller model of the same mechanism. This version would be made smaller for portability and storage needs. Also, the device, if designed for production, would probably be slightly less expensive so that schools could more easily purchase one. One feature that might be interesting would be to make the layout flat and the tablet clear. This way, the device could be put on an overhead projector so that the class could see the projection of the device and the drawn graph. This slightly modified device could be another interesting project if there were plans to produce these devices as educational models.

### 8.1.3 Display Version

Another possible version of the device would be a display model. This type of device could be in places such as the Museum of Science in Cambridge, MA. In this version, there would be some varying requirements. One such requirement would be ruggedness where numerous and unsupervised people would be using the model. Different linkages and pieces would have to be redesigned to ensure that under even abusive use, the model would not break. In this model, there would also have to be some sort of temperature shutoff switch in case the motor was stalled too long leading to overheating of the coils.

### 8.1.4 Other Engineering Topics to Model

Looking at this device as just one of many possible mechanisms to teach about engineering principles, there may be a lot of interesting models for different engineering

subjects. For example, a device that draws the bode plot of a system as the student adjusts the frequency input would be an interesting mechanism to design. Any engineering topic that a device could be built to bridge the gap between the theory learned in classes and some real mechanism would be a good area in which to look.

## 8.2 Further Computer Simulation Revisions

Looking at the computer simulation that I designed, many various possibilities arise for further areas of exploration. Some of these include just giving the model more flexibility and others include complete revisions of the simulation.

### 8.2.1 Web Based Model

An immediate addition to this simulation would be added capability allowing a student to view and manipulate the model through the internet. This way, one simulation could be run from anywhere in the world that has access to the WWW. Presently, Working Model 3D only has the capability to view a prerecorded animation on a web page, but the animation is not interactive. In this new version, a student would be able to interact with the simulation over the web.

### 8.2.2 Flexible System

Similar to one of the previous ideas about adding flexibility to the mechanical model in the way of changeable masses and springs, the computer model could be altered to allow for this. By giving students a simple user interface to change the masses of the governor and the spring constants and other characteristics of the model, the simulation becomes much more flexible. This would allow a student to experiment with ease with almost an infinite number of combinations.

### 8.2.3 Computational Issues

For the computer simulations, because of the high level of computational effort it takes to run an effective dynamics simulation, the advent of even faster computers at a relatively cheap price will make computer simulation even more attractive. Presently, with this simulation on a high-end personal computer, the simulation is still slow and the

graphics are not realistic. Also, if other simulations require collision detection, the computational need goes up even more.

## 8.3 Further Experimental Revisions

### 8.3.1 Computer Model Independent of Mechanical System

For a more even analysis of the possibilities of computer simulation technology, an independent computer model could be development to explain torque/speed curves. This model would differ from the one I built in that instead of just copying a mechanical system, this model would be designed around the specific advantages that computers offer. There are many things that computer simulations can do that a purely mechanical system can not. These things could be utilized to the computer's advantage in creating a computer model independent of a mechanical system. This model could then be compared with the mechanical device.

### 8.3.2 Haptic Versus Visual Input in Video

By studying the learning behavior of students and their responses to various media, there would be a better understanding of how future engineering curriculum should be designed. Also, given this data on learning styles, various new methods and approaches could be tailored to an individual's needs. One such possibility in learning methods would be the use of video for distance learning. By studying how a student responds to a live demo versus a video of the demo would helpful in understanding how effective distance learning could be. By using a web site to allow a student to control the gripping force through a mouse slider bar, and then having the electromechanical brake operating on the actual physical model with live video feedback to the web page, a distance learning system could be established

### 8.3.3 Gender Differences

While I do not go into any formal study of gender differences in learning styles, Katin Shields, a bachelor's thesis student will be conducting some studies to determine how gender affects performance and learning behavior. By tracking the performance data

on how students of different genders learn most effectively, a better understanding of learning styles could be developed. The results of this would help in designing educational curriculums that focus on problems in learning that occur and how to best solve them if gender differences are a cause.

### 8.3.4 Active Versus Passive Understanding

In this thesis, the experimental model that I used to test students' understanding of DC motor torque/speed curves consisted of a verbal question and scenario. In this experiment, because of time constraints, I had to rely on a passive understanding of motors by leading the student to a situation and asking specific question. In order to fully test whether the students really grasped the concepts, I would want to have a more active test in which a student would actually build a device after going through my experiment.

One possible scenario would be to have one group of students taking the 2.007 Introduction to Design class run through my mechanical device, one group through the computer device, and one given a lecture about torque/speed curves. Then, as the class progresses, observe which students design their vehicles correctly over the course of the semester.

This experiment would help to gauge longer term understanding and application of understanding torque/speed curves. Because of the long time constraint for this experiment, I was not able to do this, but I feel that this would be a more effective way to test a student's understanding. This is because the student would be tested based on an active understanding that would lead to application of their knowledge. Also, the longer time constant would allow for testing of permanent understanding rather than just short term understanding.
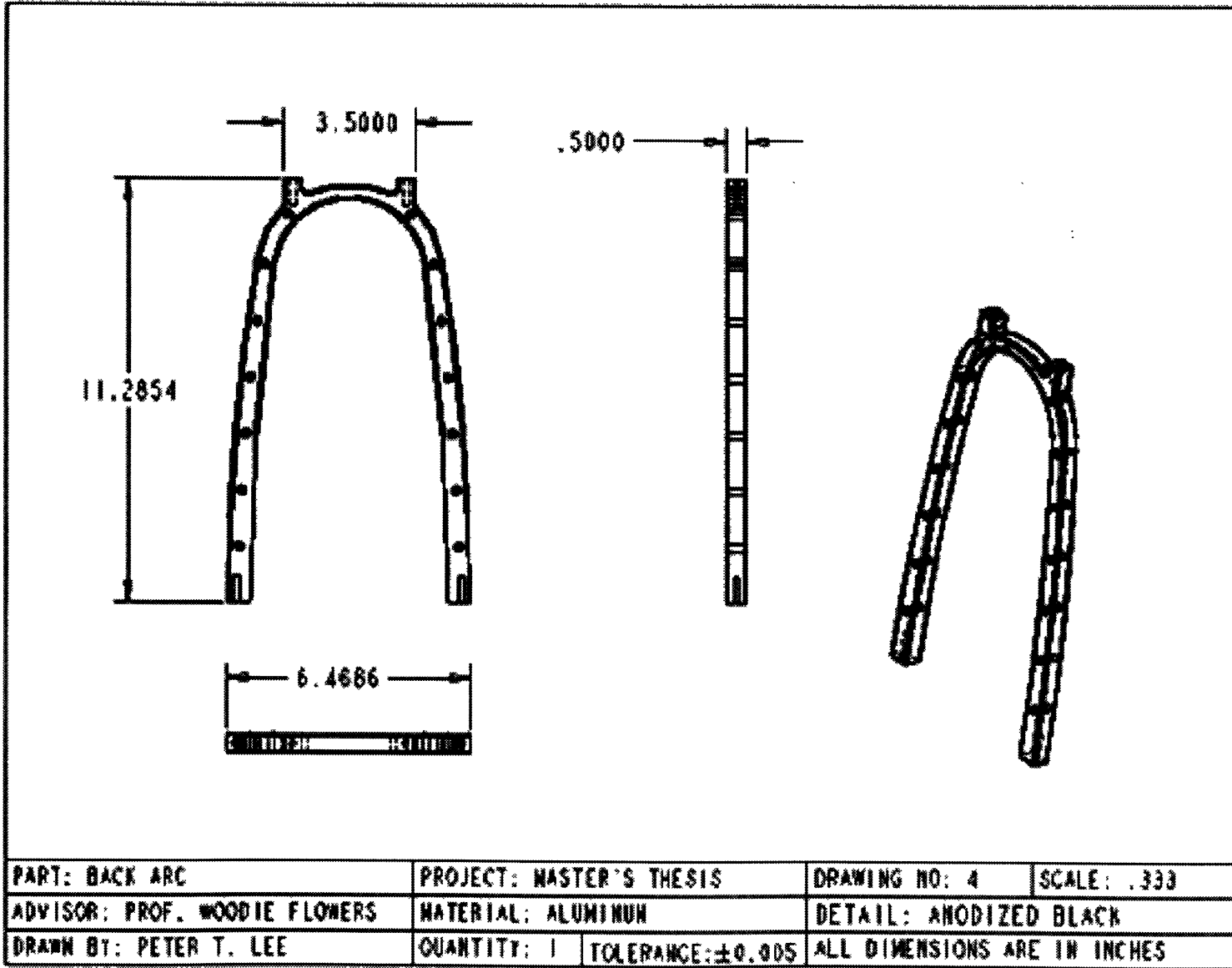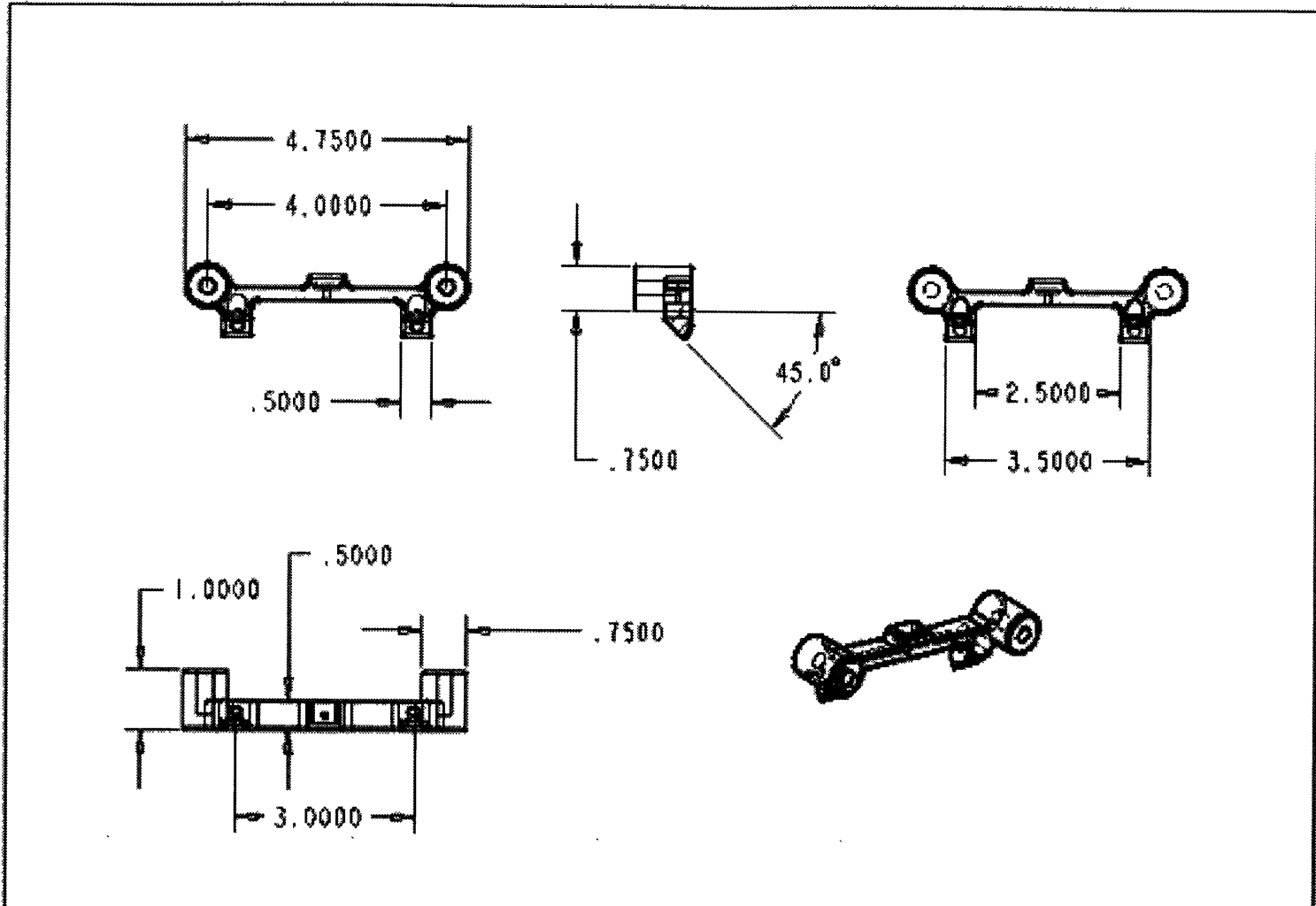
# 9 APPENDIX

