

# **A Unique String/Pulley System Apparatus Capstone Design Project for a Hands-On Senior-Level Laboratory Design Experience**

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## **1. ABSTRACT**

This paper describes a particle kinematics measurement experimental apparatus for the junior level *Engineering Mechanics – Dynamics* course. The *Engineering Mechanics - Dynamics* course is geared to introducing students to fundamental principles of Kinematics and Kinetics of particles and rigid bodies, including displacement/velocity/acceleration kinematics relationships and kinetics analyses through Newtonian 2<sup>nd</sup> Law, work/energy equations, and impulse/momentum principles approaches. It has been the Mechanical Engineering Department's philosophy that theory learned in the classroom be augmented by experiential knowledge gained by laboratory experience. In this light, hands-on laboratory experiments have been developed that are integrated with the course material. This paper presents a unique experimental apparatus, designed and built at Oakland University by the senior students, which is a precursor to the *Capstone Design Project* at Oakland University, to introduce students to particle kinematics properties measurement techniques to measure particle's positions, velocities, and accelerations in a string/pulley system. The *Capstone Design Project* is geared to taking students through the entire taxonomy of the design process; from knowledge, comprehension and application, to synthesis, analysis, and finally evaluation. The experiment covers basic concepts of kinematics of particles, specially focusing on the relative motion of multiple particles. Results of the students' experiences will be presented in this paper.

## **2. PROJECT MOTIVATION**

The goal of this project was to design, build and test an apparatus that would relate the theory taught in ME 321, the senior level *Engineering Mechanics – Dynamics* course at Oakland University, about pulleys to practical applications. Most students know the theory of pulleys and their basic design but few have seen the actual applications of them. The best way for students to understand how the theory of what they are learning is to see it being used in real world situations. This laboratory experiment will let students see how small changes in the setup of a pulley system can affect the output, something that can not be taught very well just from a book. The knowledge of the workings of a pulley system will help to cultivate the students engineering sense which can be an engineering student's greatest tool.

### 3. DESIGN OF EXPERIMENT

The laboratory was developed in order to get a better understanding of the material being taught in the class. The experiment covers basic concepts of kinematics of particles, focusing on the relative motion of two particles. This project is to create a pulley system that has a fixed input velocity, travels thru the system and has a measured output velocity. A motor controls the input velocity which is attached to a cord that goes through the designated system that is attached to weight which is the output velocity. The goal was to create a highly versatile experiment that could be changed easily and quickly. This was accomplished by having a varying input velocity and pulleys that could be placed anywhere in the plane of travel. For the varying velocity a pulley with four different diameters was attached to a motor that has a given RPM rating. The cord that is used to run the system is attached to the pulley on the motor creating four different velocities that can be used. The system allows the pulleys to be arranged in any position desired, this was accomplished by mounting a slotted bar to the top and bottom of the apparatus, which allows the pulleys to slide freely into any position. The design of the box was done in such a way that the experiment would not be crowded. With a large height experiments could be run longer because there is more room for the weight to travel. Also having a long width gives the ability to space out the pulleys so that the experiment does not look cluttered and can be more easily understood by the students.

The cost of this experiment was a defining factor in the design of the experiment. The overall cost should be low enough that the experiment is worth the university investing into it. One way cost was cut was by doing most of the expensive labor portions by students for their *Capstone Design Projects* or by having it done free of charge through contacts in the industry.

One thing that was at the center of the project design was that the experiment apparatus be highly durable. Having an experiment that had a limited number of trails was not acceptable. During the selection of materials durability played a larger role in selection. High tension load cable, heavy duty anchor pulleys, an internal gearbox for the motor and solid pine for the box were all used because of their durability.

With all of this in consideration many sketches and proposals were discussed until a final design was agreed upon. Computer aided design software was used to create and modify our design. AutoDesk Inventor 8 software package was used for all of the design purposes. Creating 3-dimensional solid models of the apparatus allowed for complete layout views that were fully dimensioned. This made the actual creating of all the components and assembly purposes much easier.

Outside from the mechanical side of the experiment, designing on the electrical side was also encountered. Since the lab is run from an electric motor, in order to create a user friendly setup which would be easy to use, a timer (Figure 8) was incorporated. This also helps prevent damaging of the setup; if the motor stays on for too long it could break random components. Three On/Off switches were installed so that if the system was in any danger of being damaged it could be easily shutoff. The whole design concept is to

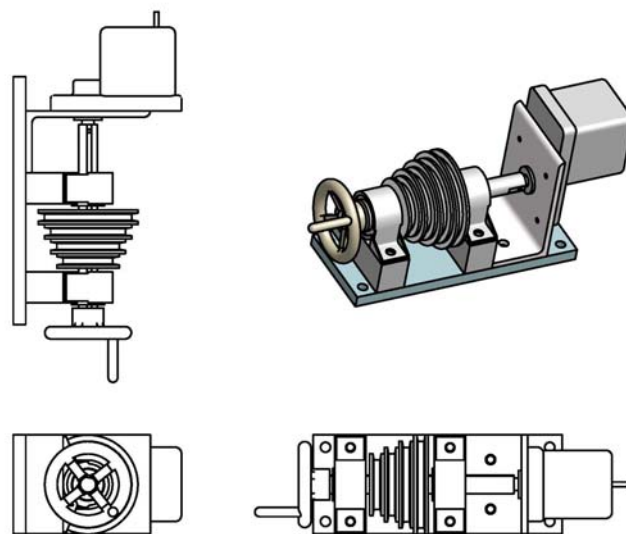
take as many precautions as possible anyone could run the lab without the worry of having difficulties.

#### 4. MANUFACTURING

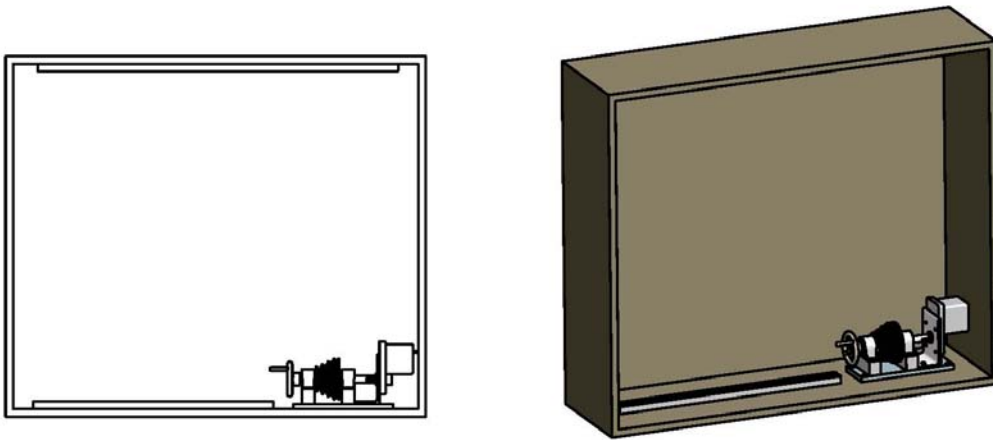
The construction of the lab took roughly a month to complete. The wooden box had to be glued together and then sanded for a smooth finish. The box was then stained with a dark color so the light colored components would vividly stick out. The box was coated with satin three times while sanding in between each. The motor mounting assembly went together smoothly after all the machining was completed. A coat of paint was used to finish the components, giving them a professional look.

