A Slider/Ramp Apparatus Capstone Design Project for a Hands-On Senior-Level Laboratory Design Experience

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1. ABSTRACT

This paper describes a particle/rigid body kinematics measurement experiment for the senior 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 2nd 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, which is a precursor to the *Capstone Design Project* at Oakland University, to introduce students to particle and rigid body kinematics properties measurement techniques to measure particle and rigid body's positions, velocities, and accelerations from a slider/ramp apparatus. 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 and kinetics of particles and rigid bodies. Three objects were used on this slider/ramp apparatus, they were a sphere, a disk, and a hoop which were considered as particles first. The theoretical distance in the horizontal and vertical directions would have to be calculated by the students before running the experiment. It would be noticed that these three objects (considered initially as only particles) would not follow the theoretically calculated trajectory. This is because these objects should have been considered as rigid bodies instead, not just particles, as the experimenters will learn themselves about the differences between particles and rigid bodies, the students were asked to validate the laws of particle/rigid body kinematics, and the law of conservation of energy. Results of the students' experiences will be presented in this paper.

2. OBJECTIVES

The purpose of this project was to design, analyze, manufacture, test, and validate an experiment that relates ME 321, the senior level *Engineering Mechanics – Dynamics* course at Oakland University, to a real world situation. The apparatus had to be mobile, sturdy, safe, and functional so that any student can easily run the necessary tests to validate theoretical data with experimental observations. A simple ramp profile apparatus yielded a minimum error of -0.1% with a rolling sphere at an angle of 45º while a maximum error of -43.58% was observed with an imperfect rolling hoop (a disk was also tested).

It is sometimes difficult to relate the techniques and applications learned in class to real world problems. While learning the theory, equations and applications in class, students can heighten their understanding if they observe it first-hand in a laboratory experiment. To create an experiment that will help the students better understand the concepts and how they can be used to solve real world problems. The particular experiment that we have created encompasses the concept of particle and rigid body kinematics in addition to the energy principle.

The main experimental objective of this experiment is to relate experimental data with theoretical calculations that validate the laws of particle/rigid body kinematics, and the law of conservation of energy.

3. DESIGN OF EXPERIMENT

This particular lab was to be designed so that it was user-friendly and durable so it would not break as it is transported and used by many students over a number of years. The idea that was decided upon was an experiment that consisted of four ramps were made of profiles and interchangeable ramp blocks that three objects, considered as particles first and then rigid bodies, would roll off from. At the end of the ramp, they would be sent into a trajectory at an angle that could be changed easily for different trial measurements and calculations. The bodies would then go through a ring that was attached to a bar at a certain horizontal distance away from the launch point and a certain height above the zero reference point. The theoretical distance in the horizontal and vertical directions would have to be calculated by the students before running the experiment. The three objects chosen for the experiment were different in size, but all were assumed to be perfectly round. The objects were a sphere, a disk, and a hoop. It was assumed that all objects have negligible air drag and contact resistance. This was a key part of the experiment because with these assumptions, there may be error associated with the overall experimental results. It would be noticed that the sphere (considered initially as a particle) would go through the ring, but not at the theoretically calculated values. This is because the sphere should have been considered as a rigid body, not a particle, as the experimenters will learn themselves about all of the objects used.

The material chosen to build this experiment was wood with a smooth finish to provide a smooth rolling surface for all the objects used. This was also a cost-effective answer to the question of which material should be used. There was no real consideration of the properties of the material in terms of allowable or maximum stress and strain because the load (each ball) would be essentially negligible. As stated earlier, the sturdiness in order to achieve repeated usage was the main materials concern.

A groove was going to be indented down the middle of the ramp to stabilize the rolling of each object, but an aluminum sheet metal railing was determined to be the best solution. It was made certain that the adjustments would allow each object to roll freely down the center of the ramp. Another main design constraint was that the ramp could only be large enough to transport easily on a standard, four-wheeled cart. The width of the ramp had to be wide enough to stabilize the sphere, disk, and hoop on either side. There was also the part of the ramp that needed to be interchangeable due to different angle measures. Each of the four blocks represents a different, smooth launching angle. The angle measures were 30, 45, 60, and 75 degrees. This would allow for different calculations, again, of the horizontal distance and height that the ring needed to be placed at. Please refer to Figure 1 below for a detailed visual representation of the experimental apparatus as a system.

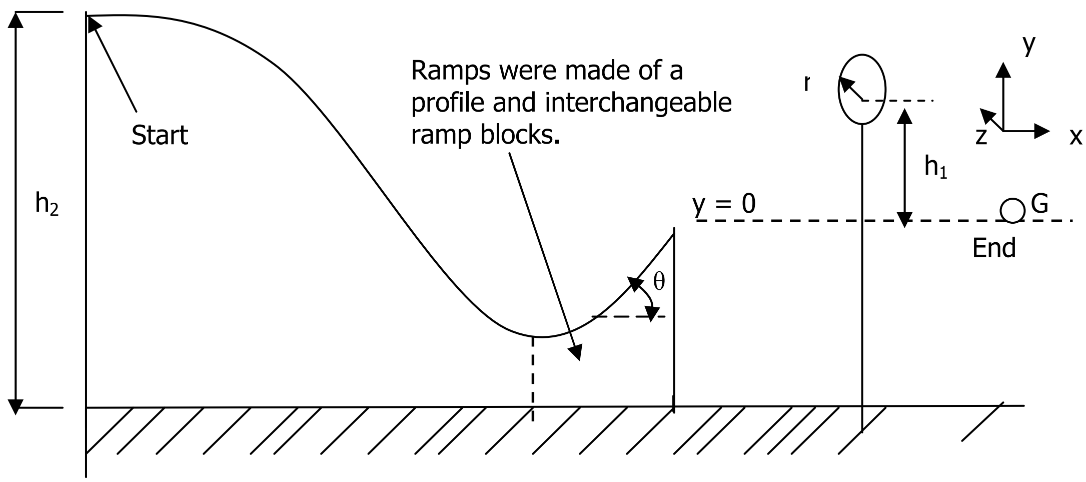


Figure 1. *Particle/Rigid Body Kinematics Apparatus*

Point G is the "ground point" where each ball will come back down to after it is dropped from the top of the ramp at h_2. Play dough was placed around ground point to measure the distance the projectile travels. This is quite a clever solution since the dent of Play dough can be determined very easily and precisely by the flexibility a material like Play dough has. For example, if the instructor wanted future students to measure different heights, it could easily be performed in lab. The height h_1 is the measurement from the leaving point of the ramp to the highest point of trajectory (where the velocity in the y-direction is equal to zero) which is figured to be the center of the ring as well.

