Physics

Commentary to support marking

Subject: Physics

Paper component: EE

Language: English

Exam session: MAY 2018

Essay: 25 A

Criterion	Mark	Out of	Justification
A	5	6	First strand: Title reflects the essence of investigation, different from RQ; topic not easy to introduce and explain, some diagrams or statements more helpful than others, similarly for relevant physics principles, purpose and focus. Once event understood communication becomes clearer. Level: 5 Second strand: the RQ is clear, focused and relevant to the investigation. Level:6 Third strand: appropriate and informed sources. General set-up, instruments and procedure appropriate, limited number of plates of different curvatures, a number of repeats, time for only one oscillation measured, no test about using a greater number of oscillations. Level: 5. Overall level: 5.
B	4	6	First strand: Sources relevant, their use in relation to theory limited, not done in depth, qualitative considerations. The physics connecting the essence of the tautochrone pendulum (cycloid) and the constancy of the period of this pendulum by opposition to the period of the simple pendulum not clearly established. Level: 4 Second strand: absence of some data table or diagram, and lack of quality and completeness of diagrams shown in the essay limits good communication. Lack of reference to specific diagram or table. Limited terminology. Lack of consistency in the use of unit symbols. Level 4. Overall level: 4
C	8	12	First strand: The research is in line with RQ, generally appropriate. Level 9. Second strand: uncertainties considered, origin of some uncertainties not explained (e.g. video), uncertainty of curvature

			confusing, propagation of errors not respected, no clear consideration of uncertainty attached to singular reading and random uncertainty in repeated readings; no example of calculation of average value with its uncertainty; some processed data not in a table; empirical analysis of best-fit, however no physics model, with prediction, to which compare the experimental results or information from literature. Conclusion partly supported. Level 8 Third strand: results discussed, non-zero intercept discussed, argument limited in the absence of a model, some speculation. Experimental limitations discussed, impact on results considered, not all completely. Level 7. Overall level: 8
D	3	4	Structure of essay: generally appropriate, organization not always clear. Format and layout: cookbook recipe style, label and axis on some graphs not correctly described, hence confusion, some diagrams not helpful, no diagram describing event *in action*. One data table missing. Bibliography: access dates on Online sources missing, one source not referred to in core of essay. Level: 3
E	5	6	First reflection session: identification of an interesting topic, planning research including finding and consulting sources, identifying the nature of the "problem". Interim, session: methodology, procedure discussed; presentation style of citation, reference and bibliography. Final reflection session: how a challenge was met, surprising conclusion however no mention of related theory. Clear initiative taken by student, challenging topic and RQ. Overall level: 5.
Total:	25	34	

Candidate Marks Report

Series : M18 2018

This candidate's script has been assessed using On-Screen Marking. The marks are therefore not shown on the script itself, but are summarised in the table below.

Centre No :		Assessment Code :	PHYSICS EE EXTENDED ESSAY in ENGLISH
Candidate No :		Component Code :	EE(ENG)TZ0
Candidate Name :			

In the table below ‘Total Mark’ records the mark scored by this candidate.
‘Max Mark’ records the Maximum Mark available for the question.

Examiner:	
Paper:	**M18physiEEEE0XXXX**
Paper Total:	**25 / 34**
Question	Total Mark / Max Mark
Criterion A	5 / 6
Criterion B	4 / 6
Criterion C	8 / 12
Criterion D	3 / 4
Criterion E	5 / 6

Coursework confirmation
Yes

Hours supervisor spent with candidate
3

Title: Huygens and the Tautochrone (Isochronous Pendulum)

IB Extended Essay

Research Question: How does the curvature of the plates surrounding the pendulum in a tautochrone affect the time necessary for one complete oscillation?

Subject: Physics

Word Count: 3851

Topic not clearly/effectively communicated, event not clearly described (fig 1 not very helpful, only fig 4, p.12)), physics principles re simple and isochronous pendulums incomplete, connection/comparison between them not clear; RQ clear, focused; methodology: generally well thought steps but the design of the cycloid curve (for plates) not clear ; procedure to get period not all clear; sources relevant

K & U: the physics connecting the essence of the tautochrone pendulum (cycloid) and the constancy of the period of pendulum by opposition to the simple pendulum not established clearly; terminology: absence of some key data table and diagrams limits communication, units not all consistent, no reference to set-up diagram; definition of period ..?

Table of Contents

1 Introduction

1.1 Research Question

How does the curvature of the plates surrounding the pendulum in a tautochrone affect the time necessary for one complete oscillation?

1.2 Initial Encounter and Interest

During junior year, I took a Calculus 3 course in which we learned about curvature. More specifically, the professor was interested in teaching the class how curvature was related to the tautochrone pendulum, including the contribution of Christiaan Huygens in furthering knowledge behind the mechanism. Since it was mentioned that there were many physics-based analyses on the tautochrone, I chose to make it the main focus of my Extended Essay.

1.3 Background Information

The most well-known kind of pendulum is the simple pendulum, which involves a weight attached to a string that swings in a circular path, with the string serving as the radius of the circle in creating the path. Simple pendulums can be found in several objects, such as within classic timekeeping devices like the grandfather clock. However, other kinds of pendulums follow different paths with contrasting characteristics, such as the isochronous tautochrone.