The motor shaft only had a length of  $\frac{1}{2}$ " , the shaft had to be extended. A longer shaft was purchased and was attached to the motor using a role pin. Since the shaft was so long it needed to be supported because the load on it could the motor's performance or even cause damage. The solution was using two bearing for support, mounting one on each side of the pulley to make sure the shaft would stay fully constrained. The problem encountered was that the motor did not have a reverse so the cord was easily wound up, but getting it unwound was very difficult. The motor has a built in gear box to accomplish such a low RPM rating, therefore the shaft was very difficult to turn by hand. A hand crank was added which worked exceptionally for easy unwinding.

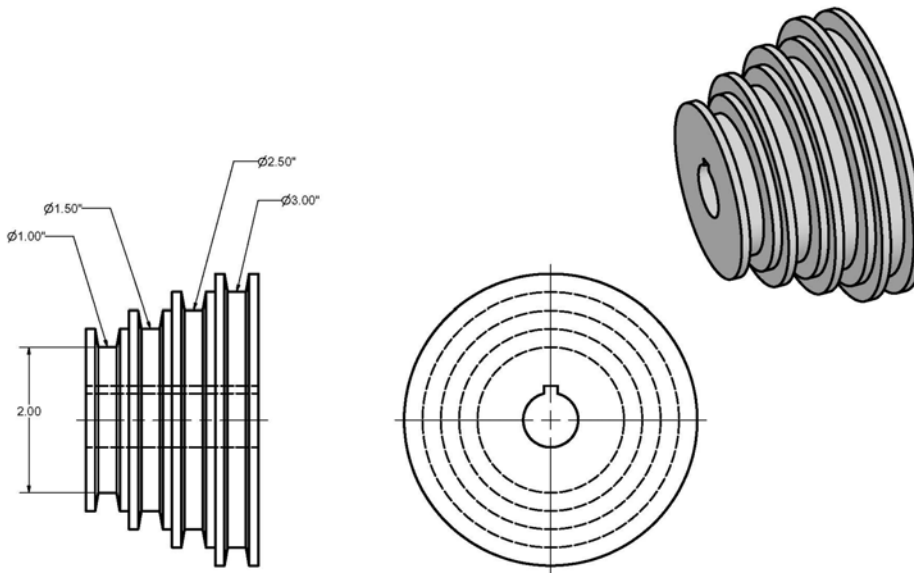
Once the assembly was complete the testing began. The testing process reinforced that the theoretical designed model worked. Adding the crank to the shaft was the only problem that was found during the testing phase. The mechanism worked exactly like it was designed.



**Figure 1:** Motor Mounting Assembly



**Figure 2:** Box and Motor Assembly



**Figure 3:** Pulley Specifications



**115 VAC Gearhead 18.75 RPM CW Rotation High Torque 75 lb-in Merkle Korff “SF” Series Shaded pole motor.**

1.2 Amps, 0.250 quick connect male terminals for connection. Shaft end mounting with 4 tapped (10/32) holes in gear box. Shaft size 1/2" dia x 9/16" long with 3/16" dia hole through shaft for pinning. Rear shaft 3/16" dia x 3/4" long for fan attachment (not supplied). O/A size 5-1/4" H x 3" W x 4" Deep. New.

**Figure 4:** Motor Specifications



**Relay, Time Delay.**

Time Delay Relay, Coil Voltage 120 VAC, Contact Form DPDT, Contact Current Rating Resistive 10 Amps, Maximum Time Range 999 Minutes, Minimum Time Range 0.05 Second, Pins 11, Multi Time Range and Multi Function



**Socket, Relay, 11 Pins.**

Relay Socket, Number of Pins 11, Mounting DIN/Screw, Length 2.20 Inches, Depth 0.97 Inch, Width 2.33 Inches, Current Rating 10 Amps, Electrical Ratings.

**Figure 5.** Timer Control Specifications and Required Accessory



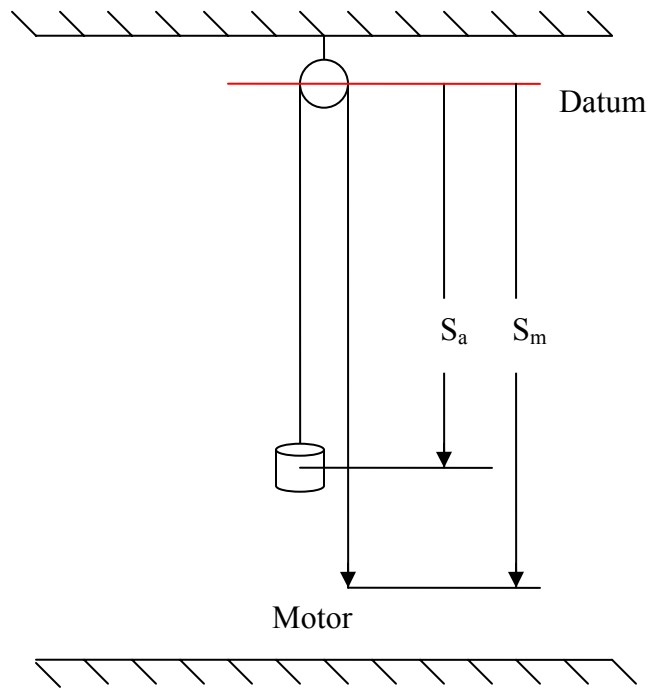
**Figure 6:** Setup the Experiment

## 5. OBJECTIVES

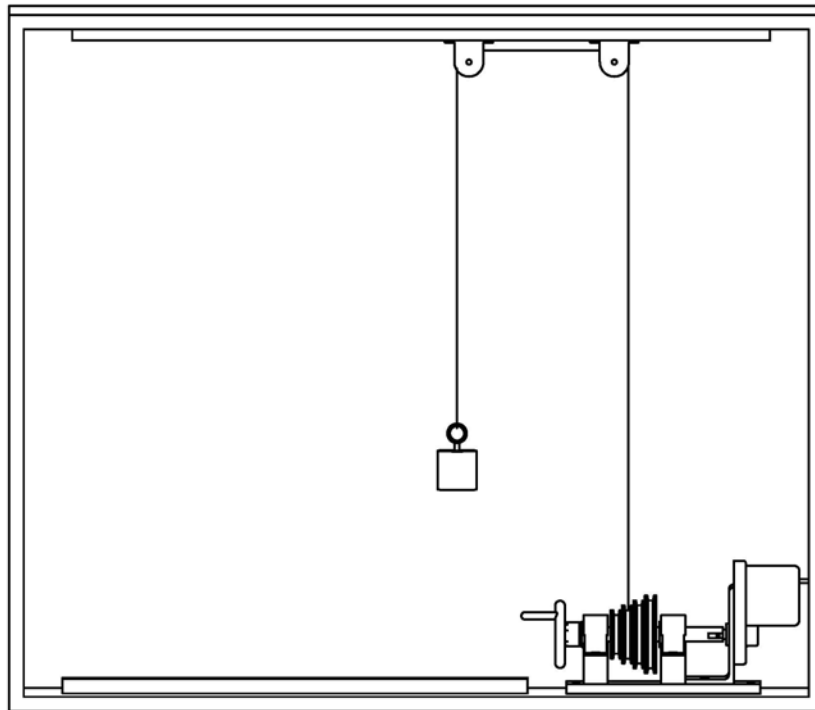
This laboratory was designed so students could get a hands on introduction to kinematics of particles. Seeing concepts carried out in person helps to reinforce all the theoretical material learned from the class. Using the experimental apparatus, two different setups each with four different velocities were conducted recording 10 trials for each, for a total of 80 trials. The objects change in distance was the only measurement from each trial that had to be recorded. The time for each trial was given, so the velocity was easily found. Theoretical data was then compared with the measured data and percent error was calculated. The lab shows how different pulley systems have a relationship with an objects output velocity.

