

Uniform Circular Motion: Investigating Centripetal Force, Radius, Period, and Frequency

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1. Introduction

1.1. Purpose

This report seeks to examine the effect of centripetal force on variables essential to uniform circular motion.

1.2. Question

What is the relationship between centripetal force and:

1. radius?
2. period?
3. frequency?

1.3. Hypothesis

Based on the following accepted formulae¹:

$$F_c = \frac{mv^2}{r}$$
$$v = \frac{2\pi r}{T} = 2\pi r f$$

It is derived that:

$$F_c = \frac{4\pi^2 mr}{T^2} = 4\pi^2 mr f^2 \quad (1)$$

Therefore, it is implicated that:

1. Centripetal force and radius are directly proportional ($F_c \propto r$)
2. Centripetal force and the square of period are inversely proportional ($F_c \propto \frac{1}{T^2}$)
3. Centripetal force and the square of frequency are directly proportional ($F_c \propto f^2$)

¹For definitions of symbols, please refer to Appendix A

2. Variables

2.1. Part A (Period & Radius)

Manipulated variable:

- Radius of the path of circular motion (r)

Responding variable:

- Period (T)

Control variables:

- Centripetal force (F_c)
- Mass of the object experiencing uniform circular motion (m)

2.2. Part B (Period & Centripetal Force)

Manipulated variable:

- Centripetal force (F_c)

Responding variable:

- Period (T)

Control variables:

- Radius of the path of circular motion (r)
- Mass of the object experiencing uniform circular motion (m)

3. Equipment and Materials

- Rubber stopper
- String (fishing line)
 - At least one meter
- Hollow tube
- Paperclip
- Masking tape
- Meter stick
- Timer
- Set of various hooked masses
 - 130 grams, 110 grams, 90 grams, 70 grams
- Digital balance

3.1. Setup

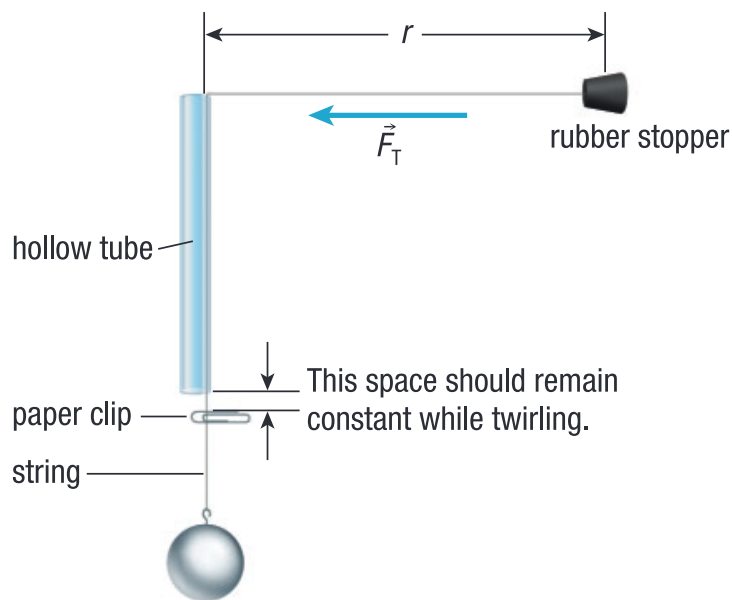


Figure 1: Experimental Setup

4. Procedure

4.1. Preparation

1. The rubber stopper was weighed on the balance and the mass was recorded.
2. Approximately 1 meter of string was measured and cut.
3. A rubber stopper was tied to one end of the string.
4. The other end of the string was threaded through the hollow tube.
5. The desired radius was measured as shown in Figure 1. The tube was fixed in place to mark this length.
6. A paperclip was taped securely to the string at the other end of the tube.
7. The desired hanging mass was tied to the loose end of the string.

4.2. Trial

1. For each trial, steps 5–7 in Section 4.1 were repeated.
2. The hollow tube was held in one hand and the hanging mass in the other. The apparatus was then slowly lifted.
3. Begin twirling the rubber stopper horizontally. Keep the hanging mass stationary.
4. Slowly release the hanging mass, maintaining a constant speed.
5. If the paperclip is too low, rotate faster.
6. If the paperclip is touching the tube, rotate slower.
7. Once the paperclip is just below the hollow tube, maintain a constant speed.
8. Time and record how long it takes to complete ten revolutions.