The convenience, user-friendliness, and technical factors were all considered before the production of this very design. All this was achieved keeping in mind that the technical data needed to be as accurate as possible. The values needed to be convenient enough to build the desired size apparatus while making sure that the measurements were accurate enough to take a somewhat precise measurement with a standard ruler or meter stick.

4. MODERN ENGINEERING TOOLS

The use of modern engineering tools is important in any project. SolidWorks was utilized in the design of this experiment before construction. Figures 2a, b, c, d, e, and f show the profile, 30, 45, 60, 75 degree ramps, and the target in SolidWorks CAD software, respectively.

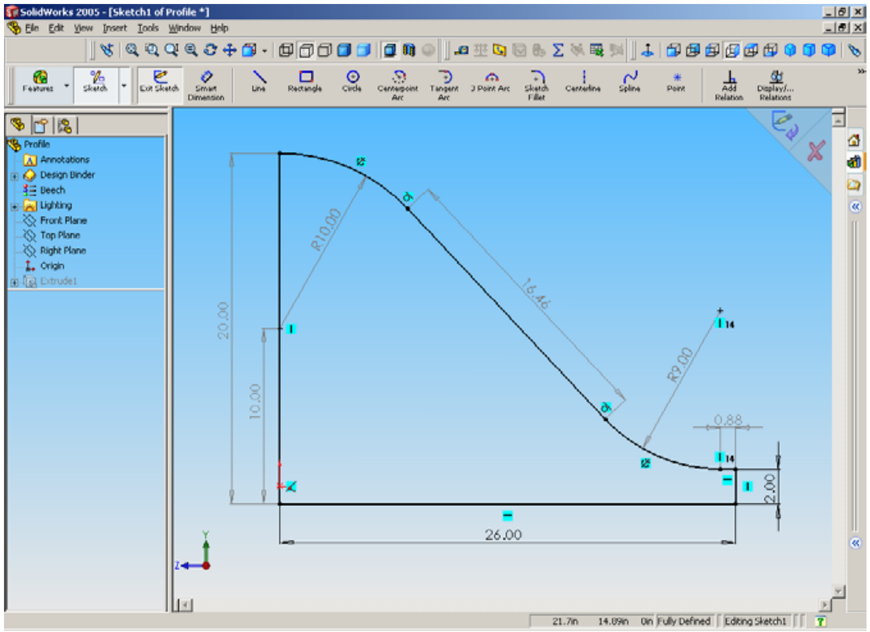


Figure 2a. *Profile CAD Drawing*

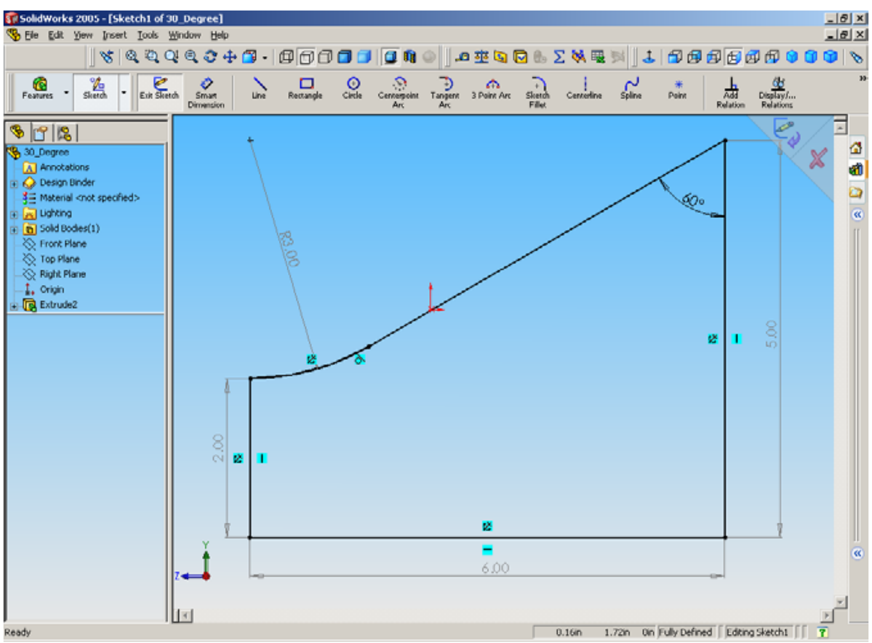


Figure 2b. *30° CAD Drawing*