## 9.1 Mechanical Design

### 9.1.1 ProEngineer Drawings and Assembly

Figures 9.1: CAD Models of Parts from ProEngineer



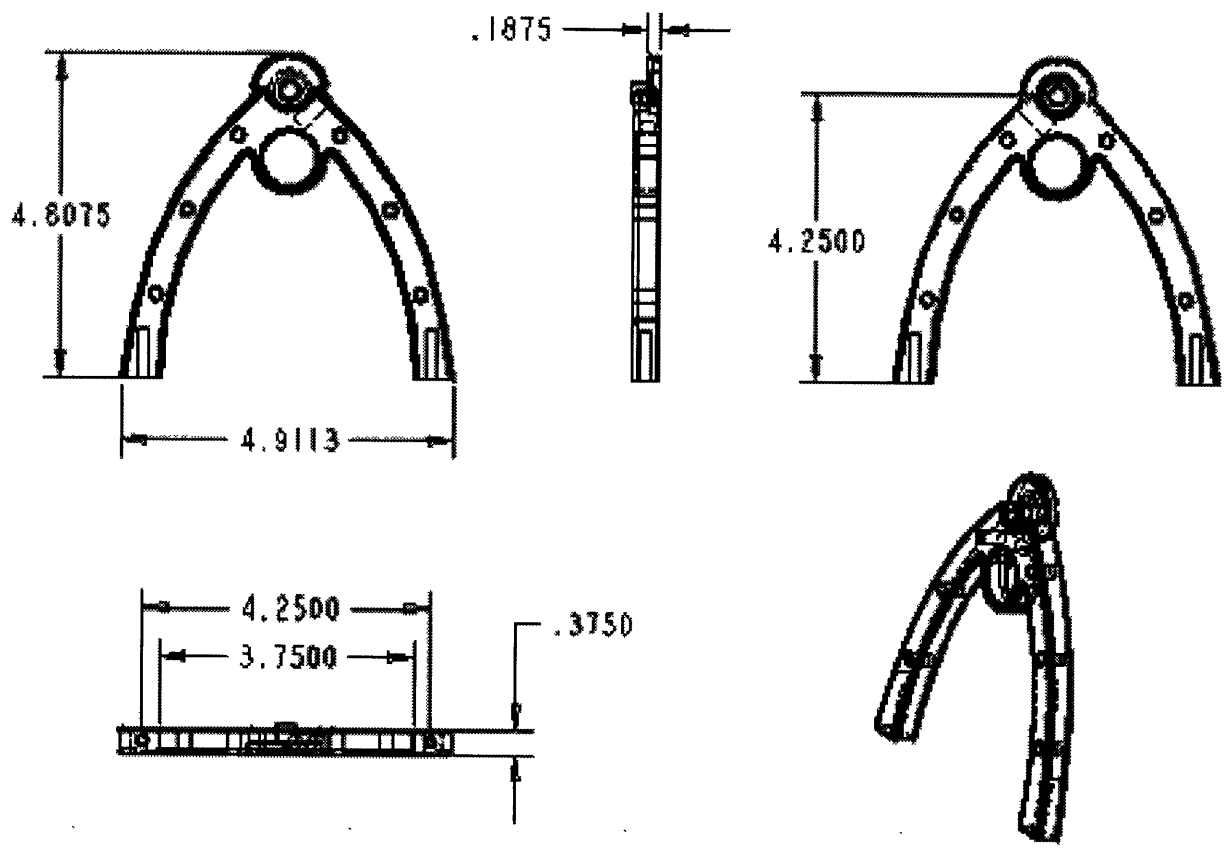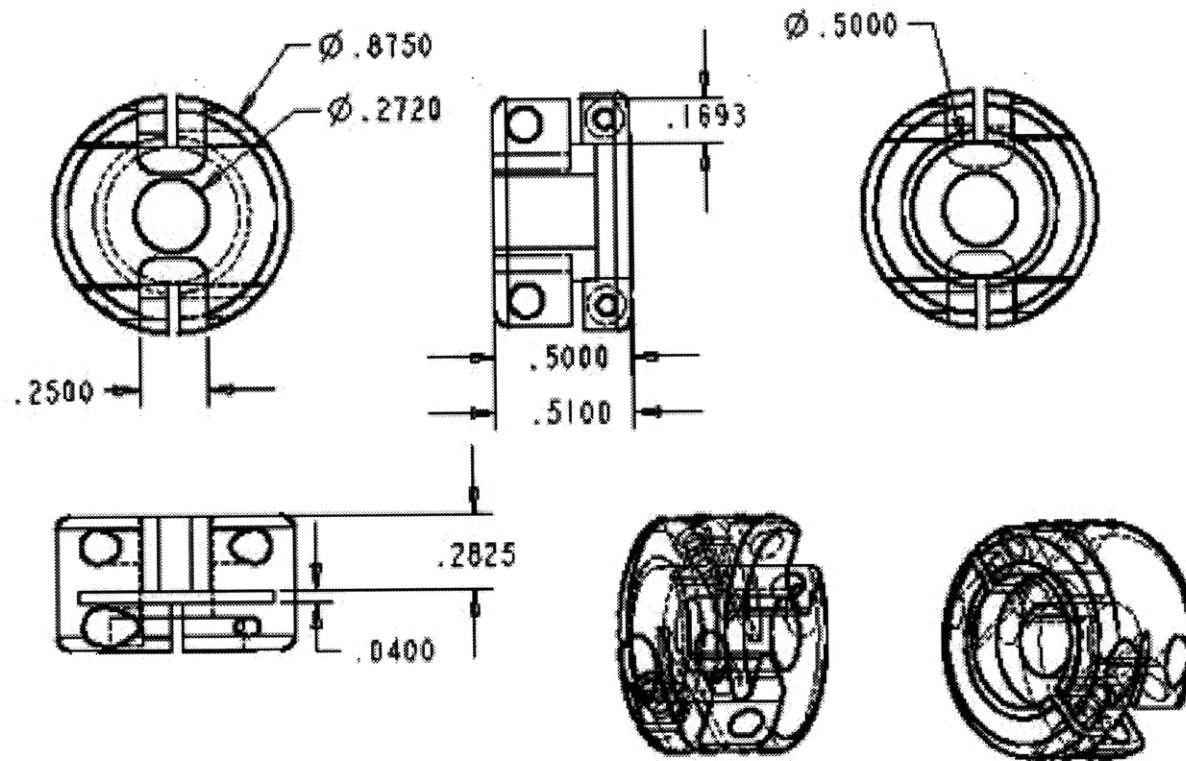| PART: BACK ARC | PROJECT: MASTER'S THESIS | DRAWING NO: 4 | SCALE: .333 |
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| DRAWN BY: PETER T. LEE | QUANTITY: 1 | TOLERANCE:±0.005 | ALL DIMENSIONS ARE IN INCHES |