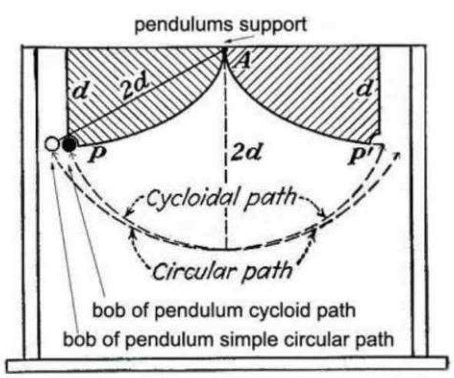
During the 17^{th} century in Holland, physicist and mathematician Christiaan Huygens published his findings on the isochronous pendulum. The isochronous pendulum is essentially a pendulum for which the period of oscillation is independent of the amplitude of swing, which, previous to Huygens' findings, was considered unfeasible. That is, for the typical pendulum (with no forces acting on the pendulum aside from gravity and some drag from air resistance), the period of oscillation changes with larger or smaller amplitudes. For some Dutch sailors, this implied unreliable time-keeping as well as an inability to precisely define one's location while travelling by sea (Baker & Blackburn 236).

physics behind?

With the invention of the isochronous pendulum, time keeping was independent of the amplitude of the pendulum's swing, which had not been true for the traditional pendulum. This was done by placing curved plates to restrain the string responsible for the pendulum's motion. By restricting the motion of the pendulum to the space contained within these two curved plates, period became independent of swing amplitude – thus allowing more accurate time-keeping (Lodder & Pengelley 169).

It is in this way that a pendulum's motion in a cycloidal path is distinct from its motion in simple motion, which is completely circular. This difference is depicted in the diagram below, with the black pendulum swinging in a cycloidal path, and the white pendulum following a circular path. As viewed in the figure below, the cycloidal path tends to be more tightly curved about the origin of the pendulum, which also means a greater curvature.

plates on diagram? context not all clear re role of plates



no description of event, how string fits curved plates before release...contrary to free simple pendulum

Figure 1: Cycloid versus Simple Oscillation (Jim & Rhoda Morris)

assumption in derivation of simple pendulum equation ..? torque et all B

1.4 Introduction of Theory

By analyzing the forces acting on the pendulum when its motion is restricted by such plates, it is possible to investigate how the curvature of the plates surrounding the pendulum in a tautochrone specifically affects the time necessary for one complete oscillation (i.e. period).

Within the context of a typical pendulum, gravity will be acting upon the pendulum causing it to have a net, downward force. However, since the location of the pendulum is continually changing as it moves back and forth between two extremes, the net force acting on the bob will vary. More specifically, the angle the pendulum makes with the vertical will affect the force acting on the pendulum. From Newtonian physics, we can identify that the force due to gravity acting on the bob is **F** = mg, and can be expressed as the sum of two forces, the tangential force ($\mathbf{F}_t$) and the perpendicular force ($\mathbf{F}_p$). The tangential force is the tangential component of **F** along the motion of the bob, while the perpendicular force is the component of **F** perpendicular to $\mathbf{F}_t$. The reason we cannot call this perpendicular force a centripetal force is because the plates along which the pendulum are traveling are not circular in nature, but rather in the shape of a cycloid. Thus uniform circular motion is not achieved (Allum and Talbot 262).

no reference to diagram

magnitude of tangential speed not constant

It is also possible to express these forces quantitatively: the magnitude of $\mathbf{F}_t$ is $mg \sin \theta$, while the magnitude of $\mathbf{F}_p$ is $mg \cos \theta$. Keeping in mind that the tension and perpendicular force are in the same direction, the tension in the thread and $\mathbf{F}_p$ can be added to form a single vector. As the curvature is changed, the ratio between the tangential force and tension in the string will vary, causing there to be a change in the acceleration of the pendulum in the direction of the pendulum's motion. This change in acceleration could potentially lead to a change in period, which is the focus of this experiment.

CriB

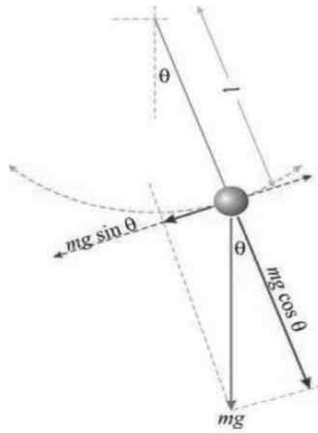


Figure 2: "Force Diagram for a Pendulum" (Pendulum Waves)

2 Experimentation

2.1 Experiment Design

In order to investigate how changing the curvature of the plates surrounding the pendulum will affect oscillation period, my experiment procedure will involve constructing multiple plates of different curvature, and then applying these plates to the same pendulum. By using the same pendulum for each set of plates, variables pertaining to the pendulum itself (pendulum size, thread material, pendulum weight) will be controlled. This will allow for a more focused investigation of the variables in the initial research question.

Additionally, the construction of these plates surrounding the pendulum will necessarily have to be created with precision, since even small changes in the curvature of the plates could result in changes in the time of oscillation. To achieve such precision, the shape of the plates will be laser-printed and then carved out of wood, using the print as a guide for incision. This will allow for the curves to be shaped precisely according to the shape of the cycloid.