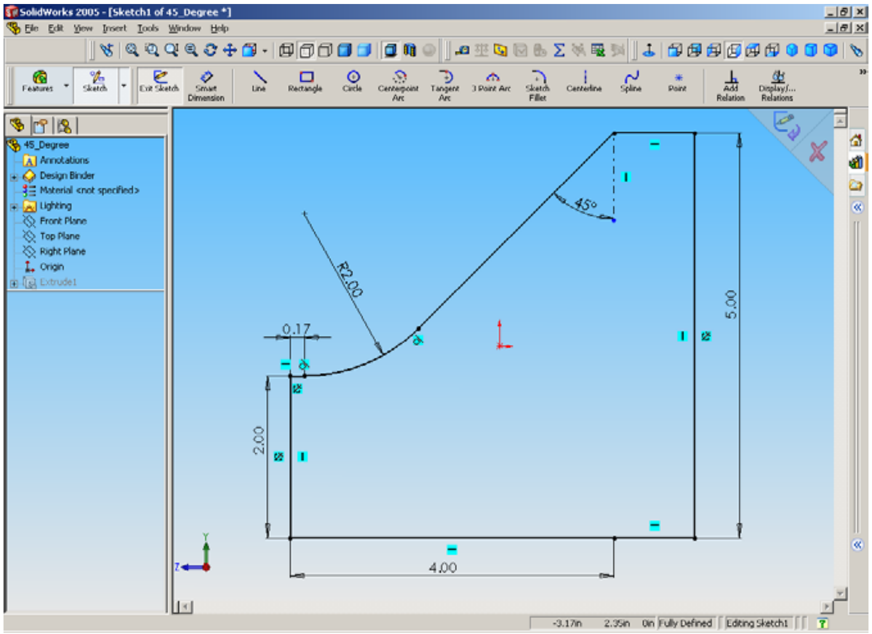


Figure 2c. *45º CAD Drawing*

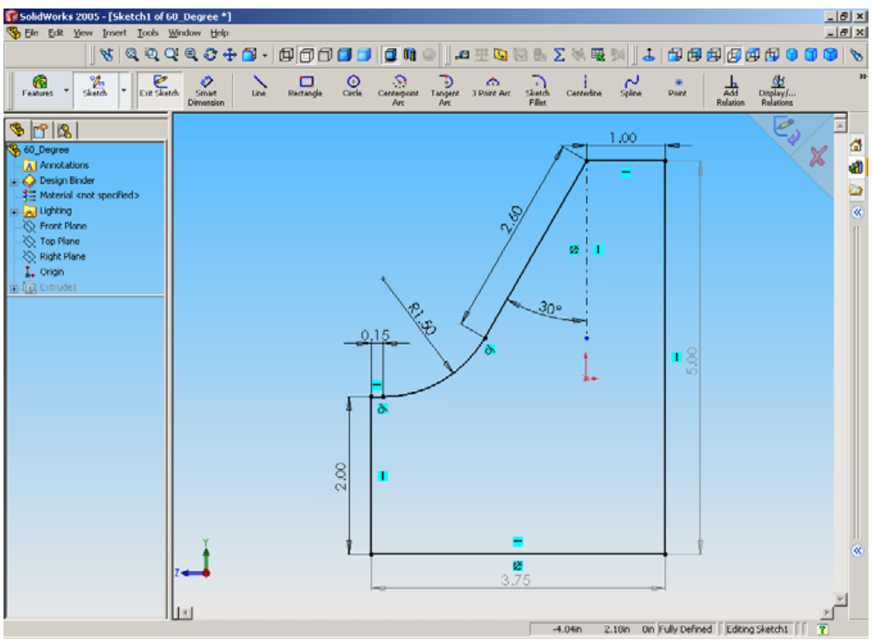


Figure 2d. *60º CAD Drawing*

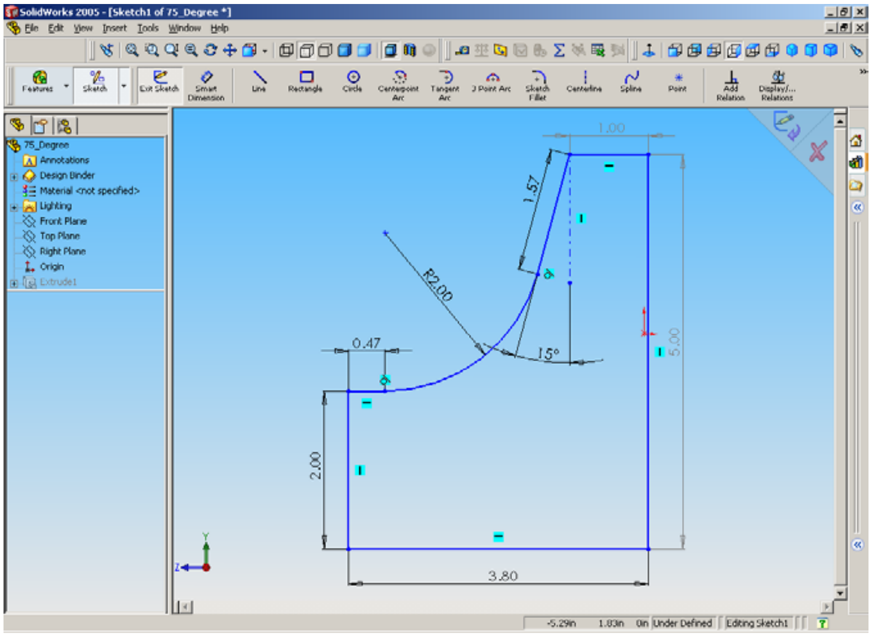


Figure 2e. *75° CAD Drawing*

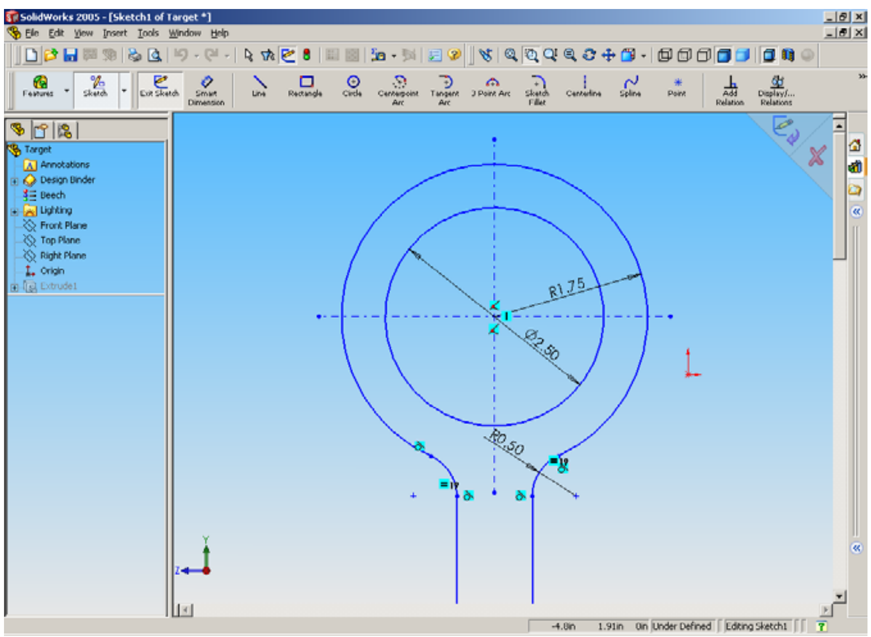
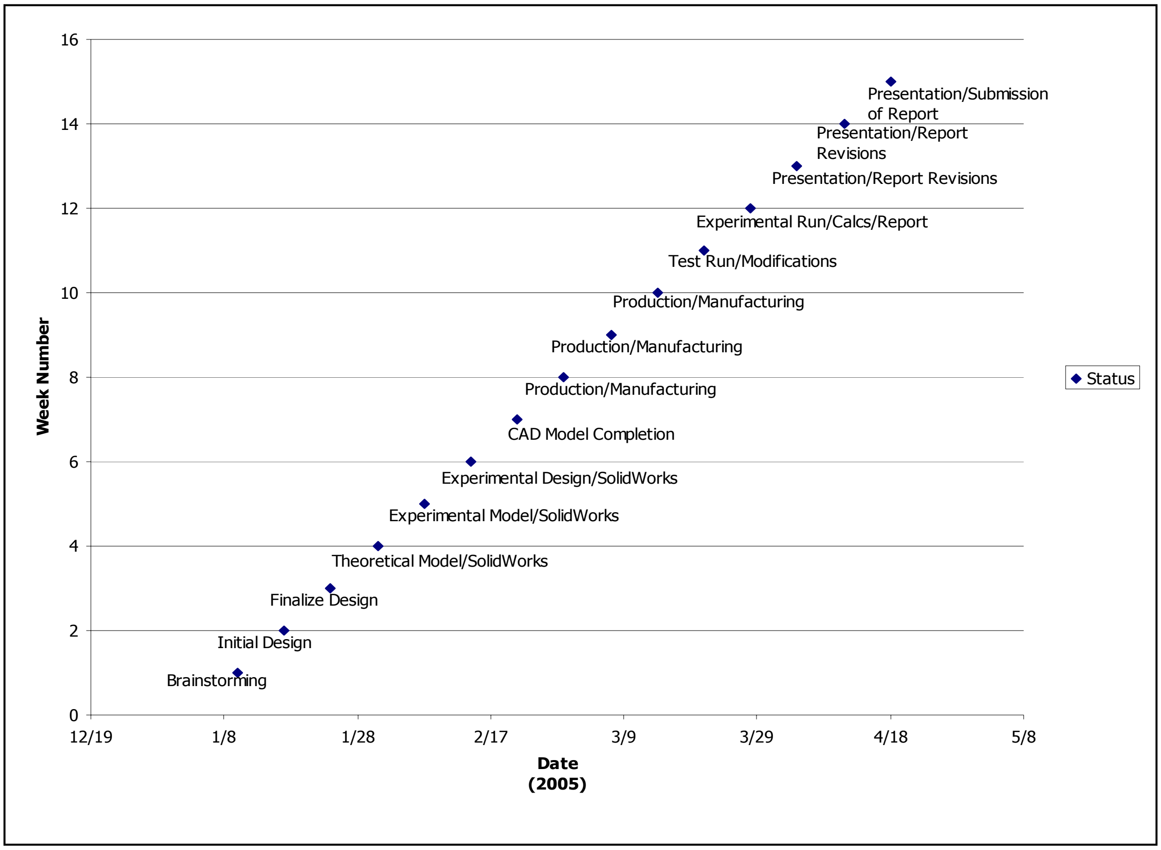


Figure 2f. *Target CAD Drawing*

5. MANUFACTURING PROCESS

After design and theory were considered, it was time to bring the apparatus to life. A timeline can be seen below in Table 1, describing the amount of time that was utilized for each process in creating this experiment.

Table 1. *Timeline Analysis*



A small, yet effective change was made to all of the ramp blocks in the manufacturing stage of the project. It was noticed that the higher angle ramps were too pointy at the edges and needed some type of integrity to ensure long life. The answer to this problem was just adding another inch of material at the end of each ramp. Refer to Figure 2 and 3 for details. This gave each ramp block more integrity so that it could be handled somewhat roughly during experiments. A one inch extension was added to the beginning of the profile to ensure consistent results as well. The students are not asked to push the object to get it rolling, but rather to "let it drop" so that the energy principle can correctly be applied.

The target that was used had to be made of a material that was lightweight so that an aluminum bar would be able to support it firmly in cases where objects would hit the sides of the target rather than go through the middle. The chosen material was a type of urethane called Renboard.

Once the apparatus was designed, constructed, customized, and assembled, it was time to finish the surfaces with three coats of primer for surface protection and aesthetics. Total estimated production time was 45 hours.