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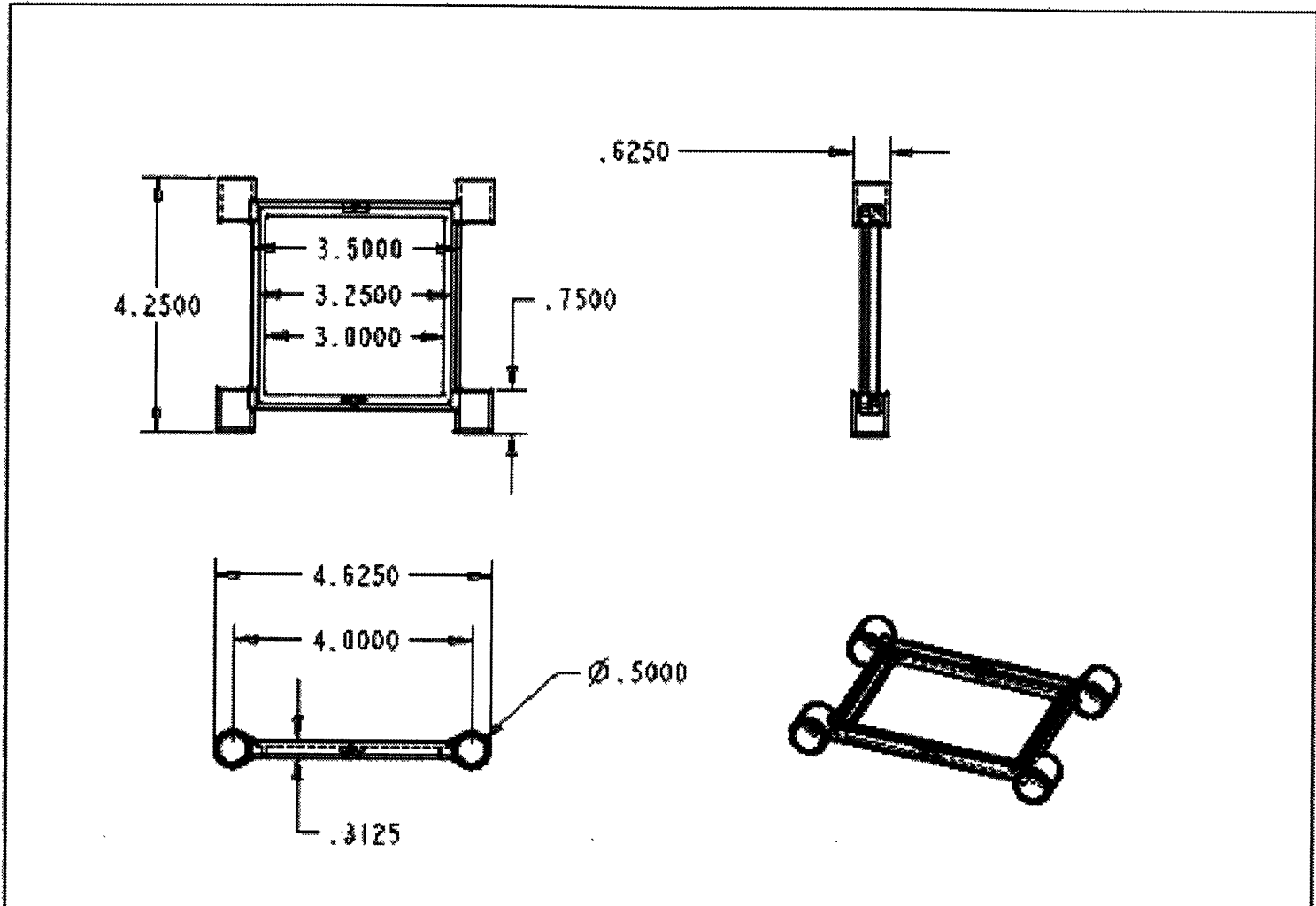| PART: BACK TOP | PROJECT: MASTER'S THESIS | DRAWING NO: 5 | SCALE: 0.5 |
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| DRAWN BY: PETER T. LEE | QUANTITY: 1 TOLERANCE:±0.005 | ALL DIMENSIONS ARE IN INCHES | |

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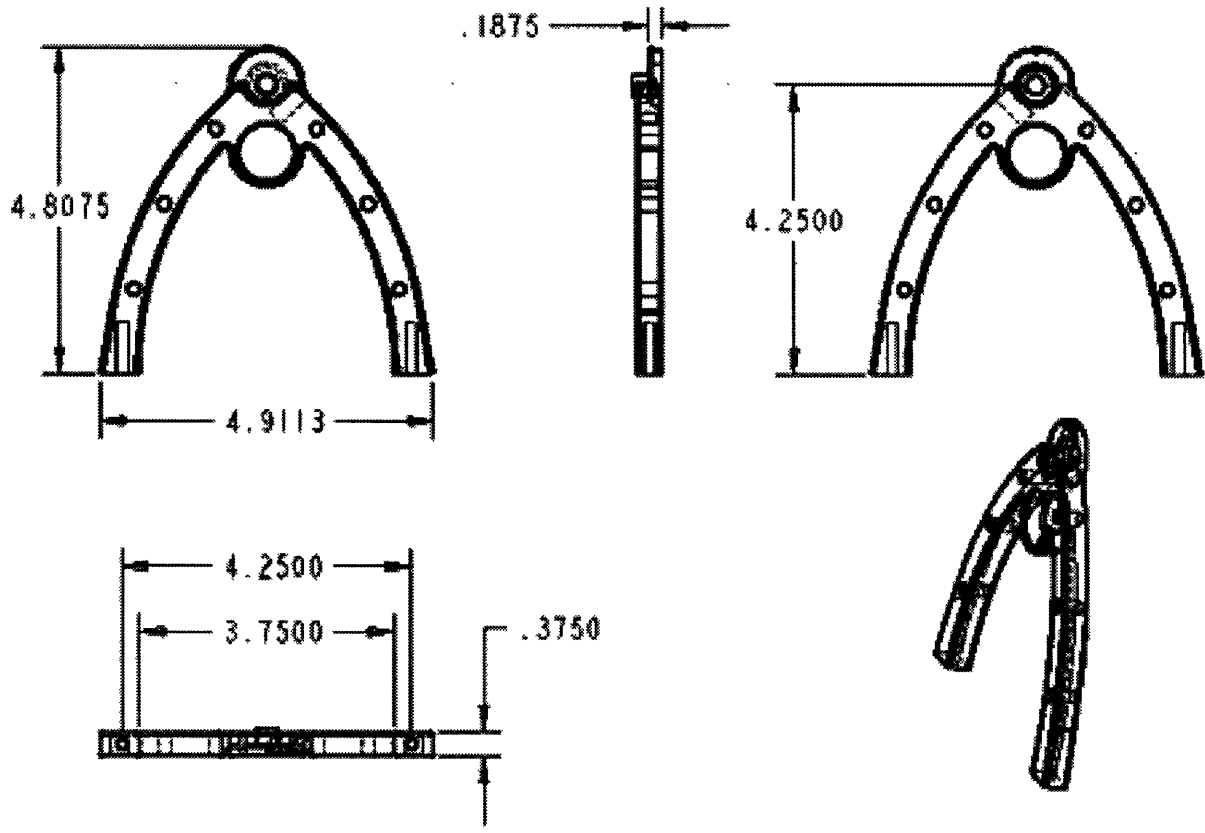
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MIRROR IMAGE OF BEARING ARC LEFT