## 6. THEORY

For some systems the motion of one particle is related to another particles corresponding motion. This type of motion is referred to as an Absolute Dependent Motion Analysis of Two Particles. This is evident in systems where particles are attached by a cord that will not stretch which is wrapped about a number of pulleys. The related motion of one particle to another can be solved using position coordinates.



**Figure 7:** Theoretical Schematic of Setup 1



**Figure 8:** Experimental Schematic of Setup 1

Position coordinates are always referenced from a fixed point called a datum. The datum is used to cut the cord in a way that splits the pulleys directly in half so that only the linear portion remains. The position coordinates should be measure in the direction of motion and have a positive direction (Figure 7), which is the first setup for the experiment, is used to demonstrate the theory of the position coordinates. Since the setup would look clustered if done exactly like the theoretical model the experimental schematic was altered slightly so that the experiment is more open. The datum theoretical cuts the cord so that only the vertical component of it remains, which allows for some horizontal changes (Figure 8). This was one of the reasons why the box was designed with a larger width. The velocity ratio of one in the first setup gives that the weight and the block are moving with equal but opposite velocities, hence the velocity of the motor can be found from setup one and used as a base line for setup 2 (Figures 9 and 10).

For setup 2, the total lengths of the cords should be related to the position coordinates by equations 1 and 2.

$$L_1 = (S_m - S_c) + (S_0 - S_c)$$

$$L_1 = S_m + S_0 - 2 \cdot S_c \quad \text{Eq 1.}$$

$$L_2 = S_c + 2 \cdot S_a \quad \text{Eq 2.}$$

Since the velocity of block A is desired and the velocity of the motor is known, equations 1 and 2 can be combined.

$$S_c = \frac{1}{2}S_m + \frac{1}{2}S_0 - \frac{1}{2}L_1$$

$$L_2 = \left(\frac{1}{2}S_m + \frac{1}{2}S_0 - \frac{1}{2}L_1\right) + 2 \cdot S_a \quad \text{Eq 3.}$$

Solving for the combined lengths of cord gives equation 4.

$$L_1 + 2 \cdot L_2 = S_m + S_0 + 4 \cdot S_a \quad \text{Eq 4.}$$

Taking the time derivative of equation 4 realizing that  $L_1$ ,  $L_2$  and  $S_0$  remain constant while  $S_m$  and  $S_a$  measure the lengths of the changing segments of the cord gives equation 5.

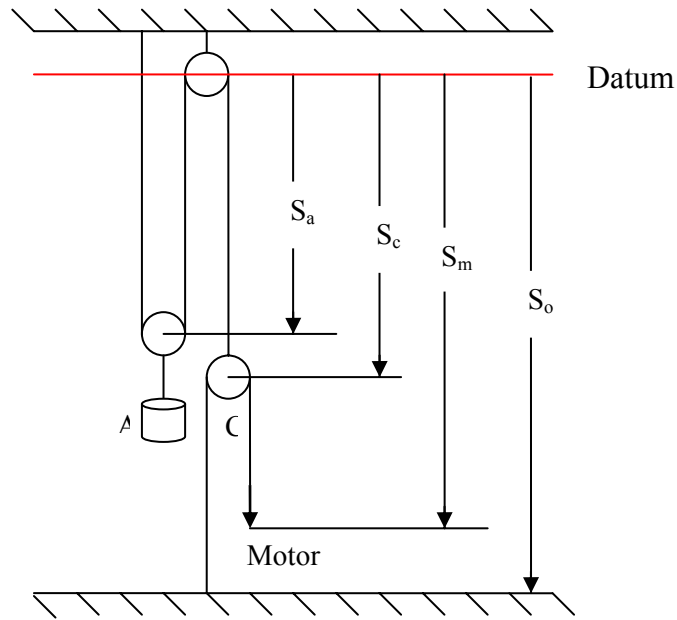
$$\frac{\partial L_1}{\partial t} + 2 \cdot \frac{\partial L_2}{\partial t} = \frac{\partial S_m}{\partial t} + \frac{\partial S_0}{\partial t} + 4 \cdot \frac{\partial S_a}{\partial t}$$

$$0 = V_m + 4 \cdot V_a$$

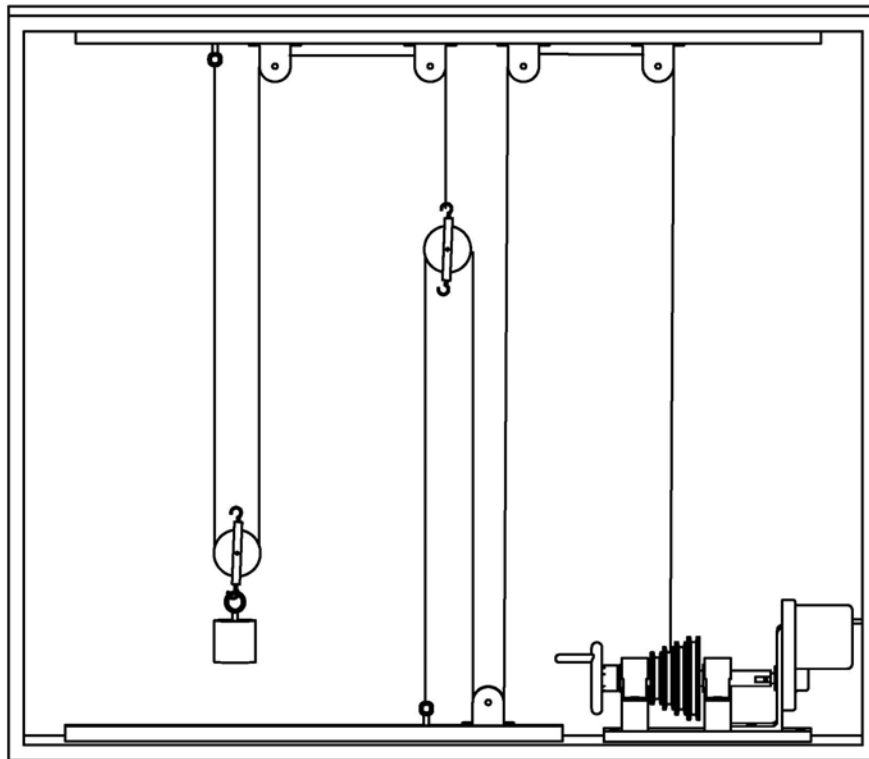
$$V_m = -4 \cdot V_a \quad \text{Eq 5.}$$

The equation gives that the velocity of block A is four times the velocity of the motor and in the opposite direction.