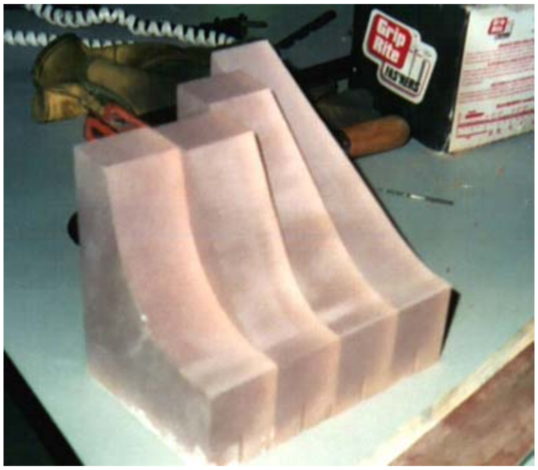


Figure 3a. Cutout of Ramp Blocks

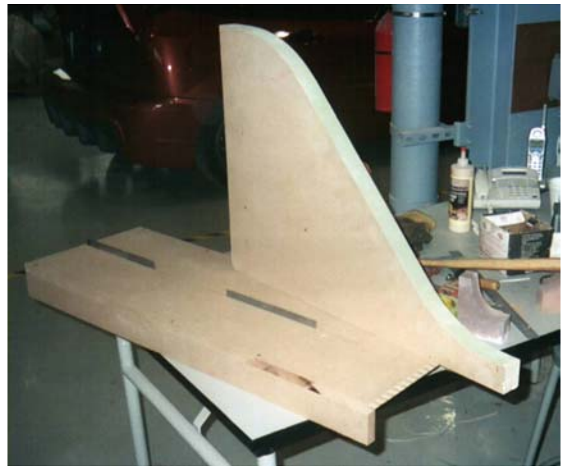


Figure 3b. Preliminary Profile & Base

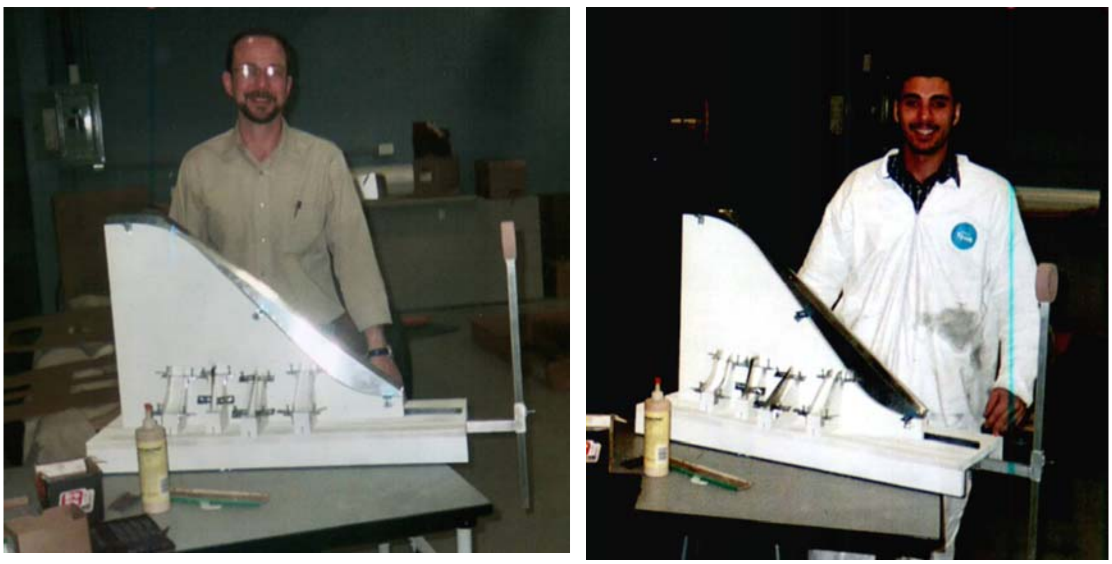


Figure 3c. Finished Product & Team Members (Left: Paul Fink, Right: Alex Salmu)

6. THEORY

In this case, a 2-D motion profile can be applied as seen in Figure 4. Most of this theory comes from the textbook used for ME 321, which is currently *Statics & Dynamics, Seventh Ed.*, by Beer and Johnston. Once the assumptions of perfect rolling, negligible drag, and downward acceleration of 9.81 m/s^2 are made, the theories may be applied.

For all angles, the initial velocity is 107.667 in/s. At 30º, if time is found using the process below, the maximum height of the projectile can be found. All of the initial launching heights (where the ramps end) were taken to be equal to the final landing heights (where the play dough is). The horizontal and vertical distances are found by using measuring tape divided into increments of 1/16 in.

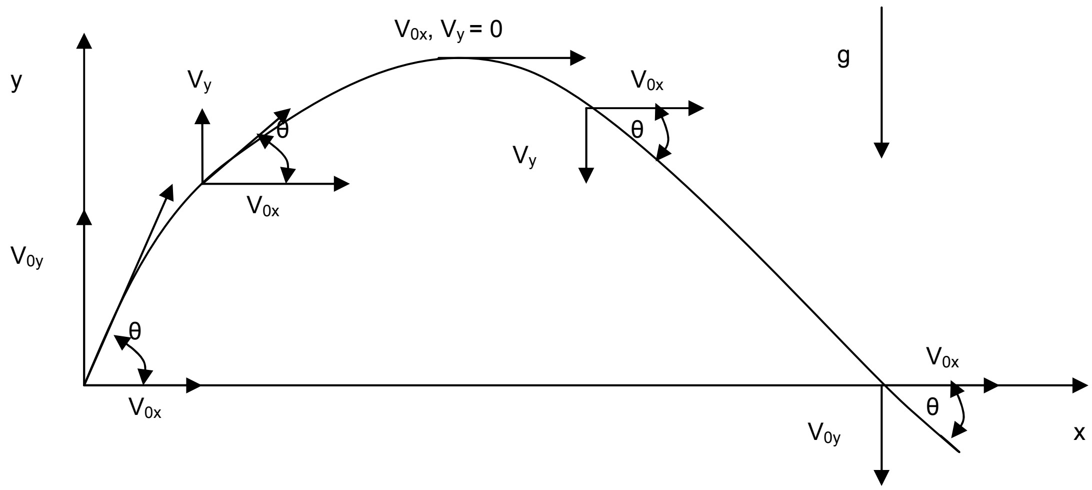


Figure 4. *2-Dimensional Motion Profile*

Using trigonometry, equations 1a and b can be yielded from the profile diagram (Figure 4):

$$v_{0_x} = v_0 \cos\theta \Rightarrow v_x = v_0 \cos\theta = const \qquad 1a$$

$$v_{0_y} = v_0 \sin\theta \Rightarrow v_y = v_0 \sin\theta - gt \qquad 1b$$

After taking the integral with respect to time of the above equations, displacements x and y are determined to be the following (equations 2a and b, respectively):

$$x = (v_0 \cos\theta)t \qquad 2a$$

$$y = (v_0 \sin\theta)t - \frac{1}{2}gt^2 \qquad 2b$$

The time can be determined with either the x component or y component. This is represented in equations 3a and b.