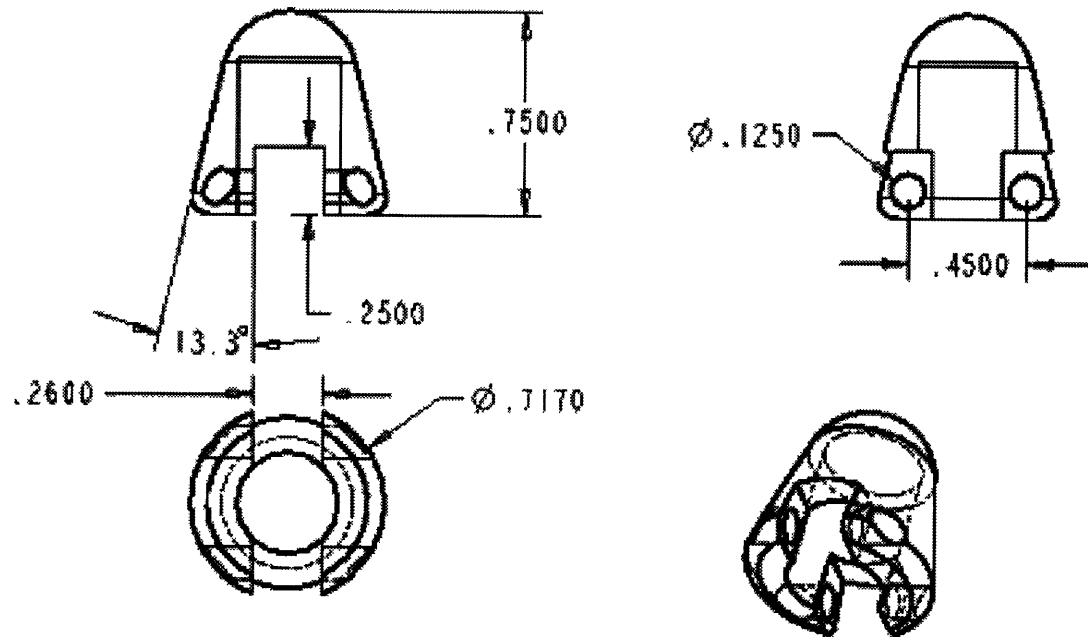| PART: BEARING ARC RIGHT | PROJECT: MASTER'S THESIS | DRAWING NO: 2 | SCALE: 0.5 |
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| PART: BEARING MOUNT | PROJECT: MASTER'S THESIS | | DRAWING NO: 11 | SCALE: 2 |
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| ADVISOR: PROF. WOODIE FLOWERS | MATERIAL: ALUMINUN | | DETAIL: ANODIZED RED | |
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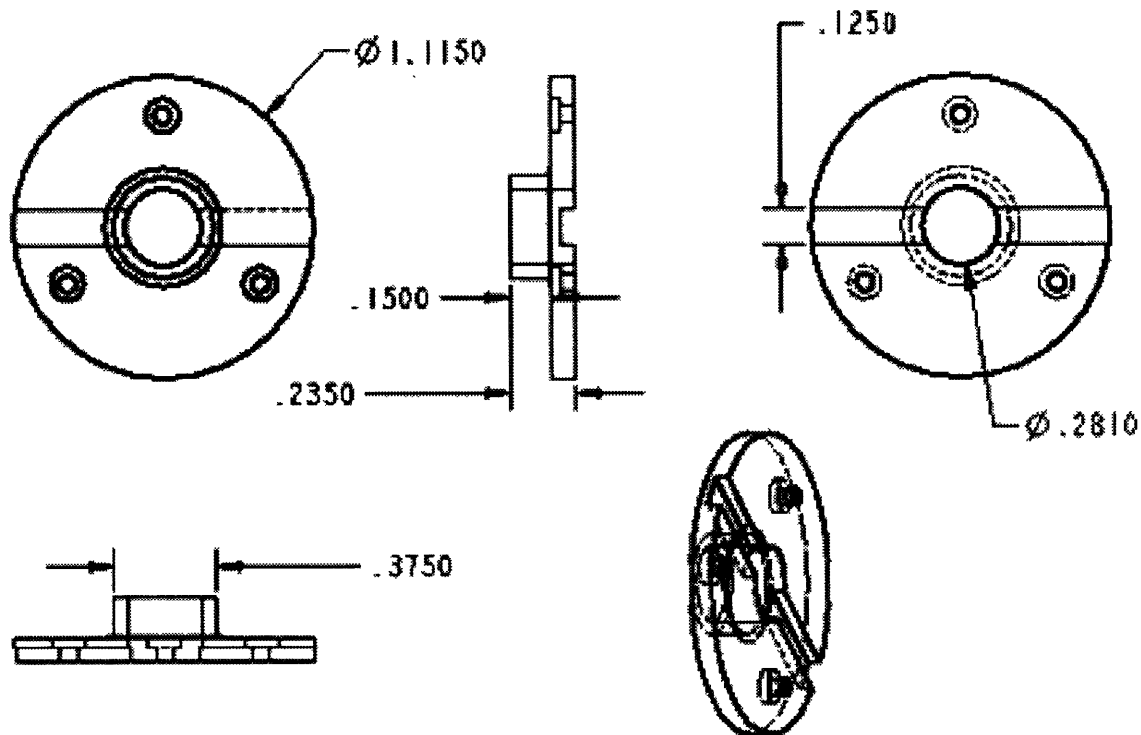| PART: CARRIAGE | PROJECT: MASTER'S THESIS | | DRAWING NO: 6 | SCALE: 0.5 |
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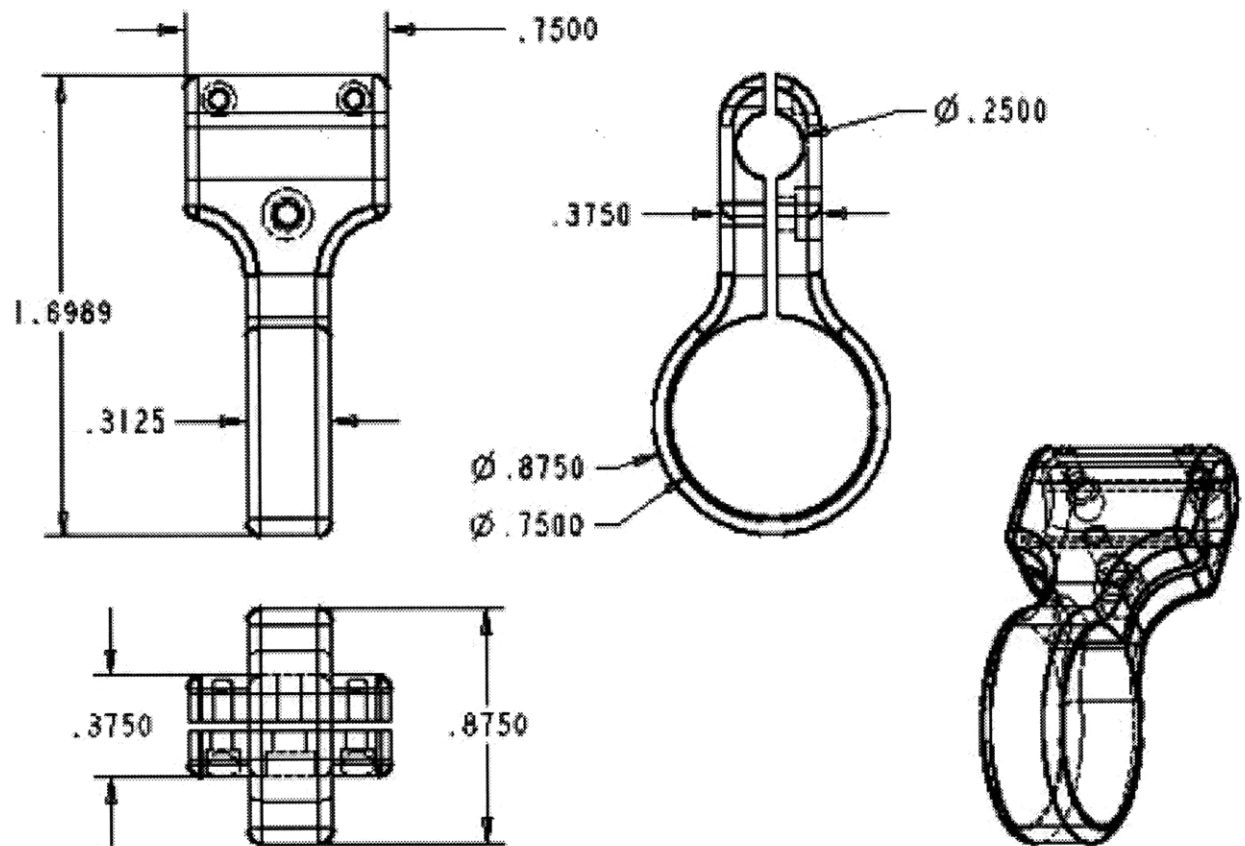
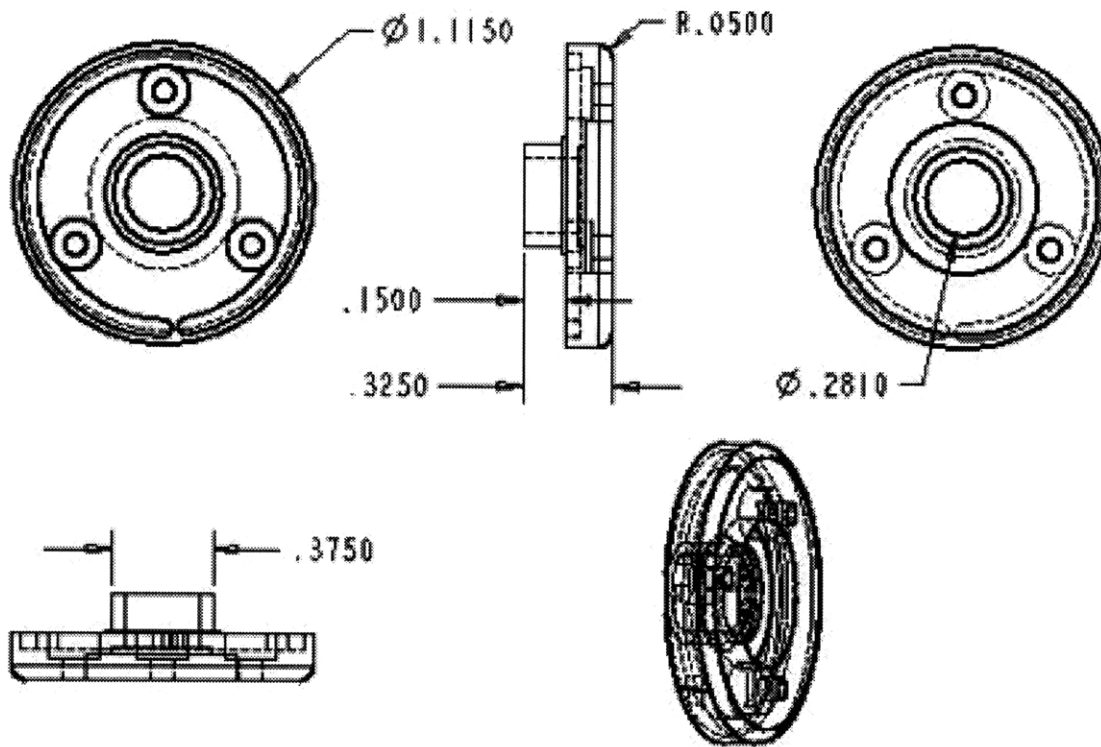| PART: DAMPER BEARING | PROJECT: MASTER'S THESIS | DRAWING NO: 10 | SCALE: 2 |
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| ADVISOR: PROF. WOODIE FLOWERS | MATERIAL: ALUMINUM | DETAIL: ANODIZED RED | |
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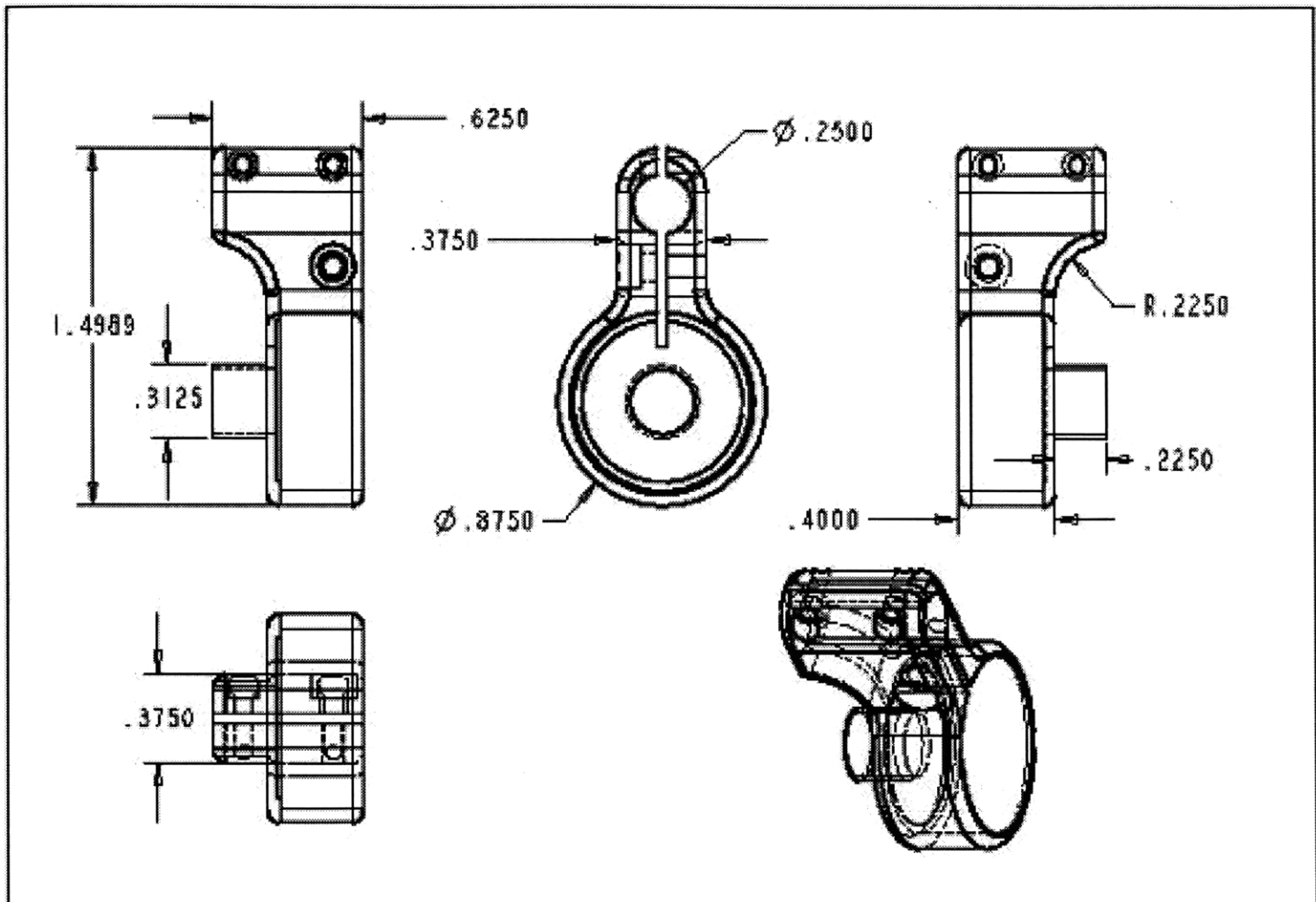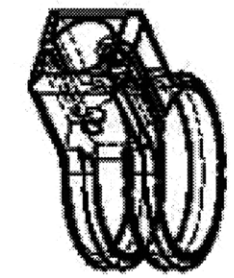| PART: MASS | PROJECT: MASTER'S THESIS | DRAWING NO: 13 | SCALE: 2 |
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| ADVISOR: PROF. WOODIE FLOWERS | MATERIAL: ALUMINUM | DETAIL: ANODIZED RED | |
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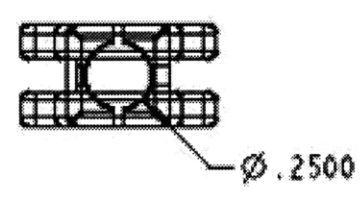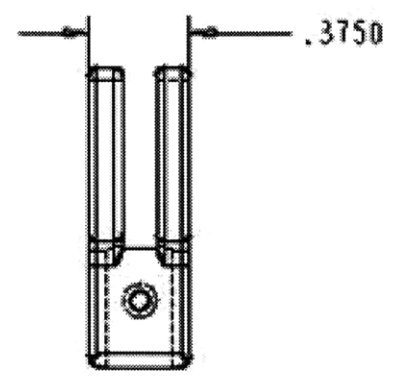| PART: MOTOR MOUNT LEFT | PROJECT: MASTER'S THESIS | DRAWING NO: 7 | SCALE: 2 |
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| PART: BEARING ARC RIGHT | PROJECT: MASTER'S THESIS | DRAWING NO: 8 | SCALE: 1:2 |
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| ADVISOR: PROF. WOODIE FLOWERS | MATERIAL: ALUMINUM | DETAIL: ANODIZED BLACK | |
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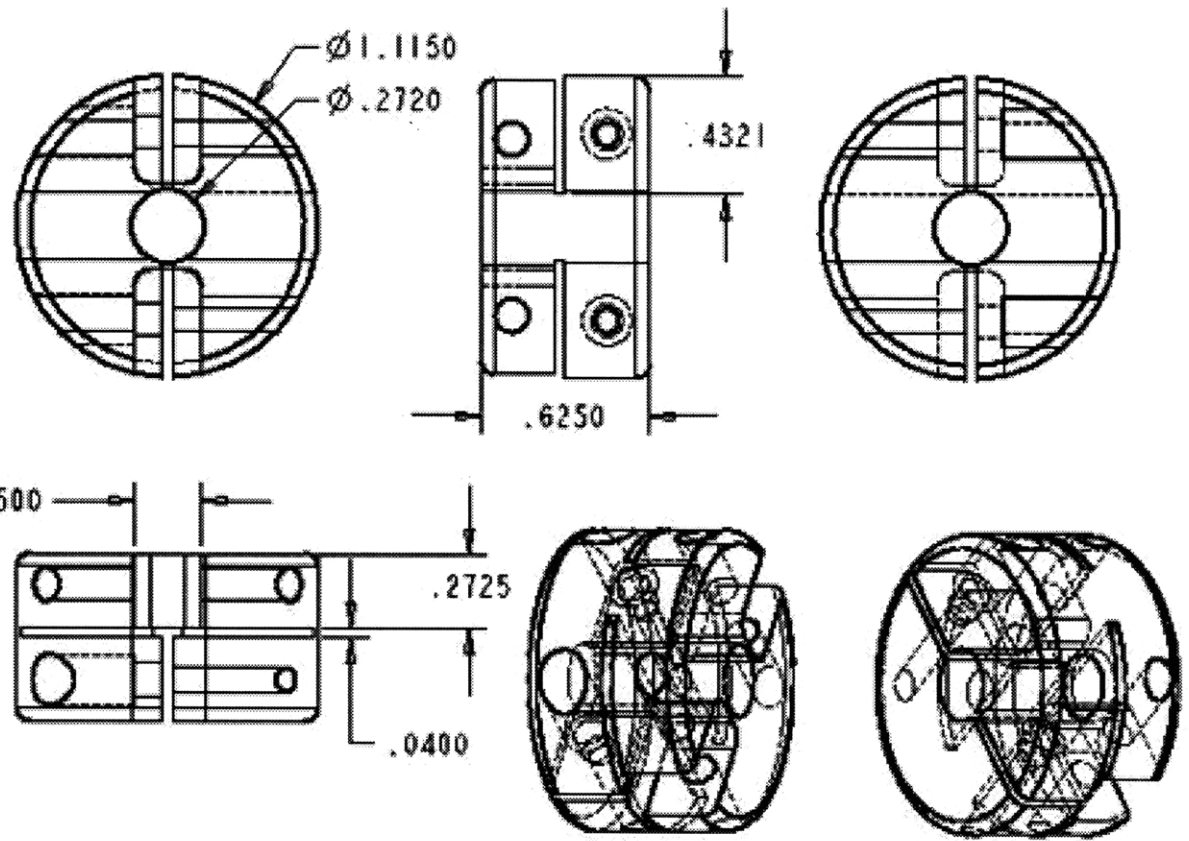| PART: PEN BEARING | PROJECT: MASTER'S THESIS | DRAWING NO: 9 | SCALE: 2 |
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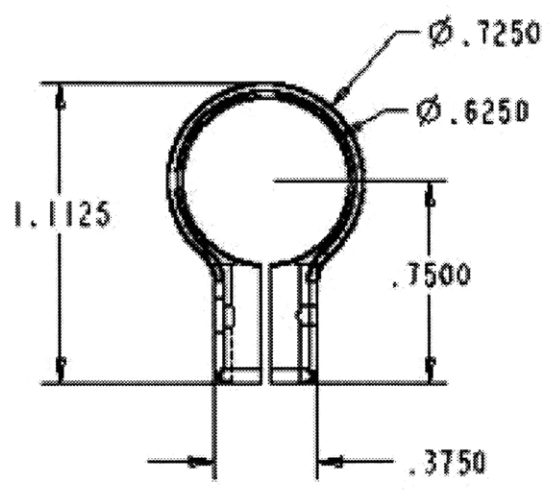
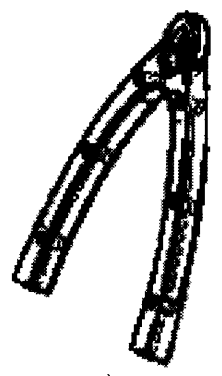| PART: PEN HOLDER | PROJECT: MASTER'S THESIS | DRAWING NO: I | SCALE: 2 |
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| ADVISOR: PROF. WOODIE FLOWERS | MATERIAL: ALUMINUM | DETAIL: ANODIZED RED | |
| DRAWN BY: PETER T. LEE | QUANTITY: I   TOLERANCE:±0.005 | ALL DIMENSIONS ARE IN INCHES | |