**Figure 9.** Theoretical Schematic of Setup 2



**Figure 10:** Experimental Schematic of Setup 2

## 7. ANALYSIS

The experiment gave off very good results, but some error still occurred. The initial velocity is dependent on the motors speed and also the diameter of the pulley which the cord is being wound. The motors RPM rating is always constant so most of the error from initial velocity is attributed to the diameter of the pulley. Although the diameter is given, when the cord winds it overlaps on top of itself causing the diameter to increase as the experiment runs. This can be noticed by looking at the difference in percent error of pulleys #1 through 4. Since pulley #1 is the smallest it has to wind up the most amount of times, which results in a large change in diameter. Pulley #4 has very little overlap, so the given diameter stays almost constant throughout, giving very accurate results. Other error was obtained from friction and human error. Although friction is an issue, it is neglected due to its small influence over the system. Human error always plays a role in experiments results. Human error could consist of inaccurate measurements of change in distance and setup problems. For the experiment to provide accurate results a good setup is necessary. The pulleys must run parallel with one another; this is accomplished by lining them up by eye. Therefore the more consideration taken in the setup and measurement of the experiment the more accurate the results will be.

## 8. ETHICS

One of the main themes of the project was that it must be safe. It would be unethical to design and fabricate an experiment, pass it on to the students knowing that it could cause them harm. Every piece of the apparatus was designed with safety in mind. One of the first features introduced to help make the experiment safer was the timer control box. Soon after construction was complete it became clear that the lab could danger itself if left on for too long, hence the timer control box. It allows for the experiment to be run without fear of having to shut it off as long as the timer is set correctly. The cord used also went through some modification. Originally a plain 1/16<sup>th</sup> inch galvanized wire rope was used, but the cord could easily cut into students hands and splinter at points where it had been cut. To overcome this hazard a nylon coated cord was used. Also the cord itself was chosen for the fact that it has a 270 pound weight limit which far out cedes the weights actually used. The hand crank was added so that the students did not have to unwind the motor pulley by hand which easily tires the hand. Throughout the entire project design the students' safety was put first.

## 9. CONCLUSION

The laboratory performed just as expected. The use of the step pulley for variable velocities, showed how the smaller the pulley size the greater the percent error will be. Pulleys 1 and 2 were the smaller two and showed much more error than the larger two, pulleys 3 and 4. Pulleys 3 and 4 showed almost no error, this was due to a smaller opportunity for overlapping of the cord. Since pulleys 1 and 2 give off a good amount error, it creates a question for students to figure out why the different diameters relate to the accuracy of the results. Overall the experiment was great success, but for optimal results pulleys 3 and 4 should be used.

## 10. ACKNOWLEDGEMENT:

The author would like to acknowledge two students, Mr. Cesare Scalfani and Ryan Stapleton who have participated in this particular design project in winter 2005 semester at Oakland University. Their enthusiasm, creative thinking, and inquiring questions during their attempts to synthesize better designs, continually fuels the enthusiasm as teachers to discover and develop new ideas and methods to enhance our effectiveness as engineering educators.

## 11. REFERENCES

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Beer, P.F., and Johnston, E.R. (2004). *Vector Mechanics for Engineers Statics and Dynamics*, 7<sup>th</sup> edition, McGraw-Hill.

ME 321 Fall 2004 Homework on 9/7/2004.

ME 321 Fall 2004 Quiz on 9/9/2004.

## 12. PROFESSOR YIN-PING CHANG'S VITA

Yin-ping (Daniel) Chang received his B.S. and M.S. degrees from Department of Mechanical Engineering, National Sun-Yat-San University, Taiwan. He worked for Mitsubishi Motor Corporation (MMC), primarily focused on engine/transmission design; Electric Vehicle/Hybrid Electric Vehicle (EV/HEV) development; and Noise, Vibration, and Harshness (NVH) studies. He was also a new-engine development project manager working with GM, Delphi, Siemens, and Lotus. Dr. Chang later studied transportation, specifically in FEM, computational solid mechanics, and vehicle/tire dynamics fields. Later working in the Vehicle Simulation Research Center, Pennsylvania Transportation Institute, the Pennsylvania State University since fall 1999, Dr. Chang was doing research focused on both physical vehicle crash tests and virtual simulations. He was awarded a Graduate Teaching Fellowship and became an instructor of the undergraduate courses Machine Dynamics, Finite Element Analysis, in Department of Mechanical Engineering at Penn State University. He received his Ph.D. degree in 2002 and continues his research as an assistant professor at Oakland University, Rochester, Michigan. His current research interests include vehicle/tire dynamics, FEA computational solid mechanics, biomechanics, machine dynamics, machine design, and classical mechanism synthesis and analysis



## ME 321 : Dynamics and Vibrations

### Laboratory Experiment #1 Assignment : Lab Handout

#### Particles Kinematics : Absolute Dependent Motion Analysis of Two Particles

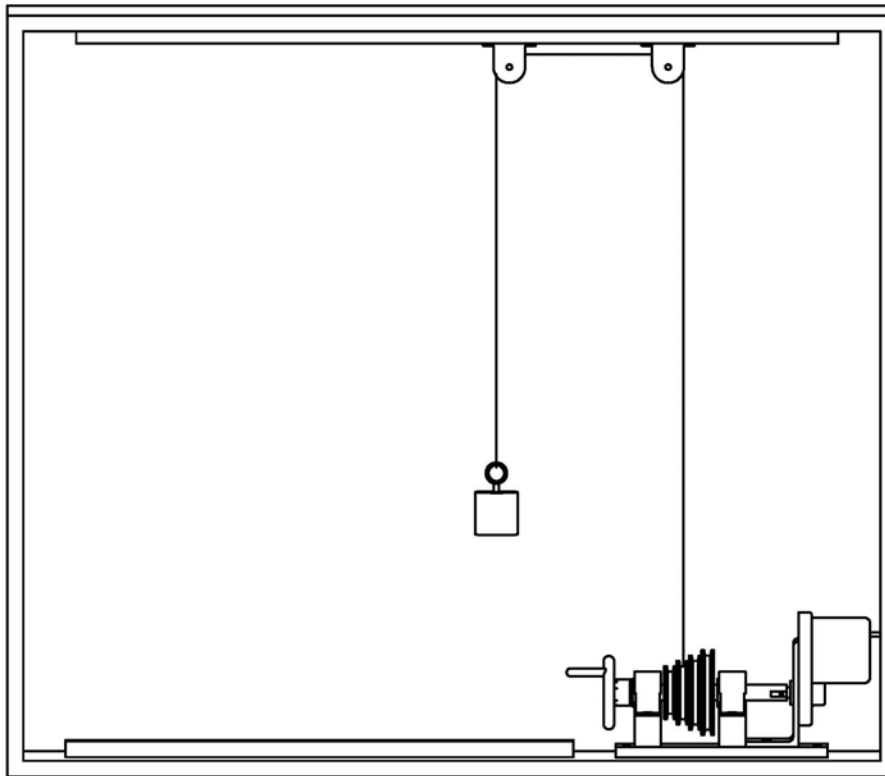


Figure 1. Schematic of Setup 1

### **Objective**

The purpose of this experiment is to introduce the principles of absolute dependent motion analysis of two particles. This principle is used to on problems of motion where one particle is dependent on another particle, i.e. a weight attached to a pulley by an

inelastic cord attached to a motor. As the motor pulls the cord the pulley system can change the velocity of the weight. The setup of the system determines the resulting velocity of the weight.