$$t = \frac{x}{(v_0 \cos\theta)} \qquad 3a$$

$$t = \frac{-b \pm \sqrt{b^2 4ac}}{2a} = \frac{-\left(v_0 \sin(\theta)\right) \pm \sqrt{\left(v_0 \sin(\theta)\right)^2 - 4(-0.5g)}}{2\left(-0.5g\right)} \qquad 3b$$

Once the relationship between work and kinetic energy is verified, the initial kinetic energy and final potential energy are dropped from the equation. The initial velocity becomes a function of gravity and height. In experimentation, it was intuitive to go this route because the increments of time for the projectile would be too small to measure practically. Stored energy at the top of the ramp (initial height) is gravitational potential energy from the reference point. This energy is only dependent on the position of the object. Refer to equation 4.

$$U(y) = mgy \qquad 4$$

$$W(x_1, x_2) = \frac{1}{2}mv_f^{\ 2} - \frac{1}{2}mv_i^{\ 2} \qquad 5$$

From the work-energy theorem, the work done is equal to the gain in kinetic energy, refer to equation 5. Rigid body kinematics takes into account the energy required due to inertia. The most common bodies analyzed are spheres, hoops, and disks, which have all been used in this particular experiment. Weight is then used to relate inertia to energy and a variation for the velocity of a particle is determined.

Energy is conserved by summing the initial individual energies with the final individual energies.

$$U_i + \frac{1}{2}mv_i^{\ 2} = U_f + \frac{1}{2}mv_f^{\ 2} \qquad 6$$

The velocities of rigid bodies were calculated by substituting the inertias and summarized in Table 2.

$$Sphere \Rightarrow \bar{v}^{2} = \frac{2gh}{1+\left(\frac{\frac{2}{5}mr^2}{mr^2}\right)} = \frac{2gh}{\left(1+\frac{2}{5}\right)} \Rightarrow \bar{v} = \sqrt{\frac{2gh}{1.4}} \approx 0.845\sqrt{2gh} \qquad 7$$

$$Disk \Rightarrow \bar{v}^{2} = \frac{2gh}{1+\left(\frac{\frac{1}{2}mr^2}{mr^2}\right)} = \frac{2gh}{\left(1+\frac{1}{2}\right)} \Rightarrow \bar{v} = \sqrt{\frac{2gh}{1.5}} \approx 0.816\sqrt{2gh} \qquad 8$$

$$Hoop \Rightarrow \bar{v}^{2} = \frac{2gh}{1+\left(\frac{mr^2}{mr^2}\right)} = \frac{2gh}{(2)} \Rightarrow \bar{v} = \sqrt{\frac{2gh}{2}} \approx 0.707\sqrt{2gh} \qquad 9$$

Table 2. *Rigid Bodies and Corresponding Values*

Geometry	$\bar{I}$	$\bar{v}$
Sphere	$\frac{2}{5}mr^2$	$0.845\sqrt{2gh}$
Disk	$\frac{1}{2}mr^2$	$0.816\sqrt{2gh}$
Hoop	mr^2	$0.707\sqrt{2gh}$

Because the time interval from launch to 'ground' was small, the vertical distance was measured to determine the experimental velocity using the following equation:

$$v_0 = \sqrt{2gh} \qquad 10$$

Where h is equal to the height from the final point of reference to the initial point. Theoretical particle calculations can be seen in Table 3.

Table 3. *Theoretical Results for a Particle*

Where final height is equal to initial height:					
Angle (rad)	Angle (deg)	Time to Ymax (s)	**Ymax (in)**	Total Time (s)	**X distance traveled (in)**
0.5236	30	0.1393	**3.7500**	0.2786	**25.9807**
0.7854	45	0.1970	**7.5000**	0.3941	**30.0000**
1.0472	60	0.2413	**11.2500**	0.4826	**25.9808**
1.3090	75	0.2691	**13.9952**	0.5383	**15.0001**

Rigid body kinematics will be used to determine the total kinetic energy taking into account the effects of rolling. The assumptions here are absence of slipping and no energy loss due to friction or heat transfer during rolling.

Taking a closer look at where rotational kinetic energy comes from, the rolling object that is looked at to be continuous can be looked at in terms of many little pieces of mass.

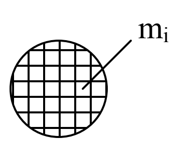


Figure 5. *A little piece of mass* m_i

Stating that the piece m_i is at a distance r_i from the axis, the total kinetic energy can be described as follows:

$$KE_{rolling} = \sum K_i = \sum \frac{1}{2} m_i v_i^2 = \frac{1}{2}\left(\sum m_i r_i^2\right)\omega^2 \qquad 11$$

The quantity in parentheses above is the mass moment of inertia for the object. It is the basic relationship for rotational motion similar to translational motion's term of $\frac{1}{2}mv^2$, but using $\frac{1}{2}I\omega^2$ instead. Finally, the rolling kinetic energy is described by the equation below.

$$KE_{rolling} = \frac{1}{2}I\omega^2 \qquad 12$$

Taking the motion as simple rotation about the point of contact with the ground, the kinetic energy is completely rotational and is described by equation 9.

By the parallel-axis theorem:

$$I = I_{cm} + MR^2 \qquad 13$$

So the final total kinetic energy becomes:

$$KE = \frac{1}{2}(I_{cm} + MR^2)\omega^2 = \frac{1}{2}I_{cm}\omega^2 + \frac{1}{2}MR^2\omega^2 \qquad 14$$

This equation, since $v = R\omega$, gets reduced to the following:

$$KE = \underbrace{\frac{1}{2}I_{cm}\omega^2}_{\text{Rotational Component}} + \underbrace{\frac{1}{2}Mv^2}_{\text{Linear (translational) Component}} \qquad 15$$

Theoretical sphere, disk, and hoop calculations can be seen in Tables 4, 5, and 6, respectively.