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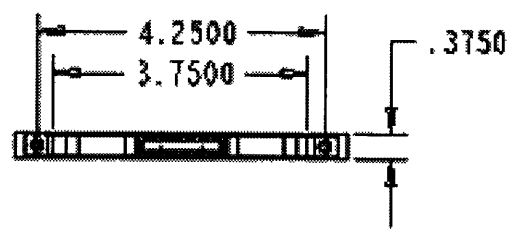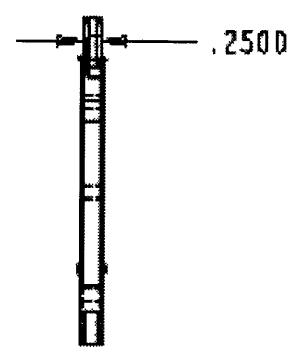| PART: STILL MOUNT | PROJECT: MASTER'S THESIS | DRAWING NO: 12 | SCALE: 2 |
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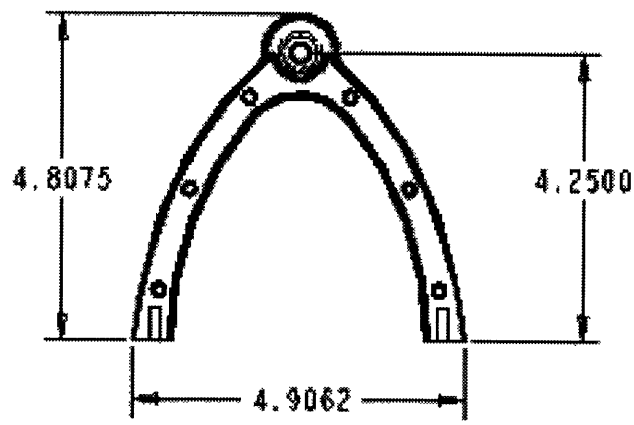| | | |
|---|---|---|
| PART: VELOCITY ARC | PROJECT: MASTER'S THESIS | DRAWING NO: 2 | SCALE: 0.5 |
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| DRAWN BY: PETER T. LEE | QUANTITY: 1 | TOLERANCE:±0.005 | ALL DIMENSIONS ARE IN INCHES |