The various curvatures of the plates used in the experiment procedure will be determined by constructing curves with circles of different radii. More specifically, the curves used will be created by choosing circles of different radii and then tracing one point along each circle's circumference as it rolls along a horizontal line. For each set of plates, the following values for radius of curvature will be used: 2.50 cm, 5.00 cm, 7.50 cm, 10.00 cm, and 12.50 cm.

methodology not clear, A (impact on B and C)

diagram B C

Presumably, smaller circles will result in smaller curves with increased curvature, while larger circles will result in larger curves with decreased curvature. The plates will be constructed such that they can easily be removed and attached from the body of the tautochrone pendulum.

The pendulum itself will be constructed using a 50.0 gram steel weight attached to a smooth silk string. The pendulum must be at least 50.0 g in mass to maintain sufficient momentum in travelling from one plate to another for at least 2 oscillations. That is, since we know momentum (***p***) is equal to mass multiplied by velocity (m*v*), a mass that is too light will result in insufficient momentum. The string is also designated to be made of silk to minimize the friction between the string and the plates as the pendulum swings, since silk generally has few microscopic ridges. The string will be adjusted at intervals along its length to allow for it to hang according to the plate size.

CriA

After constructing the necessary plates and pendulum, time of oscillation will be recorded several times for each set of plates. This will be recorded with a video-recording device in order to measure a precise time of oscillation.

CriA

2.2 Experiment Variables

The independent variable in my experiment will be curvature of the plates within the tautochrone, which is derived from the radius of the circle used to construct each plate.

not all clear

Essentially, curvature is the inverse of the radius used to approximate the shape of the curve at each point along the curve. In this experiment, the curvature of the cycloidal plates will be determined at the point of lowest curvature, for the purpose of consistency. An example is given below for a general curve:

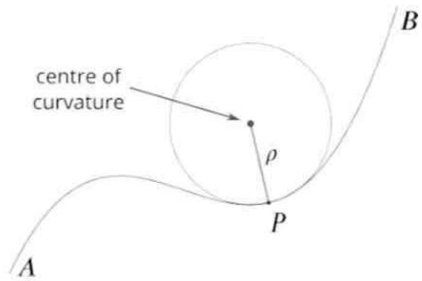


Figure 2: "Curvature and Centre of Curvature" (University of Cambridge)

As the curvature of the plates is changed, we will measure the corresponding period of the pendulum's swing while using these plates. In other words, the period (time of oscillation) will serve as the dependent variable of the experiment.

Variables that will necessarily be kept constant are the weight, material, and shape of the pendulum, as well as the strength and material of the string. Maintaining these variables will allow the investigation to be focused solely on curvature and period, rather than external factors. Other variables that will be controlled are the material of the plates and plastic guides placed along the curves of the plates, which will respectively be made using the same materials.

2.3 Apparatus Description and Construction

The tautochrone will be main component of this experiment, which will be made mostly of 2.0 cm thick wood and metal (see Appendix 1 for a detailed list of materials). It will be constructed to be 60.0 cm tall, 60.0 cm in length, and 15.0 cm in width. The plates themselves will be constructed based on cycloids made with circles of radii 2.50 cm, 5.00 cm, 7.50 cm, 10.00 cm, and 12.50 cm. The plates, which will restrict and control the motion of the swinging pendulum, will be carved out of dense wood using a high-precision jigsaw after laser-printing the shape of the cycloid onto the board. The shape of the curves is shown below for a radius of 2.50 cm.

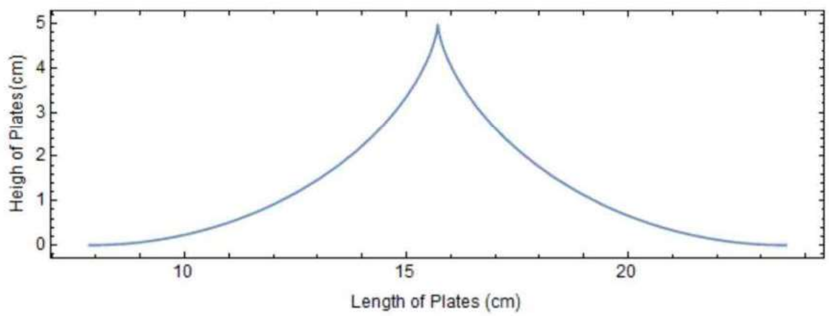


Figure 3: 2.0 - thick Plates Projected onto a 2D Graph (created with Mathematica)

These plates will be attached to a headpiece, which will be a 60.0 cm long board from which the plates will hang. Small hooks will be used to attach the plates to the headpiece, and these will be fastened with metal clamps. These hooks will be 10.00 cm apart to ensure that the plates are secure while the experiment is taking place. The wooden headpiece itself will be attached to two wooden legs, 60.0 cm in length, which will in turn each be attached to a 40.0 cm long wooden base.

A 50.0 g pendulum made of steel will be placed such that it hangs between the two plates, so the string attached to the pendulum is attached to the cusp between the two plates. A metal clamp will be placed where the pendulum hangs from the headpiece to ensure that the position of the pendulum's attachment to the headpiece does not shift. Additionally, the length of the string will be equal to the length of the curve found along each plate, so that it may swing freely between the two plates when released.

Finally, plastic guides will be attached to the 2.0 cm thick plates to ensure that the string of the pendulum is restrained to a path specifically along the plates. That is, the plastic guides will force the pendulum to swing only along the curves of the plates while in motion, rather than straying from the path.