Table 4. *Theoretical Results - Sphere*

Calculations for a sphere where initial and final height are equal:					
Angle (rad)	Angle (deg)	Time to Ymax (s)	**Ymax (in)**	Total Time (s)	**X distance traveled (in)**
0.5236	30	0.1177	**2.6776**	0.2355	**18.5509**
0.7854	45	0.1665	**5.3552**	0.3330	**21.4207**
1.0472	60	0.2039	**8.0328**	0.4078	**18.5509**
1.309	75	0.2274	**9.9929**	0.4549	**10.7103**

Table 5. *Theoretical Results - Disk*

Calculations for a disk where initial and final height are equal:					
Angle (rad)	Angle (deg)	Time to Ymax (s)	**Ymax (in)**	Total Time (s)	**X distance traveled (in)**
0.5236	30	0.1137	**2.4970**	0.2274	**17.2995**
0.7854	45	0.1608	**4.9939**	0.3215	**19.9757**
1.0472	60	0.1969	**7.4909**	0.3938	**17.2994**
1.309	75	0.2196	**9.3188**	0.4392	**9.9877**

Table 6. *Theoretical Results – Hoop*

Calculations for a hoop where initial and final height are equal:					
Angle (rad)	Angle (deg)	Time to Ymax (s)	**Ymax (in)**	Total Time (s)	**X distance traveled (in)**
0.5236	30	0.0985	**1.8744**	0.1970	**12.9865**
0.7854	45	0.1393	**3.7489**	0.2786	**14.9955**
1.0472	60	0.1706	**5.6233**	0.3412	**12.9864**
1.309	75	0.1903	**6.9955**	0.3806	**7.4977**

It was expected prior to the experiment that the hoop would most likely have the most associated error due to its "unfriendly" shape. The sphere was concluded to be the most user-friendly due to its self-centering nature during rolling. It was noted that the higher the angle, the more likely error would occur because the effect of fillets in the ramp blocks will be interfering with the smooth rolling of the objects.

7. EXPERIMENTAL ANALYSIS

The experimental results observed show that the objects used should be considered as rigid bodies. This makes sense because the objects are not physically similar to particles in motion at all. The experimental data in Table 7 validates these conclusions.

Overall, the results do support the claim that these objects behave as rigid bodies. The errors are mainly due to the accuracy of measurements and possibly manufacturing errors. For example, the disk was custom made so it may not be of perfectly circular geometry. The uncertainty data can be seen in Table 8 for various angle measures. Error is also associated with the "smoothness" of each ramp angle that the object will be subjected to. For example, if an angle is exactly 45º with no straight horizontal, the rolling object would most likely be subjected to an angle somewhat lower than 45º. Consequently, the lack of straightness in the ramps may have caused some error.

Table 7. *Experimental Observations vs. Theoretical Data*

SPHERE	Trial 1			Trial 2			Trial 3+			Theoretical	
Angle (deg)	Ymax (in)	X final (in)	% Error	Ymax (in)	X final (in)	% Error	Ymax (in)	X final (in)	% Error	**Y (in)**	**X (in)**
30	2.5000	18.2500	-2.25	2.5000	18.3750	-1.67	2.6250	18.5000	-0.49	**2.6776**	**18.5509**
45	5.0000	22.5000	2.70	5.2500	21.5000	***-0.10***	5.5000	21.5000	0.84	**5.3552**	**21.4207**
60	6.8250	17.5000	-8.50	6.8750	17.8125	-7.13	7.1250	17.8750	-5.96	**8.0328**	**18.5509**
75	9.0000	9.8750	-8.83	9.1250	10.2500	-6.42	9.2500	10.5000	-4.60	**9.9929**	**10.7103**

DISK	Trial 1			Trial 2			Trial 3+			Theoretical	
Angle (deg)	Ymax (in)	X final (in)	% Error	Ymax (in)	X final (in)	% Error	Ymax (in)	X final (in)	% Error	**Y (in)**	**X (in)**
30	2.5000	17.7500	2.29	2.8750	17.8750	4.82	3.3750	17.1250	3.55	**2.497**	**17.2995**
45	5.4375	20.3750	3.38	5.3750	20.1250	2.12	5.0625	21.0625	4.63	**4.9939**	**19.9757**
60	7.2500	15.3750	-8.73	7.1250	15.5000	-8.73	7.1250	15.5000	-8.73	**7.4909**	**17.2994**
75	8.5000	8.7500	-10.65	8.6250	8.1875	-12.92	9.0000	9.1250	-6.12	**9.3188**	**9.9877**

HOOP	Trial 1			Trial 2			Trial 3+			Theoretical	
Angle (deg)	Ymax (in)	X final (in)	% Error	Ymax (in)	X final (in)	% Error	Ymax (in)	X final (in)	% Error	**Y (in)**	**X (in)**
30	2.0000	13.7500	5.98	2.0000	13.3750	3.46	2.0000	13.6250	5.14	**1.8744**	**12.9865**
45	4.2500	15.5000	5.36	4.0000	15.2500	2.70	4.0000	16.0000	6.70	**3.7489**	**14.9955**
60	5.2500	5.2500	***-43.58***	5.3750	5.7500	-40.22	5.7500	10.5000	-12.68	**5.6233**	**12.9864**
75	6.5000	4.5000	-24.10	6.7500	4.5000	-22.38	6.7500	4.7500	-20.65	**6.9955**	**7.4977**

It was interesting to observe that less uncertainty would occur between angles of 50º and 70º, most likely due to the direct amount of measurement necessary. The more there is to measure, the higher the uncertainty will be in this case.