## 9.1.2 Parts List

| No. | Part Description | Quantity | Supplier | Price |
|---|---|---|---|---|
| 1 | DC Maxon Motor 2322.980-52.235-200 | 1 | Maxon Precision Motor Inc. | $198.00 |
| 2 | DC Power Adapter 9V | 1 | Radio Shack | $  9.00 |
| 3 | High Density Polyethylene 2'x1.5'x0.5" | 1 | Commercial Plastics Inc | $  6.00 |
| 4 | bearingarcleft - machined part | 1 | Eastern Tool Corp. | $245.00 |
| 5 | bearingarcright - machined part | 1 | Eastern Tool Corp. | $245.00 |
| 6 | velocityarc - machined part | 1 | Eastern Tool Corp. | $220.00 |
| 7 | backarc - machined part | 1 | Eastern Tool Corp. | $220.00 |
| 8 | backtop - machined part | 1 | Eastern Tool Corp. | $320.00 |
| 9 | carriage - machined part | 1 | Eastern Tool Corp. | $450.00 |
| 10 | motormountleft - machined part | 1 | Eastern Tool Corp. | $120.00 |
| 11 | motormountright - machined part | 1 | Eastern Tool Corp. | $120.00 |
| 12 | penholder - machined part | 1 | self machined | $  1.00 |
| 13 | penbearing - machined part | 1 | self machined | $  1.00 |
| 14 | damperbearing - machined part | 1 | self machined | $  1.00 |
| 15 | bearingmount - machined part | 1 | self machined | $  1.00 |
| 16 | stillmount - machined part | 1 | self machined | $  1.00 |
| 17 | mass - machined part | 2 | self machined | $  1.00 |
| 18 | pencollar - machined part | 1 | self machined | $  1.00 |
| 19 | steel pin - machined part | 1 | self machined | $  1.00 |
| 20 | aluminum pin - machined part | 8 | self machined | $  1.00 |
| 21 | Delrin grip - machined part | 1 | self machined | $  1.00 |
| 22 | ABS tablet sheet | 1 | self machined | $  1.00 |
| 23 | Airpot Dashpot S 160 A 400 F 475 | 1 | Airpot Corp. | $ 52.00 |
| 24 | Linear Bearing Shaft 6253K12 | 3 | McMaster-Carr | $ 15.00 |
| 25 | Stainless Steel Wire Rope MCX-37 | 1 | Small Parts Inc. | $  1.00 |
| 26 | Ball Bearings - Rotary SSRI1038ZZ | 2 | Aircraft Bearing Corp. | $ 13.00 |
| 27 | Ball Bearings - Rotary 60355K73 | 1 | McMaster-Carr | $  4.00 |
| 28 | Ball Bearings - Rotary 57155K46 | 8 | McMaster-Carr | $  5.00 |
| 29 | Ball Bearings - Rotary S610MCHH3 | 4 | Miniature Precision Bearings | $ 15.00 |
| 30 | Ball Bearings - Linear 6489K61 | 5 | McMaster-Carr | $ 14.00 |
| 31 | Spring Steel Bands | 4 | self machined | $  1.00 |
| 32 | Cable End Eye MCEY-37 | 1 | Small Parts Inc. | $  1.00 |
| 33 | Sleeve Bearing - Rulon-J SBP-2/4 | 4 | Small Parts Inc. | $  2.00 |
| 34 | Extension Spring 9654K55 | 1 | McMaster-Carr | $  1.00 |
| 35 | Extension Spring 9654K191 | 1 | McMaster-Carr | $  1.00 |
| 36 | Plotter Pen | 1 | Rapidoplot | $  1.00 |
| 37 | Electrical Switch | 1 | Radio Shack | $  1.00 |

Figure 9.2: Parts List

### 9.1.3 DC Motor Specifications

| Manufacturer | Maxon Motor Company |
|---|---|
| Part Number | 2322.980-52.235-200 |
| Input Voltage | 12 V |
| Max Speed | 580 rpm |
| Max Torque | 2.83 in-lbs |
| Length | 4.40 in |
| Diameter | 0.157 in |
| Weight | 0.313 lbs |

Figure 9.3: Maxon DC Motor Specifications

See Figure 2.3 for picture of motor

# 9.2 Analysis of Design

## 9.2.1 Linearity Analysis of Governor

The design of the governor depended upon the linearity of the speed measurement. In order to create a mechanism to do this, I brainstormed several concepts while analyzing the physical characteristics of the motor.

First, because it is the speed of the motor shaft in which we are interested, I started with the principle of translating rotational speed to a displacement. The displacement as the final result was due to the requirement that the device plot the torque/speed curve of the motor. To do this, the mechanism had to move the pen along the x-axis of the graph in relation to the speed.