## Givens

Motor Pulleys Diameters:

1. 1 in
2. 1.5 in
3. 2.5 in
4. 3 in

## Procedure

### Setup 1

1. With the experimental apparatus provide in the lab, set up the experiment shown in Figure 1.
2. Attach cord to specified motor pulley and crank so that the cord bends around pulley.
3. Line up top right anchored pulley to specified motor pulley marked on the top T bar.
4. Turn on motor by moving switch push in the line. Pushing in the circle will turn off motor.
5. Check to make sure timer's second dial is on "one shot" setting.
6. Input desired time, making sure timer's first dial is set accordingly. For the "9.99S" setting an input of 1 0 0 will give a time of 1 second. For the "99.9S" setting an input of 1 0 0 will give a time of 10 seconds.

NOTE: the first or second should be the only settings used. DO NOT USE the "999S", "99.9M", or the "999M" settings.

7. Measure initial distance from floor to weight.
8. Turn on timer control box by flipping switch from "Off" to "Timer On".
9. Start the motor by flipping "Pull Timer On" switch once.

NOTE: if at any time the cord begins to become over wound (i.e. a weight or a pulley starts to become pulled into an anchored pulley) flipping "Timer On" switch to the "Off" position will stop the motor.

10. Measure final distance making sure to measure to the same spot that was measured for the initial distance.
11. Wind weight back down using hand crank.
12. Repeat steps 7 through 11 nine times for a total of ten experimental data points.

## Setup 2

1. With the experimental apparatus provide in the lab, set up the experiment shown in Figure 2.
2. Complete steps 2 through 12 for setup 1.

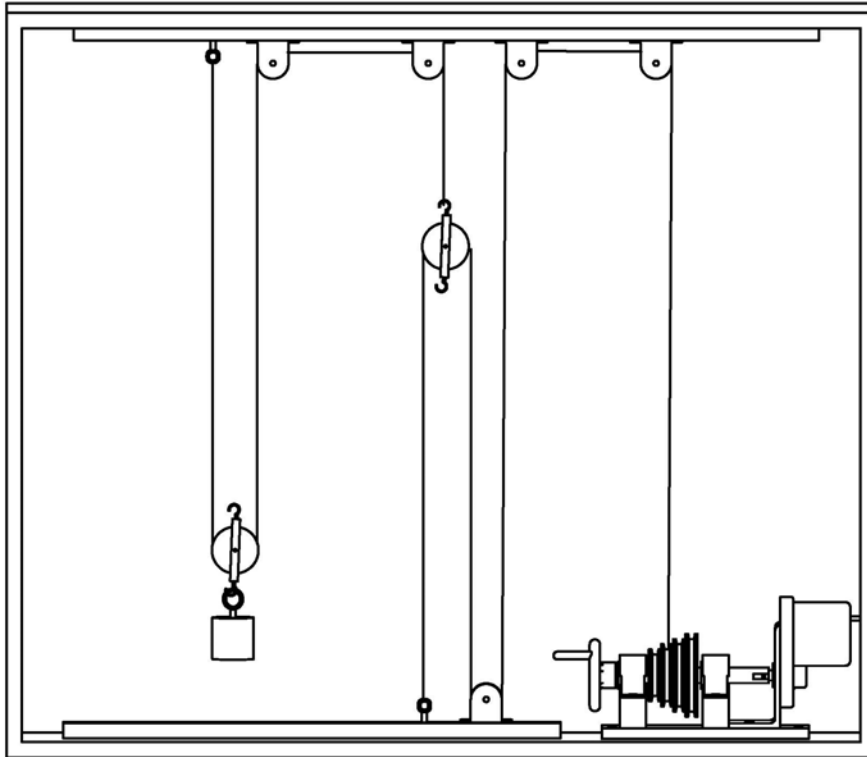


Figure 2. Schematic of Setup 2

## Assignment Specifications

1. Derive equations for the length of cord using position coordinates for setup 2.
2. From Setup 1 calculate velocity of the weight and the motor pulley velocity for each motor pulley (neglect friction of the pulleys). Tabulate data for all trials and averages.
3. With the velocities of the motor pulleys and the given diameters calculate the rpm of the motor.
4. Using the velocities of the motor pulleys solve for the velocity of the weight in setup 2. Tabulate data for all trials and averages.
5. If the motor had 18.75 rpm, calculate percent error from the trial averages for both setups.
6. Explain what reasons could cause errors during the experiment.



**ME 321 : Dynamics and Vibrations**

**Laboratory Experiment #1 Assignment: Example Lab Report**

**Particles Kinematics : Absolute Dependent Motion Analysis of Two Particles**

Submitted to: Prof. Yin-ping Chang

Prepared by:

Cesare Sclafani  
Ryan Stapleton

## Introduction

The purpose of this experiment was to introduce kinematics of particles. The velocity of the weight was dependent on the velocity of the motor pulley. For each of the two setups a total of ten trials were conducted on each motor pulley. By using the experimental apparatus the velocity of the weights was related to the velocity of the motor using a velocity ratio.

## Theory

The total lengths of the cords should be related to the position coordinates by equations 1 and 2.

$$L_1 = (S_m - S_c) + (S_0 - S_c)$$
$$L_1 = S_m + S_0 - 2 \cdot S_c \quad \text{Eq 1.}$$

$$L_2 = S_c + 2 \cdot S_a \quad \text{Eq 2.}$$

Since the velocity of block A is desired and the velocity of the motor is known equations 1 and 2 can be combined.

$$S_c = \frac{1}{2}S_m + \frac{1}{2}S_0 - \frac{1}{2}L_1$$
$$L_2 = \left(\frac{1}{2}S_m + \frac{1}{2}S_0 - \frac{1}{2}L_1\right) + 2 \cdot S_a \quad \text{Eq 3.}$$

Solving for the combined lengths of cord gives equation 4.

$$L_1 + 2 \cdot L_2 = S_m + S_0 + 4 \cdot S_a \quad \text{Eq 4.}$$

Taking the time derivative of equation 4 realizing that  $L_1$ ,  $L_2$  and  $S_0$  remain constant while  $S_m$  and  $S_a$  measure the lengths of the changing segments of the cord gives equation 5.

$$\frac{\partial L_1}{\partial t} + 2 \cdot \frac{\partial L_2}{\partial t} = \frac{\partial S_m}{\partial t} + \frac{\partial S_0}{\partial t} + 4 \cdot \frac{\partial S_a}{\partial t}$$
$$0 = V_m + 4 \cdot V_a$$
$$V_m = -4 \cdot V_a \quad \text{Eq 5.}$$

The equation gives that the velocity of block A is four times the velocity of the motor and in the opposite direction.



## Results and Discussion

Using the data for motor pulley four in setup one the experimental rpms of the motor was found to be 18.8 revolutions per minute.

The velocity for the weight at each pulley for each setup was calculated ten times. The averages were also found and used to find the percent error of the apparatus. These data points can be seen in Tables 1 through 4. For the first motor pulley in setup one had the highest percent error of any pulley in setup one (Table 2). This is due to the fact that as the motor turns the pulley the cord is wound around the pulley which increases its diameter every time it completes a revolution. This increase in diameter changes the velocity of the motor pulley because the velocity of the motor pulley is the angular velocity of the motor multiplied by the diameter. The change in velocity cause the weight's velocity to increase as the time wears on. For motor pulley two in setup one the percent error is still high but is decreased because of the fact that it has a larger circumference and the cord is not wrapped around as many times. Motor pulleys three and four, in setup one, have drastically smaller percent errors because of even larger circumferences that will wrap the cord to the side not on top (Table 3).