5. Observations

5.1. Qualitative Observations

It was difficult to maintain the paperclip at a consistent level. Often, the paperclip would become stuck and not respond as expected to changes in speed.

It was also noted that it was difficult to maintain the rotation on a flat horizontal plane. The stopper's axis of rotation often tilted, and the stopper's plane of rotation tended to be below the top of the tube.

5.2. Quantitative Observations

For all eight trials in Part A and Part B, an identical stopper was used, with a mass of 32.9g.

5.2.1. Part A (Period & Radius)

Four trials were conducted, starting with the radius at 40cm and increasing by approximately 10cm each trial. For all trials, the hanging mass was 130g.

Table 1: Data Recorded in Part A

#	r (m)	m_{stopper} (kg)	m_{hanging} (kg)	T^{\dagger} (s)	$f^{\dagger\dagger}$ (Hz)	f^2 (Hz ²)
1	0.410	0.0329	0.130	0.528	1.89	3.59
2	0.520	0.0329	0.130	0.587	1.70	2.91
3	0.600	0.0329	0.130	0.688	1.45	2.11
4	0.710	0.0329	0.130	0.758	1.32	1.74

5.2.2. Part B (Period & Centripetal Force)

Four trials were conducted, with the hanging mass at 130g and decreasing by 20g each trial. For all trials, the radius was 50cm.

Table 2: Data Recorded in Part B

#	r (m)	m_{stopper} (kg)	m_{hanging} (kg)	T^{\dagger} (s)	$f^{\dagger\dagger}$ (Hz)	f^2 (Hz ²)
5	0.500	0.0329	0.130	0.736	1.36	1.85
6	0.500	0.0329	0.110	0.749	1.34	1.78
7	0.500	0.0329	0.090	0.780	1.28	1.64
8	0.500	0.0329	0.070	0.809	1.24	1.53

[†]Calculated by dividing the time recorded on the timer by 10

^{††}Reciprocal of T

6. Analysis

6.1. Initial Assumptions

For the purpose of simplicity for later calculations, it is assumed that:

- Friction is negligible
- Air resistance is negligible
- The string is massless, inelastic, and flexible (tension at every point is constant)
- The force of gravity acting on the stopper is negligible in comparison to the tension of the string

The validity of these assumptions will be discussed in Section 7.

For all equations, assume that:

- up = \oplus , down = \ominus
- centripetal = \oplus , centrifugal = \ominus

6.2. Forces Involved

As illustrated in Figure 2, the only forces acting on the hanging mass are the force of tension on the string and the force of gravity, and these forces oppose each other.



Figure 2: Free body diagram of the hanging mass

$$F_{\text{net}} = F_T - F_{g1}$$

Since the paperclip was kept at a constant level, it is therefore necessary that:

$$F_{\text{net}} = 0N$$

Thus,

$$0 = F_T - F_{g1}$$

$$F_T = F_{g1} \tag{2}$$

As illustrated in Figure 3, the only force acting on the stopper is the force of tension (recall that it was assumed that the force of gravity is negligible in Section 6.1). Thus, this is also the net force.

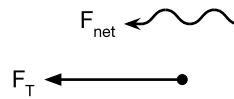


Figure 3: Free body diagram of the rotating stopper

$$F_{\text{net}} = F_T$$

Since the stopper is undergoing uniform circular motion, the net force must also be the centripetal force.

$$F_{\text{net}} = F_c$$

$$F_T = F_c \quad (3)$$

Substituting Equation (2) into Equation (3):

$$F_c = F_{g1} \quad (4)$$

Therefore, the magnitude of the centripetal force is equal to the magnitude of the weight of the hanging mass.

6.3. Part A (Period & Radius)

In all trials conducted in Part A, the hanging mass was 130g. Thus, $F_c \approx 1.28\text{N}$ for all trials².

It is intuitive that when $f = 0\text{Hz}$, $F_c = 0\text{N}$ (no force at all). Thus, a graph can be plotted for all datapoints in Table 1, drawing a line from the origin, as illustrated in Figure 4.