2.4 Experiment Method (Procedure)

cookbook recipe style

1. Construct the tautochrone, using plates corresponding to the cycloid in order to maintain a shape which keeps amplitude and period (time of oscillation) independent. Ensure that the plates are easily removable, since this is related to changing the independent variable (see Section 2.3, Apparatus Description and Construction).
2. Attach the set of the plates with the greatest curvature onto the tautochrone. To attach these plates to the headpiece of the tautochrone, use the hooks in the plates and the headpiece.
3. Attach the pendulum to the central hook in the headpiece of the tautochrone, allowing it to hang at rest between the two plates.
4. Use the appropriate knot in the string when attaching it the central hook, depending on the size of the plate being used.
    a. When hanging the pendulum, use smooth string to minimize the effects of friction as the string comes in contact with the plates.
    b. Ensure that the string is hung such that the length of the string is the same as the length of the specific plate. Use a metal clamp to ensure the pendulum's position of attachment to the headpiece does not shift.

no diagram illustrating the string at different positions from max to min position for a given set of plates

5. Lock the plates onto the headpiece of the tautochrone by positioning metal clamps along the hooks attaching the plates to the headpiece. Once the metal clamps have been positioned, release to lock the hooks into place.
6. Place the tautochrone against a high contrast background to allow the pendulum to be easily recognized in experiment footage. Place the camera lens such that the entirety of the pendulum's motion is easily viewable.
7. Position the pendulum such that it follows the outline of the one of the plates. Then release the pendulum, allowing it to swing freely between the curved plates.
    a. For recording the pendulum's motion, use a high frames-per-second setting to achieve the greatest possible precision. The period can later be observed from the slowed video using software.
8. Record the time of oscillation multiple times, each time for a single oscillation (i.e. measure the period of the pendulum's oscillation). Repeatedly record for a total of 3 trials, for each of the 5 sets of plates. CriA
    a. To maintain consistency, always record the time of oscillation for the first period in each trial. (After the first period, the pendulum may lose speed and travel with a slightly longer period.) CriA
9. Repeat steps 2 to 8 using different sized plates until trials have been recorded for each set of plates numerous times. Continue repeating this process until 3 trials have been recorded for every set of plates. CriD
10. Transfer the video files to a video editing program to slow the footage and precisely calculate the period (time of oscillation) for the pendulum. The time of release should be accurately recorded in order to find the period of oscillation. CriA

details of video analysis ...

11. Calculate the period by subtracting the time stamp of release from the time stamp ~~wherein the pendulum completes one cycle of motion~~. Compare this to the respective curvatures to calculate the relationship between the two variables.

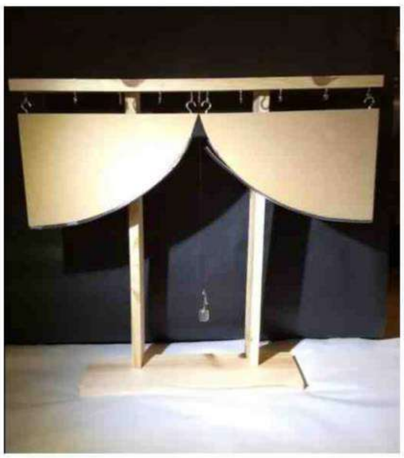
uncertainties?

back to initial position ...

any quantitative physics model?

2.5 Image of Constructed Tautochrone

The following image depicts the completed tautochrone, mounted with the largest set of cycloidal plates. As shown, both the pendulum and plates are attached the body of the tautochrone using small hooks and metal clamps.



* not annotated
* not clear re motion of pendulum (series of diagrams showing different positions of mass and string ... related to theory

Figure 4: Photograph of Main Apparatus (Tautochrone)

In addition, each pair of the five sets of cycloidal plates is shown below. The plates with the largest radius of curvature are positioned at the top of the photograph, while the plates with the smallest radius of curvature are position at the bottom of the photograph. In other words, the plates are placed in order of decreasing radius of curvature from top to bottom.

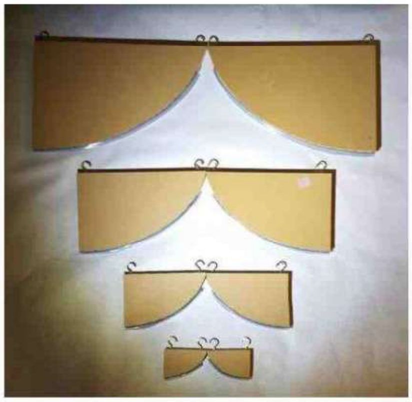


Figure 5: Set of Five Cycloid Plates

3 Data Collection and Interpretation

3.1 Experimental (Raw) Data

The camera I used to collect footage for the oscillation in each trial was an Olympus E-M10, which has a frames-per-second rate of 27.9 frames-per-second. The camera was attached to a low adjusted tripod and was positioned a total of 1.92 meters in the front of the tautochrone to fully capture the pendulum's motion. White light was placed against a black background to ensure that the camera lens could distinctly capture the exact motion of the pendulum.

Using a video-editing program, VLC Media Player, I was able to slow down the footage of each trial and calculate the period with a ± 0.005 s uncertainty. More specifically, I was able to slow the footage to find the time stamp for release of the pendulum and the time stamp for when the string was positioned along the opposing plate. For the purposes of calculation and table formation, I assigned the time to when the pendulum was dropped to be called the "Start

Time," and assigned the time to when the string was positioned along the opposite plate as the "End Time." These labels are found in Table 1.

some repeat
so half a period measured .. A

Finally, after finding the starting and ending times, I found the absolute difference between the two time stamps to find the time of oscillation for each trial, i.e. the period of the trial. This information is summarized in Table 1.