During setup every motor pulley has an increase in percent error due to longer running times. Motor pulley one gives the highest percent error for the entire experiment since it has a running time of 28 seconds. This results in the cord wrapping itself around the pulley numerous times. The percent error increases for pulley two due to the same wrapping effect as in pulley one (Table 4). Pulleys three and four also see an increase in percent error but not to the same effect as the other pulleys (Table 5).

A brief comparison of the experimental and theoretical values is listed in Table 1.

**Table 1.** A Brief Comparison of the Experimental and Theoretical Values

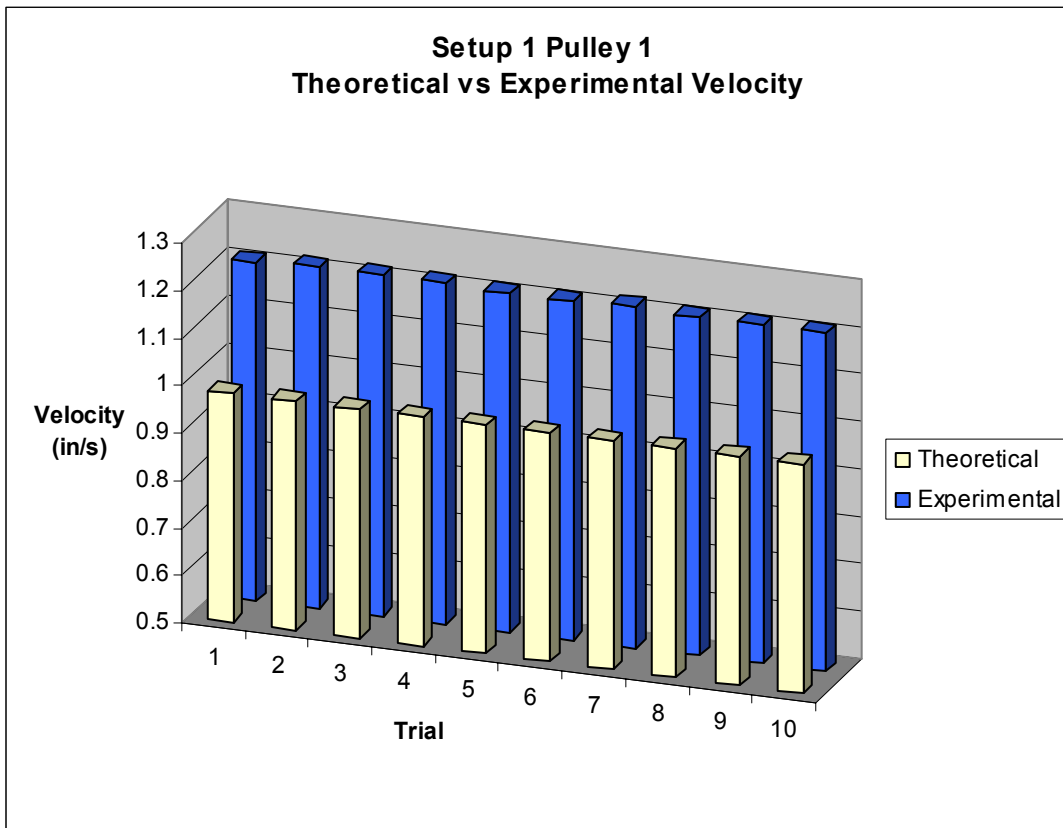
| Setup 1 |               |              |        | Setup 2 |              |              |        |
|---------|---------------|--------------|--------|---------|--------------|--------------|--------|
| Pulley  | Experimental  | Theoretical  | Error  | Pulley  | Experimental | Theoretical  | Error  |
| 1       | 1.215 in/s    | 0.98175 in/s | 19.19% | 1       | 0.32701 in/s | 0.24543 in/s | 24.95% |
| 2       | 1.57063 in/s  | 1.47263 in/s | 6.24%  | 2       | 0.41094 in/s | 0.36816 in/s | 10.41% |
| 3       | 2.46094 in/s  | 2.45438 in/s | 0.27%  | 3       | 0.63144 in/s | 0.61359 in/s | 2.91%  |
| 4       | 2.953125 in/s | 2.94525 in/s | 0.27%  | 4       | 0.75833 in/s | 0.73631 in/s | 2.90%  |

## Conclusion

Overall this experiment demonstrates the concepts of particle kinematics with clarity that is hard to find in the classroom. To be able to see how changing the system changes the output gives a better understanding of the material. Using the experimental apparatus it was possible to calculate velocities of four different motor pulleys and the velocity of the dependent weight for eight different systems. It has shown that changing the diameter of the motor pulley will change the velocity from a constant.