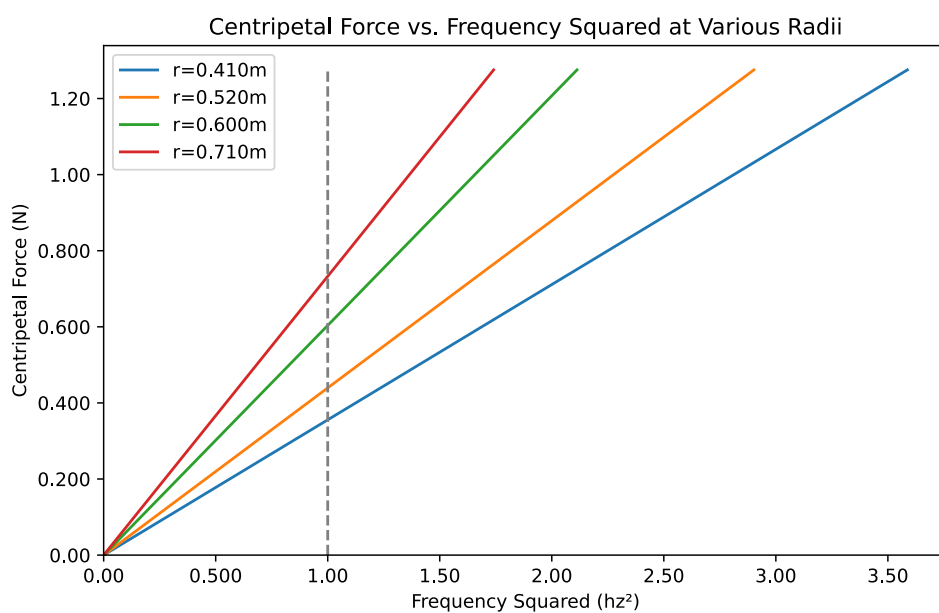


Figure 4: Centripetal Force vs. Frequency Squared at Various Radii

²See Appendix C.1. for calculations.

A vertical is then drawn at at 1.00Hz^2 . By reading vertically across each line plotted, the centripetal force for a constant f^2 at each corresponding radius was determined:

Table 3: Extrapolated Centripetal Forces at Various Radii

#	m_{stopper} (kg)	f^2 (Hz^2)	r (m)	F_c (N)
1	0.0329	1.00	0.410	0.355
2	0.0329	1.00	0.520	0.439
3	0.0329	1.00	0.600	0.603
4	0.0329	1.00	0.710	0.732

Clearly, radius and centripetal force are linearly correlated with each other, as illustrated by plotting this data in Figure 5. An r -value³ of 0.986 indicates a very strong positive correlation.

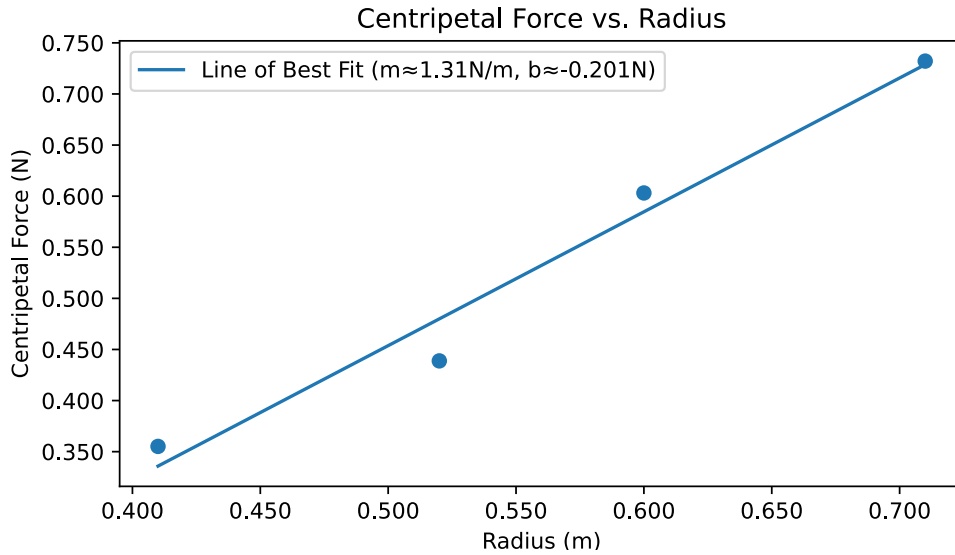


Figure 5: Centripetal Force vs. Radius ($r \approx 0.986$)

Using the equation for line of best fit from Figure 5, the following experimental equation for centripetal force arises:

$$F_c \approx \left(1.31 \frac{\text{N}}{\text{m}}\right)r - 0.201\text{N} \quad (5)$$

The theoretical formula for centripetal force based on the parameters in Table 3 is⁴:

$$F_c \approx \left(1.30 \frac{\text{N}}{\text{m}}\right)r \quad (6)$$

Equation (5) has a offset where Equation (6) has none. Although the exact error cannot be calculated, this is a significant amount of error, considering its magnitude. The error for the slope is very low, at around 0.825%.⁵ Given the error in y-intercept, this is likely coincidence.