CriB CriA CriC

Raw Data				
Curvature (1/cm) ± 0.001 1/cm	**Trial Number**	**Start Time (seconds) ± 0.005 s**	**End Time (seconds) ± 0.005 s**	**Time of Oscillation (seconds) ± 0.005 s**
0.100	1	0.950	1.340	0.390
	2	0.170	0.544	0.374
	3	1.972	2.378	0.406
0.050	1	2.100	2.557	0.457
	2	1.701	2.131	0.430
	3	1.897	2.364	0.467
0.033	1	2.451	2.964	0.513
	2	2.246	2.729	0.483
	3	2.388	2.938	0.550
0.025	1	2.495	3.159	0.664
	2	1.957	2.544	0.587
	3	2.347	2.964	0.617
0.020	1	0.245	1.059	0.814
	2	1.467	2.288	0.821
	3	2.989	3.789	0.800

origin of uncert. ?
half a period
from?
error re uncertainty on time of osc.
uncert. add up

Table 1: Raw Data for Time of Oscillation from Footage

3.2 Data Processing and Graphs

After finding the time of oscillation (period) for each trial, I averaged the three values for each to find the average value for the period of the pendulum. The following table includes information about the period for each of the trials, as well as the average period for each radius of curvature in milliseconds. Both the trial times as well as the average times are expressed in milliseconds for ease of scaling as well as enhanced readability of graphical representations.

OK

** example of calculations including uncertainty ...

from measurements using video ... details

lack of consistency in the use of units (symbols)

units cm^ -1 (confusing here)

uncertainty?

Averages				
Curvature (1/cm) ± 0.005 1/cm	**Trial 1 Time (milliseconds) ± 5 ms**	**Trial 2 Time (milliseconds) ± 5 ms**	**Trial 3 Time (milliseconds)± 5 ms**	**Average Time (milliseconds)**
0.100	390	374	406	390
0.050	457	430	467	451
0.033	513	483	550	515
0.025	664	587	617	623
0.020	814	821	800	812

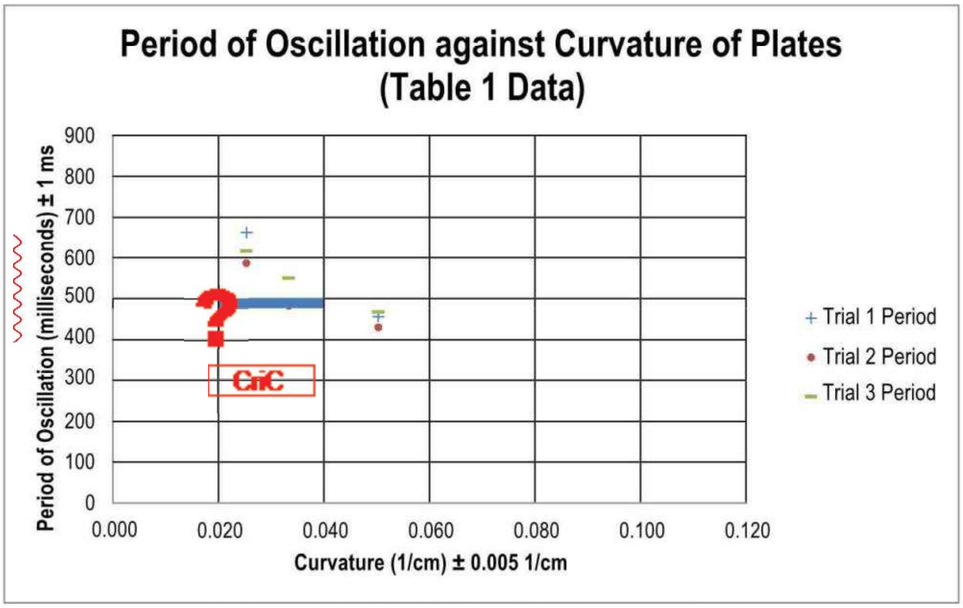
Table 2: Average Time of Oscillation for each Curvature Value

Using the data displayed in Tables 1 and 2, it was possible to graph both sets of data in order to further investigate the relationship between the independent and dependent variables. The following graphs illustrate the relationship between curvature and period of an isochronous tautochrone, with the first graph representing data for separate trials (Table 1) and the second graph representing data for averaged trial data (Table 2).