Starting with the rotational speed of the motor shaft as the characteristic to be measured, physical relationships were needed that depended on rotational speed. One such relationship is centripetal acceleration. It is known that centripetal acceleration of an object perpendicular to the motor shaft is related to the square of the rotational velocity. Given $\omega$ as the rotational speed of the motor shaft, r as the radial distance from the axis of rotation, and a as the centripetal acceleration, we have $a=r\omega^2$ for an object. From this, given that the object has mass, we have a force F from F=ma where m is the mass of the object. Given this force F, a spring can be implemented to give a distance through F=kx where k is the spring constant and x is the spring displacement. This displacement can then be used to plot the rotational speed of the motor shaft. Now, given these basic physical relationships, a mechanism was need that would translate these properties in a linear fashion.

Looking at these relationships, the only non-linear term was the first centripetal acceleration. The squared term of the speed needed to be linearized. Looking at various mechanisms, I found one that seemed promising. It is this linkage that I model as follows.

Variables:

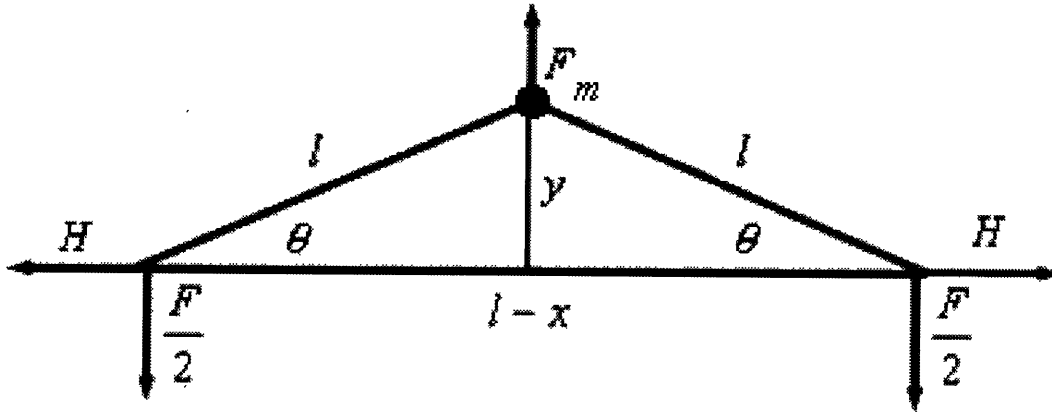| | |
|---|---|
| F | centripetal force |
| m | mass of object |
| H | horizontal resultant force |
| l | length of linkage |
| θ | angle of linkage with horizontal |
| y | radial distance from shaft |
| x | displacement of spring |



Figure 9.4: Free Body Diagram of Governor

Centripetal acceleration and force

$$a = r\omega^2 \qquad F = my\omega^2$$

Spring Force

$$H = 2kx$$

From geometry of triangles

$$\tan\theta = \frac{F/2}{H} \qquad l^2 = (l-x)^2 + y^2$$

After equation substitution and manipulation

$$H = \frac{F}{2\tan\theta} \qquad H = \frac{my\omega^2}{2\tan\theta} \qquad \tan\theta = \frac{y}{(l-x)/2} \qquad \omega = \sqrt{\frac{(2kx)(2\tan\theta)}{my}}$$

Finally, solving for ω

$$\omega = \sqrt{\frac{(2kx)\left(2\left(\frac{\sqrt{l^2-(l-x)^2}}{l-x}\right)\right)}{\left(m\sqrt{l^2-(l-x)^2}\right)}}$$

## 9.2.2 Dynamic Model of Second Order System

The dynamic analysis of the mechanical system was performed to characterize the frequency response of the system to inputs. The mechanical model primarily consists of two distinct subsystems – both of which are essentially second order systems. Because they both contain spring and mass elements, there are natural frequencies that are characteristic of their behavior. It is these natural frequencies for which I solved.

### 9.2.2.1 Discussion of the Physical System

The torque meter is a simple second order system consisting of a spring with a fixed spring constant and a tablet of fixed mass. Given these two elements, there is a fairly simple analysis of the frequency response of this system which is analyzed below.

The governor dynamic response is much more complex. Although it also contains a spring of fixed spring constant, the effective mass of the governor as seen from the spring changes according to the geometry of the governor. The geometry of the governor is dependent on the speed that the governor spins. Because the natural frequency of a second order system is dependent on the spring constant and the effective mass, the governor has the unusual characteristic of having a variable natural frequency depending on the speed and position of the governor.

Looking qualitatively at the governor system in order to get a rough idea of how the natural frequency would change depending on governor position and also the spring and mass pair used, I was able to verify my initial theory. When the governor is spinning slowly and the spring is stretched very little, the governor's linkages lie fairly flat. In this position, a small change in the spring displacement causes a large displacement in the governor masses. This results in a high effective mass of the slider. This is because the effective mass is made up of not only the slider mass but the increased governor ball masses for this position. Because of this, the natural frequency will be low. At high governor speeds, the linkages are more upright. A change in the spring displacement causes a smaller displacement in the governor masses. This results in a lower effective

mass because the slider mass dominates. Because of this, the natural frequency of the governor in this state will be higher.

For the governor, there are an infinite number of pairs of spring and mass combinations that would satisfy the initial design requirement of providing a 2" displacement of the pen when the governor is spinning at full speed, 600 rpm. To meet these criteria, the spring/mass pairs, must have the same. In terms of the governor natural frequency with these different pairs, I again studied the model qualitatively and then did the dynamic analysis. In comparing a smaller spring and mass pair to a larger pair, the performance of the governor in terms of steady state response was identical. For both pairs, at low speeds, the effective masses still became large thereby decreasing natural frequency. At high speeds though, because the mass of the slider is constant and dominates the effective mass, the larger pair has a high spring constant relative to the mass as compared with the smaller spring constant of the smaller pair. This causes the larger pair to actually have a higher resonant frequency than the smaller pair.

While this might point the governor design to use larger masses and springs, there is a limit in the inertia of the governor masses because the motor has limited torque and accelerating large masses would increase the response time. There is therefore a tradeoff between having a larger natural frequency with having a slower response time. Also, because of the large inertial masses, the torque on the motor from accelerating these masses would show up on the torque meter and possibly cause spikes in the torque measurement when high accelerations or decelerations occur.

## 9.2.2.2 Torque Meter Dynamic Analysis

x      spring displacement
k      spring constant
$m_t$     mass of the tablet
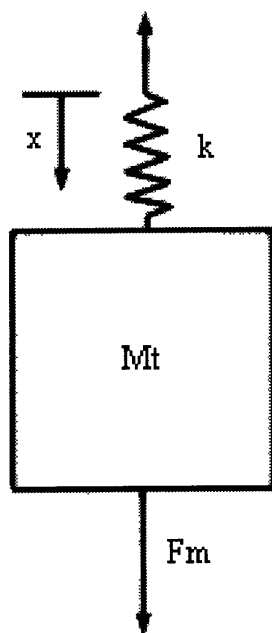$f_m$     force from motor winding



Figure 9.5: Free Body Diagram of Torque Meter

Equation for second order system

$$m_t \ddot{x} + kx = f_m$$

The natural frequency of this second order system

$$\omega_n = \sqrt{\frac{k}{m_t}}$$

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### 9.2.2.3 Governor Dynamic Analysis

$m_s$     slider mass
$m_b$     governor ball mass
k        spring constant
x        slider mass displacement
l        linkage length
$\omega$      governor rotational speed
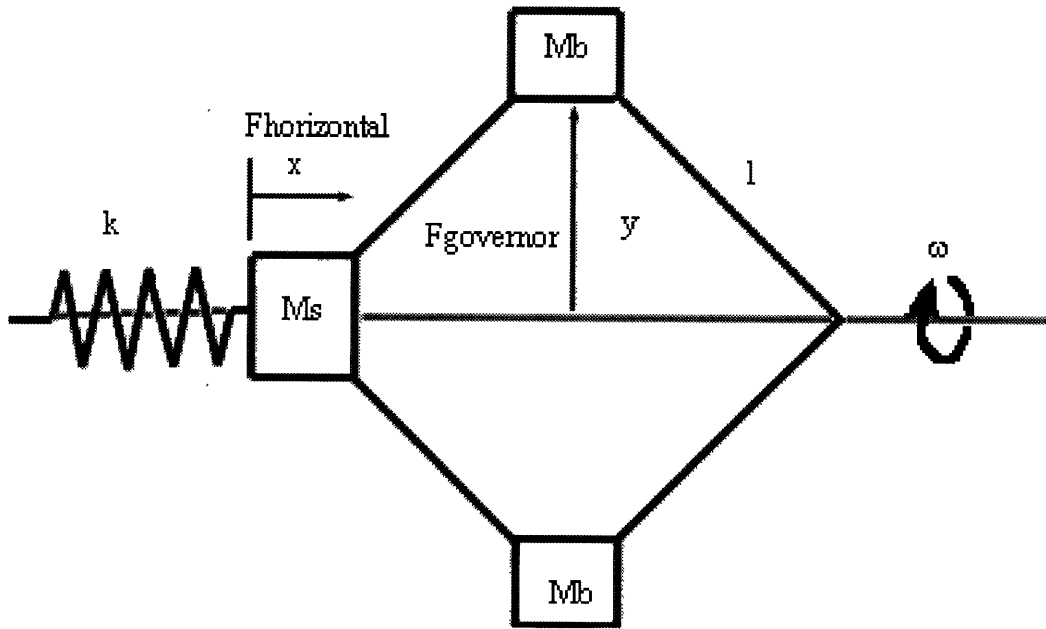y        radial distance of governor mass