³Pearson's correlation coefficient. For the formula, please see Appendix B.

⁴See Appendix C.2. for calculations.

⁵See Appendix C.3. for calculations.

6.4. Part B (Period & Centripetal Force)

Using the conclusion reached from Section 6.2, the following table can be produced by calculating the centripetal force for each trial from Section 5.2.2⁶:

Table 4: Data Recorded in Part B (Centripetal Force)

#	F_c (N)	r (m)	m_{stopper} (kg)	T (s)	f (Hz)
5	1.28	0.500	0.0329	0.736	1.36
6	1.08	0.500	0.0329	0.749	1.34
7	0.883	0.500	0.0329	0.780	1.28
8	0.687	0.500	0.0329	0.809	1.24

6.4.1. Relationship Between Centripetal Force & Period

Equation (1) from Section 1.3 hints that this relationship is likely not linear. The log-linearization technique can be applied to analyze this relationship as if it were linear:

$$F_c = \frac{4\pi^2 mr}{T^2}$$

$$F_c = (4\pi^2 mr)T^{-2}$$

$$\log(F_c) = \log((4\pi^2 mr)T^{-2})$$

$$\log(F_c) = \log(4\pi^2 mr) + \log(T^{-2})$$

$$\log(F_c) = -2\log(T) + \log(4\pi^2 mr)$$

The theoretical slope of a plot between $\log(F_c)$ and $\log(T)$ should be -2 and the y-intercept should be $\log(4\pi^2 mr)$.

By simply taking the log of F_c and T from Table 4, the following table is obtained:

Table 5: Data Recorded in Part B (F_c and T), Logarithms

#	$\log(F_c)$	r (m)	m_{stopper} (kg)	$\log(T)$
5	0.106	0.500	0.0329	-0.133
6	0.033	0.500	0.0329	-0.126
7	-0.054	0.500	0.0329	-0.108
8	-0.163	0.500	0.0329	-0.092

⁶See Appendix C.4. for calculations.

The following scatter plot and line of best fit can be generated from the data in Table 5:

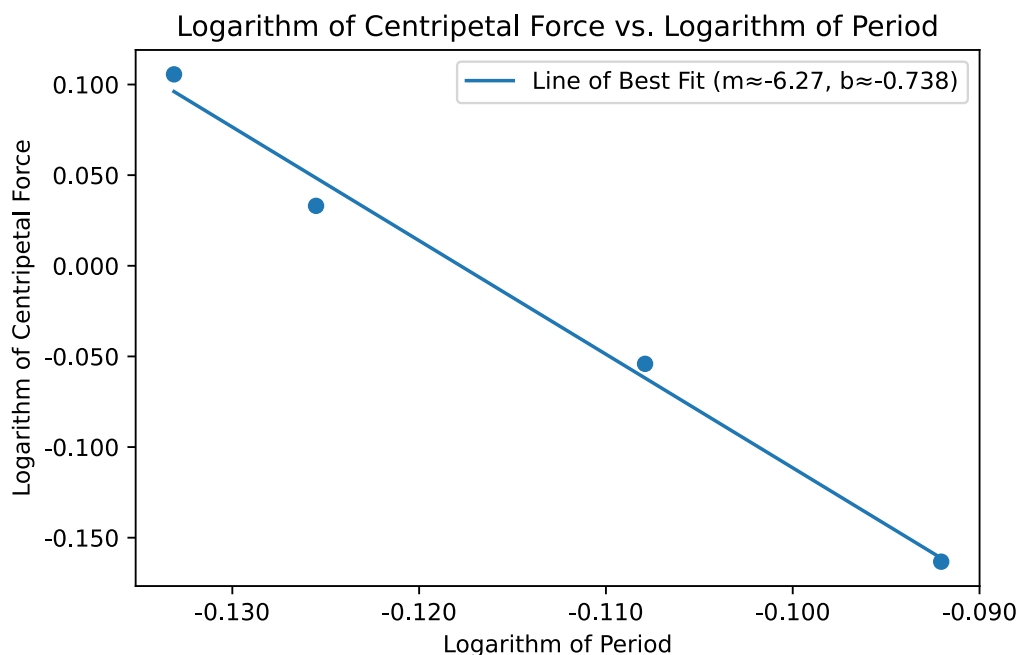


Figure 6: Logarithm of Centripetal Force vs. Logarithm of Period ($r = -0.995$)

Visually, the data displays a strong negative correlation. The r -value of -0.995 indicates an almost exact linear correlation.

However, the slope and y-intercept both show high levels of deviation from the theoretical values derived from Equation (1), at 213% and 294%, respectively⁷.

6.4.2. Relationship Between Centripetal Force & Frequency

Much of the techniques used in this section will be similar to the techniques used in Section 6.4.1.

Using similar algebraic techniques, the following linear relationship is obtained between $\log(F_c)$ and $\log(f)$:

$$\begin{aligned}
 F_c &= 4\pi^2 mr f^2 \\
 \log(F_c) &= \log((4\pi^2 mr) f^2) \\
 \log(F_c) &= \log(4\pi^2 mr) + \log(f^2) \\
 \log(F_c) &= 2 \log(f) + \log(4\pi^2 mr)
 \end{aligned}$$

Thus, the theoretical slope of a plot between $\log(F_c)$ and $\log(f)$ should be 2 and the y-intercept should be $\log(4\pi^2 mr)$.

⁷See Appendix C.5. and Appendix C.6. for calculations.

By taking the log of F_c and f from Table 4, the following table is obtained⁸:

Table 6: Data Recorded in Part B (F_c and f), Logarithms

#	$\log(F_c)$	r (m)	m_{stopper} (kg)	$\log(f)$
5	0.106	0.500	0.0329	0.133
6	0.033	0.500	0.0329	0.126
7	-0.054	0.500	0.0329	0.108
8	-0.163	0.500	0.0329	0.092

Using the above data, the below scatter plot can be produced:

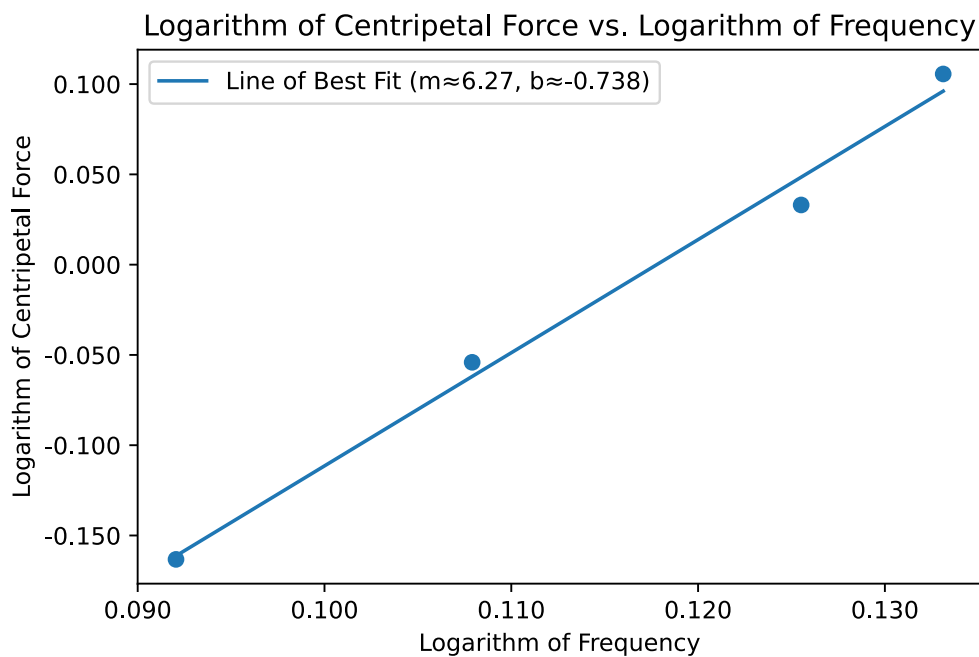


Figure 7: Logarithm of Centripetal Force vs. Logarithm of Frequency ($r = 0.995$)

Undeniably, Figure 7 shows a clear positive relationship between frequency and centripetal force. An r -value of 0.995 indicates a very strong positive correlation between the logarithms of these values.