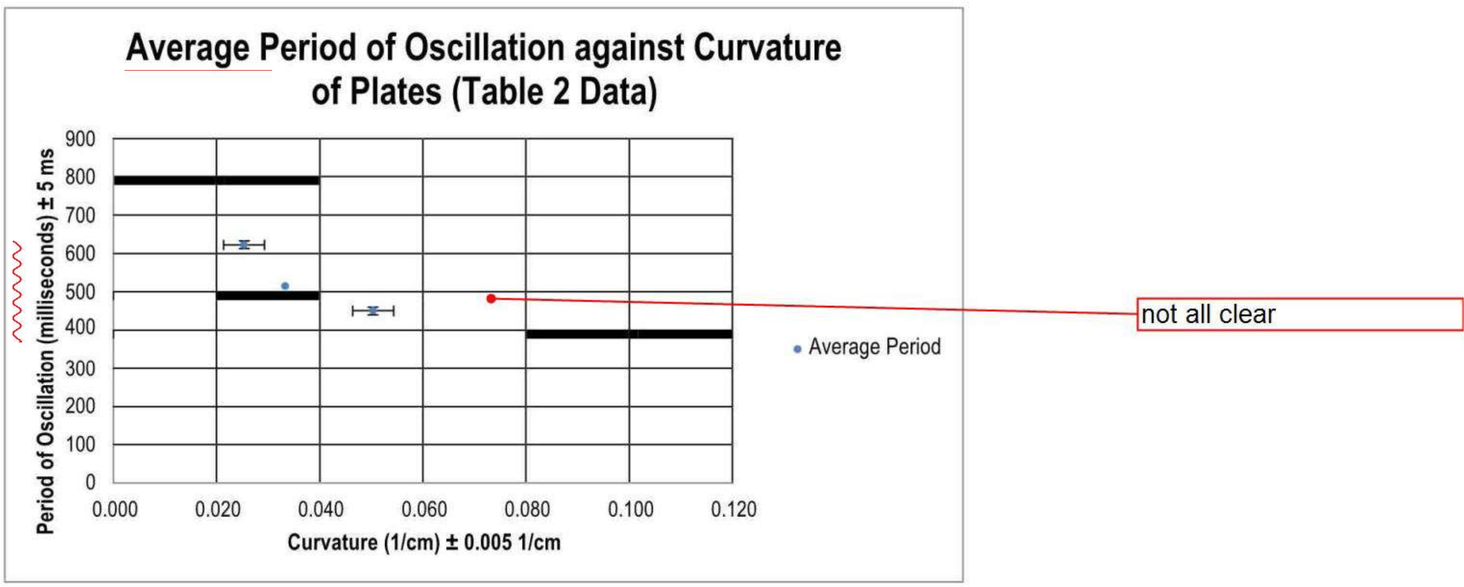
For sake of readability, error bars have been excluded from Graph 1, but are noted on the axes of the graph. To linearize the data, we will graph the period of oscillation against the inverse square of the curvature.

based on which physics model?

B C



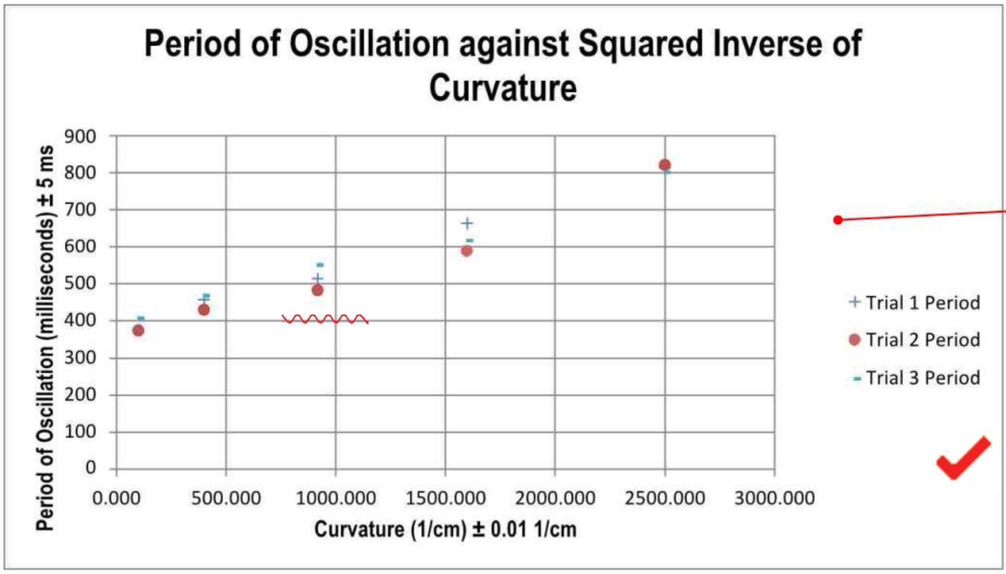
Graph 1a: Period of Oscillation against Curvature of Plates



Graph 2a: Average Period of Oscillation against Curvature of Plates

data table with values and values square with uncert. ?
B C

best fit?