Table 8. Uncertainty Results Based on 1/16" Measurements

Rigid Body Kinematics Uncertainty Table				
	Distance Traveled	Angle (degrees)	Actual Range (in)	**Uncertainty (±)**
		15	15.0000	**0.4167%**
		30	25.9810	**0.2406%**
		45	30.0000	**0.2083%**
		60	25.9810	**0.2406%**
		75	15.0000	**0.4167%**
	New Total X	Angle (degrees)	Actual Range (in)	**Uncertainty (±)**
		15	15.2727	**0.4092%**
		30	27.8468	**0.2244%**
		45	31.0357	**0.2014%**
		60	26.5714	**0.2352%**
		75	15.2727	**0.4092%**
	Sphere, Yi=Yf	Angle (degrees)	Actual Range (in)	**Uncertainty (±)**
		15	10.7103	**6.2201%**
		30	18.5509	**2.3342%**
		45	21.4207	**1.1671%**
		60	18.5509	**0.7781%**
		75	10.7103	**0.6254%**
	Sphere, Yi≠Yf	Angle (degrees)	Actual Range (in)	**Uncertainty (±)**
		15	10.8098	**0.5782%**
		30	20.4845	**0.3051%**
		45	22.4724	**0.2781%**
		60	19.1474	**0.3264%**
		75	10.9853	**0.5689%**

8. FUTURE WORK

Possible improvements and changes include using state-of-the-art equipment for measurement, running a greater number of trials, and adjustable initial/final heights.

Accounting for friction and surface roughness (tribological considerations, *not* assuming perfect rolling) would most likely lead to more accurate results. The largest error was due to 60º and 75º angles, perhaps due to the lack of "smooth angle" mainly for the hoop. Furthermore, the hoop geometry is less "user-friendly" since it is not self centering like a sphere.

9. CONCLUSIONS

This experiment is sufficient in introducing the concepts of particle and rigid body kinematics and the work-energy law, bridges the gap between theory and practice, and serves as a perfect example of how a specific apparatus can have a number of different results based on a simple variable (launch angle in this case). A minimum error of -0.1% was reached with a rolling sphere at an angle of 45º. Conversely, human manufacturing error and flaws in materials (imperfect surface finish) led to a hoop's error of -43.58% at 60º. In terms of contemporary issues, meeting the needs of a customer is of utmost concern in industry. The only way to do this is to validate theoretical results with experimental data. If the minimum error of -0.1% was applied to every math, science, and engineering application in the world, there would be no need for improvement. This is an excellent value of error for real world applications.

There is a minor safety issue with the sheet metal used in the experimental apparatus as well. A very convenient and cost-effective solution would be to border the sharp outlines of the sheet metal with the Play dough that was already purchased. Functionality is the key, but ethics and safety must always come first in any practice.

10. ACKNOWLEDGEMENT:

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11. REFERENCES

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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

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ME 321 : Dynamics and Vibrations

Laboratory Experiment #2 Assignment : Lab Handout

Particle/ Rigid Body Kinematics & Conservation of Energy

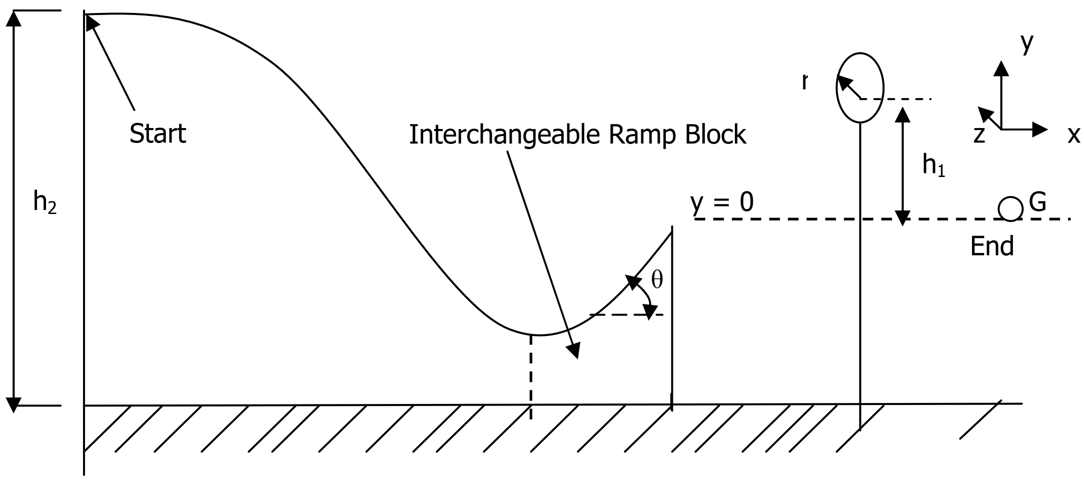

Figure 1: Particle/Rigid Body Kinematics Apparatus

Figure 1 depicts the apparatus used to roll three objects off the ramp at a start point and land on play dough at the end point G. The angles that will be used are 30, 45, 60, and 75 degrees. The objects must be allowed to "drop" at the h_2 starting point. Using kinematics and the energy principle, the velocity of each projectile can be found. This system allows for different kinematics values to be found experimentally by changing values of the angle θ.

The energy principle in combination with the laws of particle and rigid body kinematics will be used in the explanation of this experiment. Note that h_1 is the height from the reference (where y = 0) to the center of the ring. <u>This is irrelevant in calculations and measurement, but you must be consistent.</u> The three objects that will be used are a chrome pinball, steel disk (cylinder), and chrome hoop. The mass and radius are not needed for the theoretical calculations.

Note that the center of the ring must be where the velocity is equal to v_{0x} for each object used. This means that the maximum height is zero at these points for the respective bodies. These particle and rigid body calculations will be a pre-lab exercise and must be complete upon entering the lab.

The main objective of this experiment is to relate experimental data with theoretical calculations that validate the laws of particle/rigid body kinematics, and the law of conservation of energy.

Assignment Specifications

1. Perform a pre-lab evaluation for a 15º block.
2. Using your pre-lab calculations and experimentally observed data, would you conclude that the objects can be considered as rigid bodies or particles? Why and why not?
3. Tabulate the horizontal and vertical distances with respect to each angle and geometry. Note any trends from your analysis.
4. What assumptions can be made about the entire experiment?
5. Derive an expression for velocity using both particle and rigid body kinematics. Show that the values looked up for coefficients of each velocity (for a rigid body) is correct.
6. Perform an uncertainty analysis and include a graph of your findings. In which range is your uncertainty least?
7. If you were to graph launch angle vs. horizontal distance, what would your graph look like and why?
8. Perform calculations (similar to your pre-lab) for a 15º ramp block for all geometries in this experiment. Tabulate your data.