Note that the values for slope (~ 6.27) and r are both the negatives of the values found in Figure 6. This is expected, given that frequency is the reciprocal of period, and taking the reciprocal is equivalent to raising a value to the -1^{st} power.

The y-intercept is also identical, which is also expected based on the nature of log-linearization.

However, this also means that the errors for slope and y-intercept are equally as high as in Section 6.4.1, at 213% and 294%, respectively.⁹

⁸The values for $\log(f)$ are just the negatives of $\log(T)$, since f is just the reciprocal of T .

⁹See Appendix C.7. and Appendix C.6, respectively, for calculations.

7. Evaluation

7.1. Application to a Theoretical Situation

Using these results, it is possible to extrapolate the centripetal force required to rotate the rubber stopper where $r = 1.5\text{m}$ and $f = 8.0\text{Hz}$.

From Figure 7, the following equation for centripetal force arises:

$$\log(F_c) = 6.27 \log(f) - 0.738 \quad (7)$$

Comparing with the theoretical equation from Section 6.4.2:

$$\log(F_c) = 2 \log(f) + \log(4\pi^2 mr)$$

Since the experimental equation shows some deviation as discussed in Section 6.4.2, we cannot directly substitute for the mass of the stopper. Instead, we will define a constant coefficient of the radius to interpolate the y-intercept from Equation (7) into this situation.

Let $n = 4\pi^2 m$. By inspection:

$$\begin{aligned} -0.738 &= \log(nr) \\ -0.738 &= \log(n(0.500\text{m})) \\ 0.5n &= 10^{-0.738} \\ n &\approx 0.366^{\dagger\dagger\dagger} \end{aligned}$$

Finding the new y-intercept for $r = 1.5\text{m}$:

$$\begin{aligned} \log(nr) &= \log(0.36552423 \times 1.5\text{m}) \\ &= \log(0.548286345) \\ &\approx -0.261 \end{aligned}$$

Substitute $\log(nr) = -0.261$ and $f = 8.0\text{Hz}$ into Equation (7):

$$\begin{aligned} \log(F_c) &= 6.27 \log(f) - 0.26099257 \\ \log(F_c) &= 6.27 \log(8.0\text{Hz}) - 0.26099257 \\ \log(F_c) &= 5.65922972 - 0.26099257 \\ \log(F_c) &= 5.39823715 \\ F_c &= 2.50 \times 10^5 \text{N} \end{aligned}$$

Clearly, this value is outlandishly high, likely due to the experimental exponent being 6.27. As discussed, this is much higher than the theoretical exponent of 2, meaning that the experimental results expect F_c to grow at a much higher rate.

7.2. Sources of Error

There are likely several factors which contributed to the high level of error seen in this report. This section will attempt to address the most exorbitant sources and suggest solutions to mitigate this error.

^{†††}Although n has units (kg), the units are meaningless in this context as n was a constant created to account for error in a logarithm and thus, the units have been omitted.

7.2.1. Issues with Assumptions

A number of assumptions were made in Section 6.1 to reduce the complexity of calculations. The two that most likely contributed most to the error observed were neglecting friction and neglecting the force of gravity on the stopper.

As noted in Section 5.1, it was observed that the paperclip would occasionally not respond to changes in speed. This is undoubtedly due to the friction experienced by the string on the tube.

To mitigate this effect, it may be preferable to spin at slower speeds to minimize the centripetal force and thus the reaction force of the tube on the fishing line.

Furthermore, it may not be acceptable to consider the force of gravity on the stopper as negligible. Given a mass of 0.0329kg, $F_{g \text{ stopper}} = (0.0329\text{kg})(9.81 \frac{\text{m}}{\text{s}^2}) \approx 0.323\text{N}$.