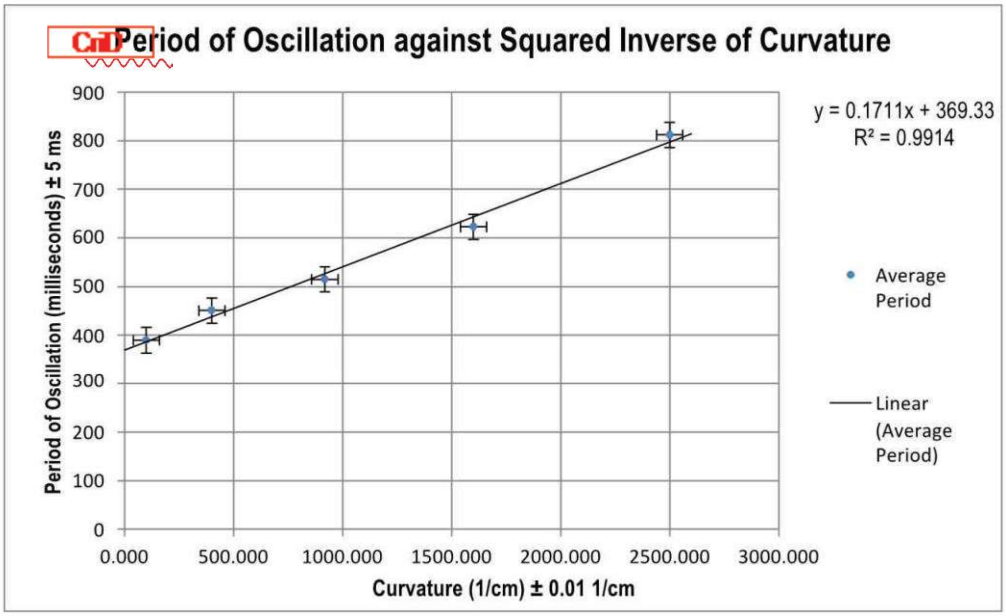


Graph 1b: Period of Oscillation against Squared Inverse Curvature of Plates

better to use physics symbols rather than x and y

** physics model behind?
B C

SD? decimals? C



Graph 2b: Average Period of Oscillation against Squared Curvature of Plates

CriD

4 Results and Discussion

4.1 Evaluation of Experiment and Conclusion

By interpreting the linearized graph of period against curvature of the plates in the tautochrone, we are able to conclude that the relationship between the period of oscillation for a tautochrone and the squared inverse of curvature very closely resembles a linear relationship. We can quantify this by the squared correlation coefficient, R = 0.9914. Since this value is close to 1, the relationship is almost linear.

what about physics predictions?

More specifically, this nearly linear relationship between the period of one oscillation (time of oscillation) and the curvature of the plates of the tautochrone is closely modeled by the linear approximation, $y = 0.1711x + 369.33$ (where x represents the squared inverse of curvature and y represents period). If we account for consistent precision, this becomes $y = 0.17x + 369.33$. This tells us that with every unit increase in the squared inverse of curvature, we can predict that there will be an increase in period of oscillation by 0.17 milliseconds. In other words, the slope of the linear approximation tells us to what degree we can expect period to change with the squared inverse of curvature.

justify ..

It is also observable from the graph and equation that the y-intercept of the linear regression is 393.33 milliseconds, which may be due to the scope of the data. If the experiment were expanded to measure the curvature of hundreds of sets of plates, with each having a larger curvature than the last one, the increased quantity of data may have shown how period nearly reaches zero once the curvature had been increased to an extremely large quantity. However, since it was not possible to create plates more than a metre long with substantial precision, the data points were chosen to create the best spread of curvature values possible. CriC procedure A

One of the early obstacles in constructing the tautochrone was constructing a pendulum that would swing between the two plates without straying from the path or coming to a rest too early for oscillation to be recorded. In order to resolve these problems, plastic guides were added to each plate to essentially force the silk string of the pendulum to stay within the bounds of the curved plates. Additionally, these plastic guides were rounded and smoothed such that the string would slip appropriately into the centerline of each plate. As a result, it was possible to have the motion of the pendulum precisely follow the curves of the plates.

To ensure that the pendulum did not come to a rest too early, a heavier pendulum (50.0 g) was used to increase its momentum. Although a 25.0 g pendulum weight was used at first, this proved to lack the sufficient momentum to guarantee that at least two complete oscillations were achieved. As a result, a heavier 50.0 g steel weight was used. On average, this allow for 4 complete oscillations from one plate to another.

CriC CriA not mentioned before, so two periods ... confusing the analysis

Besides these initial obstacles during the investigation, other sources of error were air resistance with regard to the pendulum's motion as well as friction between the string and the curves of the wooden plates. To minimize the latter source of error, materials with low levels of friction were used. For instance, silk string was used for the string of the pendulum, and the guides forcing the string to follow the curves were made of smoothed plastic rather than rubber, which has a high coefficient of friction than smoothed plastic.

a number of repeats here and below

However, it proved more challenging to further minimize the air resistance surrounding the pendulum. Since performing the experiment in a vacuum was unrealistic with the given circumstances, a heavier weight was chosen such that four complete oscillations could be performed without noticeable slowing due to air resistance. CriD

A potential expansion could be collecting data for a greater number of plates, with a larger range of curvature. For instance, if the period of oscillation could be recorded for extremely miniscule curvature values or extremely large curvature values, then it may be possible to observe whether the relationship between period of oscillation and curvature is different for extreme values.

Another possibility for further exploration of this experiment could use a mechanized tautochrone so that despite the dissipating energy of the pendulum over time, constant oscillations could be achieved with an electric motor. This would also minimize the effect of air resistance on the pendulum, since additional energy could be continually supplied by the motor to overcome any drag. The weight of the pendulum may also prove to be less significant with a motorized tautochrone, since any additional momentum necessary for continuous motion could be provided by electricity. Time of oscillation could be collected for several consecutive oscillations, thus reducing random errors through a greater number of repeated trials.

self defeating purpose, ... electric clock

Research appropriate, to RQ, consistent relevant; Analysis: limited number of plates , but with repeats, data well organized in tables (except for one missing); graphs of period vs curvature without best fit, not well analyzed ..; graph of period vs inverse curvature squared better analyzed, empirical relationship established but without any justification in physics at all; uncertainties considered but their origin , their manipulation with some errors and limitations reduce their efficiency; discussion/evaluation: centered on the non-zero intercept, with good suggestion that it might be related to limited number of curvatures (5) hence worth investigating with more plates; good discussion and evaluation, well focused, , some statements not fully justified; overall limitations identified;

for each plates does the period vary with amplitude?