**Table 2. Setup 1 Pulley 1**

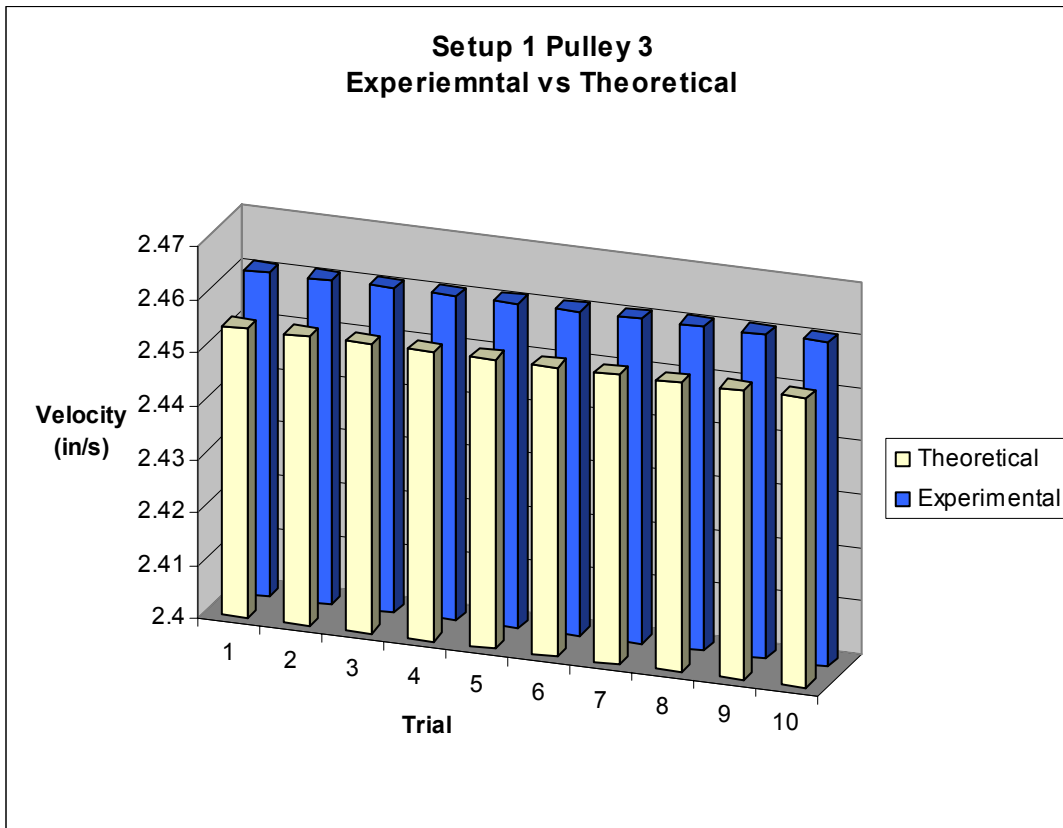
| <b>Setup 1</b>       |              |                                |                     |                                   |                 |
|----------------------|--------------|--------------------------------|---------------------|-----------------------------------|-----------------|
| <b>Pulley 1</b>      |              | <b>V measured=0.98175 in/s</b> |                     | <b>V theoretical=0.98175 in/s</b> |                 |
| <b>Trial</b>         | <b>Start</b> | <b>Stop</b>                    | <b>Displacement</b> | <b>Time</b>                       | <b>Velocity</b> |
| 1                    | 4 in         | 16.1250 in                     | 12.1250 in          | 10 sec                            | 1.21250 in/s    |
| 2                    | 4 in         | 16.1875 in                     | 12.1875 in          | 10 sec                            | 1.21875 in/s    |
| 3                    | 4 in         | 16.1875 in                     | 12.1875 in          | 10 sec                            | 1.21875 in/s    |
| 4                    | 4 in         | 16.1875 in                     | 12.1875 in          | 10 sec                            | 1.21875 in/s    |
| 5                    | 4 in         | 16.1250 in                     | 12.1250 in          | 10 sec                            | 1.21250 in/s    |
| 6                    | 4 in         | 16.1250 in                     | 12.1250 in          | 10 sec                            | 1.21250 in/s    |
| 7                    | 4 in         | 16.1875 in                     | 12.1875 in          | 10 sec                            | 1.21875 in/s    |
| 8                    | 4 in         | 16.1250 in                     | 12.1250 in          | 10 sec                            | 1.21250 in/s    |
| 9                    | 4 in         | 16.1250 in                     | 12.1250 in          | 10 sec                            | 1.21250 in/s    |
| 10                   | 4 in         | 16.1250 in                     | 12.1250 in          | 10 sec                            | 1.21250 in/s    |
| <b>Average</b>       |              |                                | 12.1500 in          | 10 sec                            | 1.21500 in/s    |
| <b>Percent Error</b> |              |                                |                     |                                   | <b>19.19%</b>   |



**Figure 1. Setup 1 Pulley 1 Experimental vs. Theoretical Velocity**

**Table 3. Setup 1 Pulley 3**

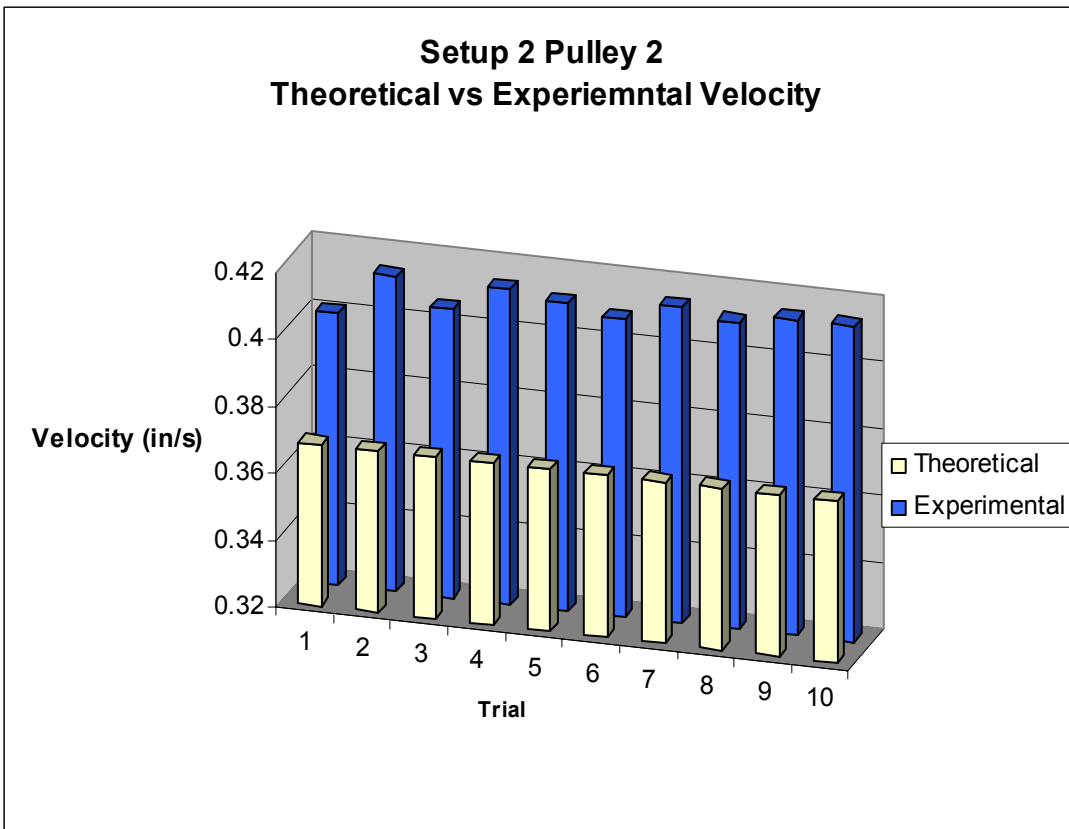
| <b>Setup 1</b>       |              |                                 |                     |                                    |                 |
|----------------------|--------------|---------------------------------|---------------------|------------------------------------|-----------------|
| <b>Pulley 3</b>      |              | <b>V measured =2.45438 in/s</b> |                     | <b>V theoretical =2.45438 in/s</b> |                 |
| <b>Trial</b>         | <b>Start</b> | <b>Stop</b>                     | <b>Displacement</b> | <b>Time</b>                        | <b>Velocity</b> |
| 1                    | 4 in         | 23.6875 in                      | 19.6875 in          | 8 sec                              | 2.46094 in/s    |
| 2                    | 4 in         | 23.6875 in                      | 19.6875 in          | 8 sec                              | 2.46094 in/s    |
| 3                    | 4 in         | 23.6875 in                      | 19.6875 in          | 8 sec                              | 2.46094 in/s    |
| 4                    | 4 in         | 23.6875 in                      | 19.6875 in          | 8 sec                              | 2.46094 in/s    |
| 5                    | 4 in         | 23.6875 in                      | 19.6875 in          | 8 sec                              | 2.46094 in/s    |
| 6                    | 4 in         | 23.6875 in                      | 19.6875 in          | 8 sec                              | 2.46094 in/s    |
| 7                    | 4 in         | 23.6875 in                      | 19.6875 in          | 8 sec                              | 2.46094 in/s    |
| 8                    | 4 in         | 23.6875 in                      | 19.6875 in          | 8 sec                              | 2.46094 in/s    |
| 9                    | 4 in         | 23.6875 in                      | 19.6875 in          | 8 sec                              | 2.46094 in/s    |
| 10                   | 4 in         | 23.6875 in                      | 19.6875 in          | 8 sec                              | 2.46094 in/s    |
| <b>Average</b>       |              |                                 | 19.6875 in          | 8 sec                              | 2.46094 in/s    |
| <b>Percent Error</b> |              |                                 |                     |                                    | <b>0.27%</b>    |