This is in fact extremely significant, especially when compared to the assumed centrifugal forces calculated in Section 6, being as much as 47.0% in the case of trial 8.¹⁰

When drawing the free body diagram for the stopper considering gravity, it becomes clear why this is significant:

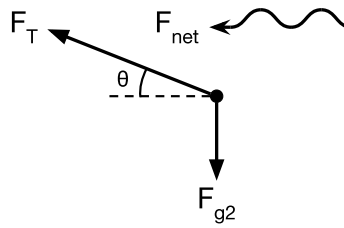


Figure 8: Free body diagram of the stopper, considering gravity

This free body diagram matches observations in Section 5.1, where it was noted the stopper would rarely be at the same level as the tube.

Clearly, some tension (resulting from the weight of the hanging mass) must counteract the weight of the stopper to prevent it from falling.

Specifically,

$$\begin{aligned} \therefore F_{\text{net } y} &= 0 \\ \therefore F_{\text{net } y} &= F_T \sin \theta - F_{g2} \\ \therefore 0 &= F_T \sin \theta - F_{g2} \\ \therefore F_T \sin \theta &= F_{g2} \end{aligned}$$

Similarly on the x-axis,

$$\begin{aligned} F_c &= F_{\text{net } x} \\ F_c &= F_T \cos \theta \end{aligned}$$

This contradicts Equation (3), which claims that $F_c = F_T$.

The error between these two interpretations of F_c grows with larger values of θ .

¹⁰Calculations: $\frac{0.322749\text{N}}{0.6867\text{N}} \times 100\% = 0.47 \times 100\% = 47.0\%$.

Thus, our previous analysis has likely vastly overestimated the centrifugal force acting on the stopper. To account for this inaccuracy, Equation (3) and Equation (4) should be replaced with more accurate equations.

Alternatively, it may be possible use a lighter stopper or a heavier hanging mass in order to make the weight of the stopper much more smaller relative to the weight of the hanging mass.

This arises from the small angle approximation for cosine.

When $F_T = F_{g1} \gg F_{g2}$, tension has to compensate less for the weight of the stopper, and θ becomes very small. The small angle approximation tells us that $\cos \theta \approx 1$ and that therefore $F_c \approx F_c \cos \theta$ when $F_{g1} \gg F_{g2}$.

7.2.2. Timing

While timing, group members noticed the difficulty associated with accurately starting and stopping the timer during the proper intervals.

Especially given the small time scales on which this experiment depends, small errors in timing can result in large discrepancies in experimental results.

Instead of only timing ten revolutions as described in Section 4.2, it may be better to time twenty or even larger numbers of revolutions and to have multiple timers to verify each other's times.

8. Findings

Given the strong positive correlations ($r > 0.95$) seen in Figure 5 and Figure 7, in conjunction with the strong negative correlations ($r < -0.95$) seen in Figure 6, the following proportionality statements can be reasonably made:

1. $F_c \propto r$
2. $F_c \propto \frac{1}{T^k}$
3. $F_c \propto f^k$

Where $k \in \mathbb{Z}_+$

These conclusions partially verify the hypotheses made in Section 1.3.

However, more work needs to be done to verify the value of k , which should theoretically be 2, and eliminate the y-intercept errors.

Overall, some general conclusions about the relationship between variables in centripetal force can be made. However, given the high error values $> 200\%$ found in Section 6.4 as well as the relatively high magnitude of y-intercept found in Section 6.3, this report has unfortunately failed to fully verify the theoretical equations for centripetal force.

Appendix

A. Definitions of Symbols

F_c : centripetal force (newtons / N)

F_g : weight (newtons / N)

F_T : tension (newtons / N)

m : mass (kilograms / kg)

r : radius—specifically of the circular path created by an object undergoing uniform circular motion (meters / m)¹¹

v : velocity—in this report, tangential velocity in particular (meters per second / $\frac{m}{s}$)

T : period—the time it takes an object experiencing uniform circular motion to complete one revolution (seconds / s)

f : frequency—the number of revolutions per second (hertz / hz / s^{-1})

π : the ratio of a circle's circumference to its diameter.