Figure 9.6: Diagram of Governor for Dynamic Analysis

From geometry

$$l^2 = y^2 + \left(l - \frac{x}{2}\right)^2 \qquad \tan\theta = \frac{y}{l - \frac{x}{2}} \qquad \tan\theta = \frac{F_{governor}}{F_{horizontal}}$$

Constituent Equations

$$F_{spring} = kx \qquad\qquad F_{governor} = 2m_b y\omega^2$$

After equation substitution and manipulation

$$F_{horizontal} = \frac{F_{governor}}{\tan\theta} = m_b l\omega^2 - \frac{m_b}{2} x\omega^2$$

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Solving for the equivalent mass of the system with is defined as the acting mass of the system equal to the kinetic energies of the component masses.

$$\frac{1}{2}m_e \dot{x}^2 = \frac{1}{2}m_s \dot{x}^2 + \frac{1}{2}(2m_b)(\dot{x}_b + \dot{y}_b)^2$$

Solving from geometry      Taking the derivative      Solving

$$y_b^2 = lx - \frac{x^2}{4}$$

$$2y_b \dot{y}_b = l\dot{x} - \frac{1}{2}x\dot{x}$$

$$\dot{y}_b = \frac{\dot{x}\left(l - \frac{x}{2}\right)}{2\sqrt{lx - \frac{x^2}{4}}}$$

$$\dot{x}_b = \frac{\dot{x}}{2}$$

Substituting

$$m_e = m_s + \frac{1}{2}m_b\left[1 + \frac{\left(l - \frac{x}{2}\right)^2}{x\left(l - \frac{x}{4}\right)}\right] = m_s + \frac{1}{2}m_b\left[\frac{l^2}{x\left(l - \frac{x}{4}\right)}\right]$$

Second Order Equation of Motion for System

$$m_e \ddot{x} - \left(k - \frac{m_b}{2}\omega^2\right)x + m_b l\omega^2 = 0$$

Substituting and Simplifying

$$\left(\frac{-m_s}{4}\right)x^2\ddot{x} + (lm_s)x\ddot{x} + \left(\frac{m_b l^2}{2}\right)\ddot{x} + \left(\frac{k}{4} + \frac{m_b\omega^2}{8}\right)x^3 - \left(lk + \frac{3m_b l\omega^2}{4}\right)x^2 + (m_b l^2\omega^2)x = 0$$

Solving

$$\ddot{x} = \frac{-\left(\frac{k}{4} + \frac{m_b\omega^2}{8}\right)x^3 + \left(lk + \frac{3m_b l\omega^2}{4}\right)x^2 - (m_b l^2\omega^2)x}{-\left(\frac{m_s}{4}\right)x^2 + (lm_s)x + \left(\frac{m_b l^2}{2}\right)}$$

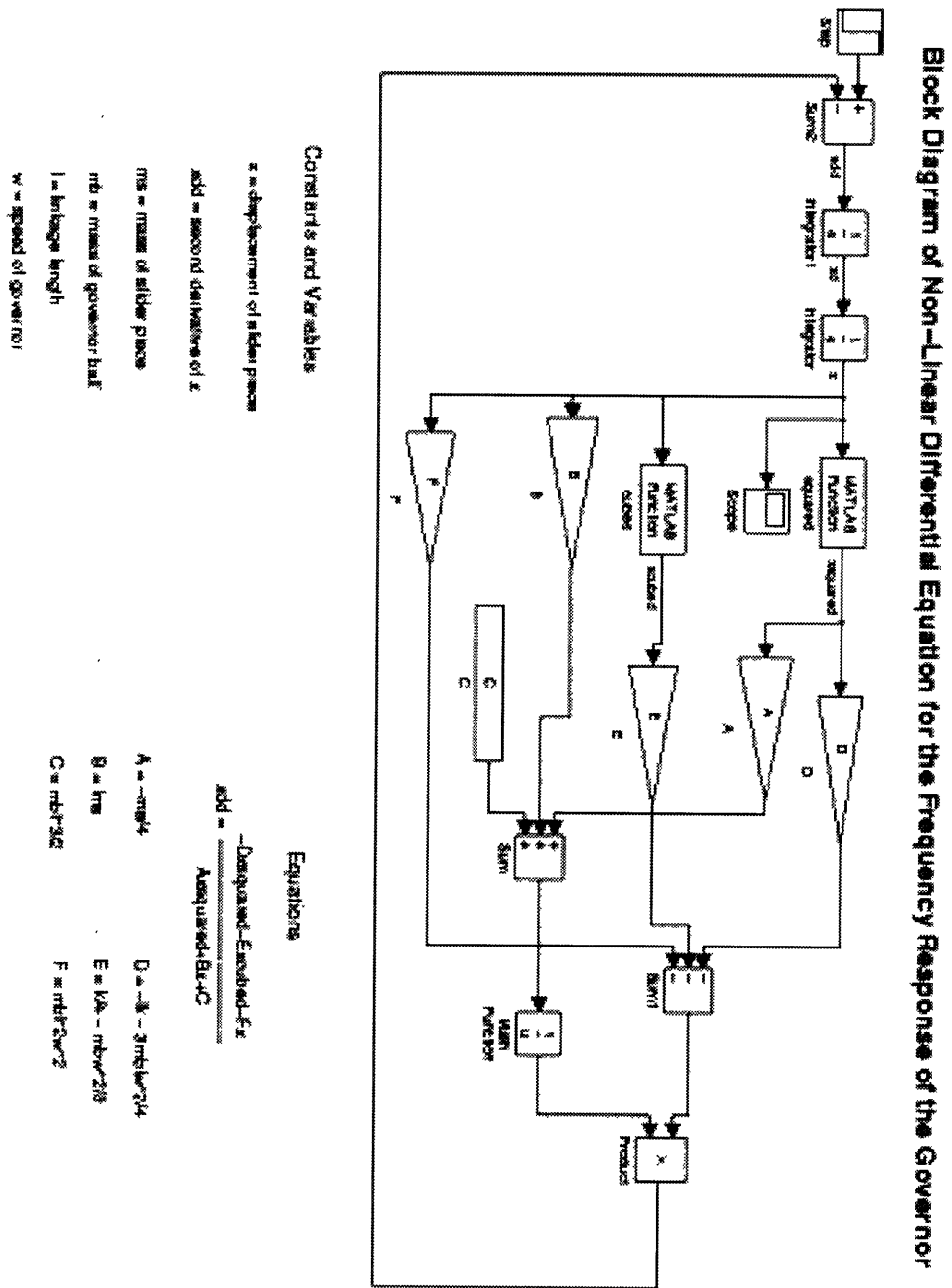9.2.2.4 Block Diagram of the dynamic equation from Simulink



Figure 9.6: Block Diagram of Differential Equation for Governor in Simulink

# DC Motor Torque/Speed Curve

DC Electric Motors have a characteristic performance that relates its torque and speed. They are inversely related. The performance of a DC motor acts on a line called the torque/speed curve as shown below when operating under a constant voltage source.

## Torque/Speed Curve of DC Motor
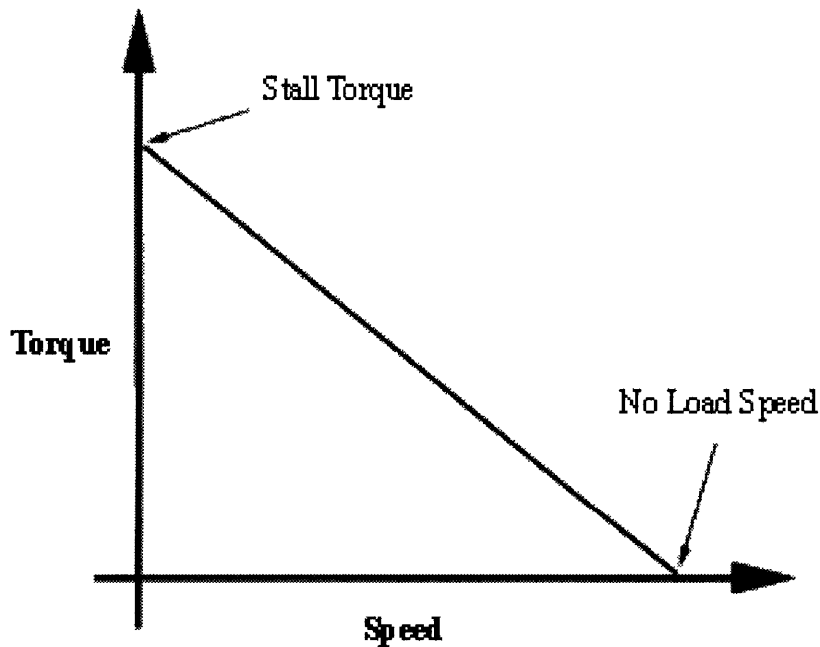


As can be seen from the graph, as the torque of the motor increases the speed decreases. Also, as the torque of the motor decreases, its speed increases. When the motor is stalled, it is applying its maximum torque. When the motor is spinning its fastest, it is applying zero torque.

Figure 9.8: Control Sheet Description of Torque/Speed Curve