**Figure 2. Setup 1 Pulley 3 Experimental vs. Theoretical Velocity**

**Table 4. Setup 2 Pulley 2**

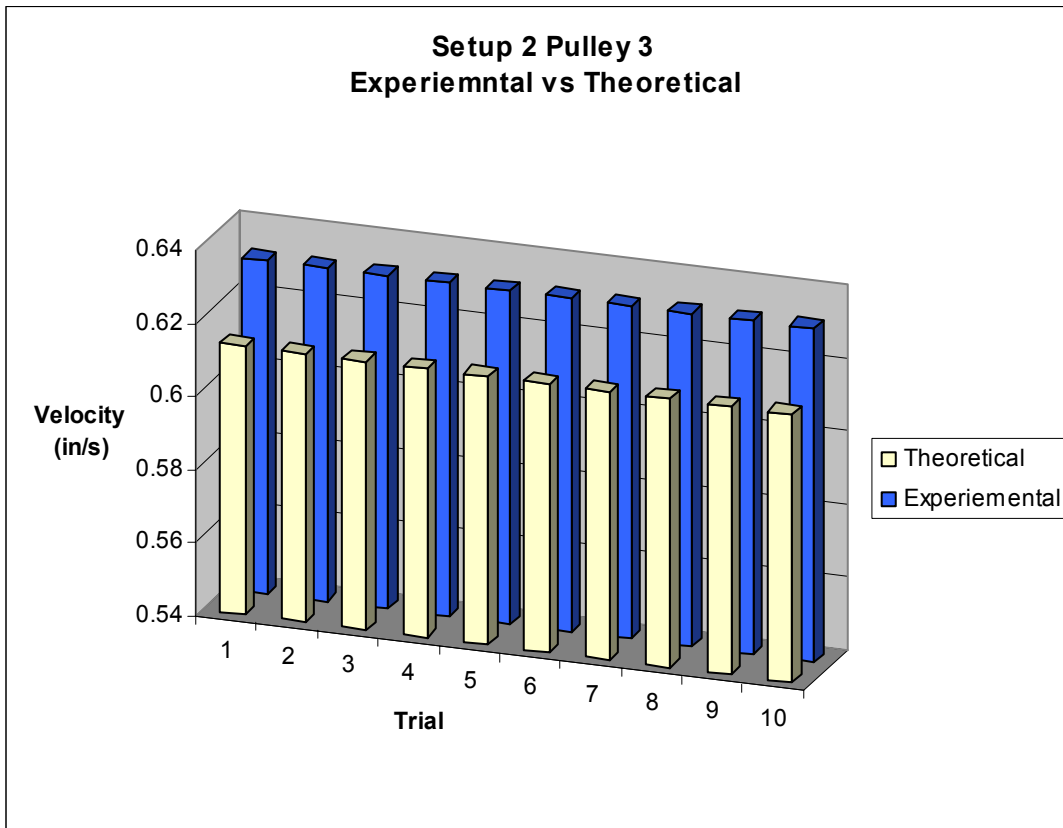
| <b>Setup 2</b>       |              |                                 |                     |                                    |                 |
|----------------------|--------------|---------------------------------|---------------------|------------------------------------|-----------------|
| <b>Pulley 2</b>      |              | <b>V measured =1.47263 in/s</b> |                     | <b>V theoretical =0.36816 in/s</b> |                 |
| <b>Trial</b>         | <b>Start</b> | <b>Stop</b>                     | <b>Displacement</b> | <b>Time</b>                        | <b>Velocity</b> |
| 1                    | 6 in         | 15.6255 in                      | 9.6255 in           | 24 sec                             | 0.40106 in/s    |
| 2                    | 6 in         | 15.9375 in                      | 9.9375 in           | 24 sec                             | 0.41406 in/s    |
| 3                    | 6 in         | 15.7500 in                      | 9.7500 in           | 24 sec                             | 0.40625 in/s    |
| 4                    | 6 in         | 15.9375 in                      | 9.9375 in           | 24 sec                             | 0.41406 in/s    |
| 5                    | 6 in         | 15.8750 in                      | 9.8750 in           | 24 sec                             | 0.41145 in/s    |
| 6                    | 6 in         | 15.8125 in                      | 9.8125 in           | 24 sec                             | 0.40885 in/s    |
| 7                    | 6 in         | 15.9375 in                      | 9.9375 in           | 24 sec                             | 0.41406 in/s    |
| 8                    | 6 in         | 15.8750 in                      | 9.8750 in           | 24 sec                             | 0.41145 in/s    |
| 9                    | 6 in         | 15.9375 in                      | 9.9375 in           | 24 sec                             | 0.41406 in/s    |
| 10                   | 6 in         | 15.9375 in                      | 9.9375 in           | 24 sec                             | 0.41406 in/s    |
| <b>Average</b>       |              |                                 | 9.8625 in           | 24 sec                             | 0.41094 in/s    |
| <b>Percent Error</b> |              |                                 |                     |                                    | <b>10.41%</b>   |



**Figure 3. Setup 2 Pulley 2 Experimental vs. Theoretical Velocity**

**Table 5. Setup 2 Pulley 4**

| <b>Setup 2</b>       |              |                                 |                     |                                    |                 |
|----------------------|--------------|---------------------------------|---------------------|------------------------------------|-----------------|
| <b>Pulley 4</b>      |              | <b>V measured =2.94525 in/s</b> |                     | <b>V theoretical =0.73631 in/s</b> |                 |
| <b>Trial</b>         | <b>Start</b> | <b>Stop</b>                     | <b>Displacement</b> | <b>Time</b>                        | <b>Velocity</b> |
| 1                    | 6 in         | 17.375 in                       | 11.375 in           | 15 sec                             | 0.75833 in/s    |
| 2                    | 6 in         | 17.375 in                       | 11.375 in           | 15 sec                             | 0.75833 in/s    |
| 3                    | 6 in         | 17.375 in                       | 11.375 in           | 15 sec                             | 0.75833 in/s    |
| 4                    | 6 in         | 17.375 in                       | 11.375 in           | 15 sec                             | 0.75833 in/s    |
| 5                    | 6 in         | 17.375 in                       | 11.375 in           | 15 sec                             | 0.75833 in/s    |
| 6                    | 6 in         | 17.375 in                       | 11.375 in           | 15 sec                             | 0.75833 in/s    |
| 7                    | 6 in         | 17.375 in                       | 11.375 in           | 15 sec                             | 0.75833 in/s    |
| 8                    | 6 in         | 17.375 in                       | 11.375 in           | 15 sec                             | 0.75833 in/s    |
| 9                    | 6 in         | 17.375 in                       | 11.375 in           | 15 sec                             | 0.75833 in/s    |
| 10                   | 6 in         | 17.375 in                       | 11.375 in           | 15 sec                             | 0.75833 in/s    |
| <b>Average</b>       |              |                                 | 11.375 in           | 15 sec                             | 0.75833 in/s    |
| <b>Percent Error</b> |              |                                 |                     |                                    | <b>2.90%</b>    |



**Figure 4. Setup 2 Pulley 4 Experimental vs. Theoretical Velocity**