5 References (Works Cited)

5.1 Text (In-print and online), Image, and Software References

Works Cited

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access date?

not referred to in core of essay

OK

6 Appendix

6.1 Detailed List of Materials

The following is a detailed list of materials used during the course of this investigation.

- 2.22 cm brass plated hooks
  - used to fasten plates and hook to headpiece
- 60.0 cm x 15.0 cm x 2.0 cm plywood board
  - headpiece of tautochrone
- 60.0 cm x 5.0 cm x 1.5 cm plywood boards
  - legs of tautochrone
- 5.00 cm iron nails
- Kumihiko 50.0 gram weight
  - pendulum weight
- 3.00 mm Silk String
- Smoothed plastic guides
  - attached to tautochrone pieces
- Cycloidal plates made of dense plywood, 1.9 cm thick

EE/RPPF

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Candidate personal code:

Extended essay - Reflections on planning and progress form

Candidate: *This form is to be completed by the candidate during the course and completion of their EE. This document records reflections on your planning and progress, and the nature of your discussions with your supervisor. You must undertake three formal reflection sessions with your supervisor: The first formal reflection session should focus on your initial ideas and how you plan to undertake your research; the interim reflection session is once a significant amount of your research has been completed, and the final session will be in the form of a viva voce once you have completed and handed in your EE. This document acts as a record in supporting the authenticity of your work. The three reflections combined must amount to no more than 500 words.*

The completion of this form is a mandatory requirement of the EE for first assessment May 2018. It must be submitted together with the completed EE for assessment under Criterion E.

Supervisor: *You must have three reflection sessions with each candidate, one early on in the process, an interim meeting and then the final viva voce. Other check-in sessions are permitted but do not need to be recorded on this sheet. After each reflection session candidates must record their reflections and as the supervisor you must sign and date this form.*

First reflection session

Candidate comments:

When I began researching possible topics for my EE, I came across a particularly interesting one relating to Huygens and the tautochrone problem. I remembered learning the same topic in a math class, but I wanted to investigate the physics aspects of it. To do this, I considered the tautochrone clock first created by Huygens, which I could manipulate the investigate the physics side of the tautochrone problem. My supervisor advised that I do more in-depth research of the topic in order to get a better sense of the problem.In addition, they advised that I read other sources to gather more information about the subject. I am interested in researching how changing the curvature of the plates in the clock could affect the motion of the pendulum in the tautochrone clock.

Date: March 1, 2017

Supervisor initials:

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Interim reflection

Candidate comments:

I have read several sources about Huygens and the tautochrone problem to obtain a substantial understanding of the physics behind the tautochrone. Additionally, I have set up a method of investigation that has been broken down into several tangible parts, and organized the materials that I'll need to carry out the procedure. This procedure will involve maintaining constant variables, such as the weight and material of the pendulum. By keeping these constant in my procedure, I will be able to measure how the curvature of the metal plates surrounding the pendulum will affect its periodicity (time of oscillation). My supervisor discussed how I might research the different ways of organizing sources when citing them in my extended essay. Since the citation of sources differs in various fields, he emphasized the importance of picking a format that is well-suited to the nature of my essay, in order to ensure clear communication.

Date: April 21, 2017 Supervisor initials:

Final reflection - Viva voce

Candidate comments:

Something I learned during the EE writing process was the importance of being willing to adjust to obstacles during experimentation. For instance, although I initially planned on using a 3D-printer as a part of my procedure, I was not able to access a 3D-printer when the time came to construct the tautochrone. I had to rethink my procedure, and eventually used a laser printer and a jigsaw to cut the tautochrone plates. Even though I hadn't anticipated the obstacle, I had to adjust appropriate in order to carry on with my procedure. A skill I've developed while writing my EE is planning ahead when it comes to bigger projects. While I was writing my EE I had to make deadlines for myself and look ahead of time. By choosing deadlines for myself, I was able to finish everything in a timely manner. As a result, I feel that if I wrote a research paper in the future I would have a much better sense of what kinds of deadlines to set for myself. As for my results, I found that my initial ideas about the topic were corroborated by the data I collected while writing my EE, but other aspects surprised me, such as the squared value in the relationship between my independent and dependent variables.

Date: September 28, 2016 Supervisor initials:

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Supervisor comments:

***Supervisor**: By submitting this candidate work for assessment, you are taking responsibility for its authenticity. No piece of candidate work should be uploaded/submitted to the e-Coursework system if its authenticity is in doubt or if contradictory comments are added to this form. If your text in the box below raises any doubt on the authenticity of the work, this component will not be assessed.*

This student created a neat project that combined her love of math and physics. She started off with a heavy math focused project that built upon a little bit of physics. Through our discussions, she realigned her background, the procedure, and the discussion to focus more on the physics behind this unique type of pendulum. One of the problems that she encountered was cutting out the curved plates. Her first choice was to 3D print the curvature, but that did not work out. Then she tried to use a jigsaw, but her hand was not too steady. Eventually she decided that the hand cut shape was good enough. She did a nice analysis of the video to collect the necessary data.

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