B. Formulae

$$F_c = \frac{mv^2}{r}$$

$$v = \frac{2\pi r}{T}$$

$$f = \frac{1}{T}$$

$$r = \frac{\Sigma(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\Sigma(x_i - \bar{x})^2 \Sigma(y_i - \bar{y})^2}} \text{ (see Footnote 3)}$$

C. Work

C.1. Centripetal Force in Section 6.3

Using Equation (4) from Section 6.2, we simply plug in known values:

$$F_c = F_g = m_1 g$$

$$F_c = m_{\text{hanging}} \left(9.81 \frac{m}{s^2} \right)$$

$$F_c = (0.130 \text{ kg}) \left(9.81 \frac{m}{s^2} \right)$$

$$F_c = 1.28 \text{ N}$$

C.2. Theoretical Formula for F_c in Section 6.3

A suitable formula for centripetal force was derived in Section 1.3:

$$F_c = 4\pi^2 m r f^2$$

Plugging in $m = m_{\text{stopper}} = 0.0329 \text{ kg}$ and $f^2 = 1.00 \text{ Hz}^2$:

¹¹In some cases, r represents Pearson's correlation coefficient.

$$F_c = 4\pi^2(0.0329\text{kg})r(1.00\text{Hz}^2)$$

$$F_c = (4 \times \pi^2 \times 0.0329 \times 1.00)r$$

$$F_c \approx (1.30\frac{\text{N}}{\text{m}})r$$

C.3. Error for Slope in Section 6.3

Given:

$$\text{experimental} = 1.309548966\frac{\text{N}}{\text{m}}, \text{theoretical} = 1.298839939\frac{\text{N}}{\text{m}}$$

$$\% \text{ error} = \left| \frac{\text{experimental} - \text{theoretical}}{\text{theoretical}} \right| \times 100\%$$

$$\% \text{ error} = \left| \frac{1.309548966\frac{\text{N}}{\text{m}} - 1.298839939\frac{\text{N}}{\text{m}}}{1.298839939\frac{\text{N}}{\text{m}}} \right| \times 100\%$$

$$\% \text{ error} = \left| \frac{0.010709026}{1.298839939} \right| \times 100\%$$

$$\% \text{ error} = 0.00824507 \times 100\%$$

$$\% \text{ error} \approx 0.825\%$$

C.4. Centripetal Force in Section 6.4

An example calculation is provided below for trial 6. Values for trials 4, 7, 8 were calculated using similar techniques.

Using Equation (4) from Section 6.2, we simply plug in known values:

$$F_c = F_g = m_1g$$

$$F_c = m_{\text{hanging}}(9.81\frac{\text{m}}{\text{s}^2})$$

$$F_c = (0.110\text{kg})(\frac{\text{m}}{\text{s}^2})$$

$$F_c = 1.08\text{N}$$

C.5. Error for Slope in Section 6.4.1

Given:

$$\text{experimental} = -6.266518067, \text{theoretical} = -2$$

$$\% \text{ error} = \left| \frac{\text{experimental} - \text{theoretical}}{\text{theoretical}} \right| \times 100\%$$

$$\% \text{ error} = \left| \frac{-6.266518067 - (-2)}{-2} \right| \times 100\%$$

$$\% \text{ error} = \left| \frac{-4.266518067}{-2} \right| \times 100\%$$

$$\% \text{ error} = 2.133259034 \times 100\%$$

$$\% \text{ error} \approx 213\%$$

C.6. Errors for y-intercept in Section 6.4.1 & Section 6.4.2

Given:

$$\text{experimental} = -0.738113824$$

$$\text{theoretical} = \log(4\pi^2mr) = \log(4\pi^2(0.0329\text{kg})(0.500\text{m})) = -0.187474361$$

$$\% \text{ error} = \left| \frac{\text{experimental} - \text{theoretical}}{\text{theoretical}} \right| \times 100\%$$

$$\% \text{ error} = \left| \frac{-0.738113824 - (-0.187474361)}{-0.187474361} \right| \times 100\%$$

$$\% \text{ error} = \left| \frac{-0.550639463}{-0.187474361} \right| \times 100\%$$

$$\% \text{ error} = 2.937145432 \times 100\%$$

$$\% \text{ error} \approx 294\%$$

C.7. Error for Slope in Section 6.4.2

Given:

experimental = 6.266518067, theoretical = 2

$$\% \text{ error} = \left| \frac{\text{experimental} - \text{theoretical}}{\text{theoretical}} \right| \times 100\%$$

$$\% \text{ error} = \left| \frac{6.266518067 - 2}{2} \right| \times 100\%$$

$$\% \text{ error} = \left| \frac{4.266518067}{2} \right| \times 100\%$$

$$\% \text{ error} = 2.133259034 \times 100\%$$

$$\% \text{ error} \approx 213\%$$

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