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

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Contents

1. Introduction

1.1. Purpose

This report seeks to examine the relationship between centripetal force and 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 formulae[1]:

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

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

It is derived that:

$$F_c = \frac{4\pi^2 m r}{T^2} = 4\pi^2 m r f^2 \tag{1}$$

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 ($F_c \propto f^2$)

[1]For 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

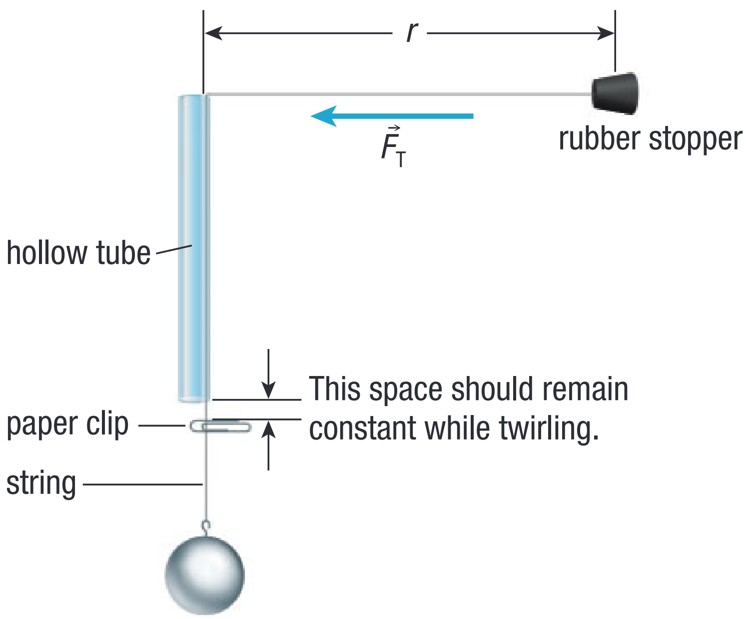

Figure 1: Experimental Setup [1]

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 held 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.

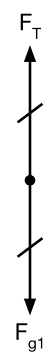

Figure 2: Free body diagram of the hanging mass

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

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 below 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.

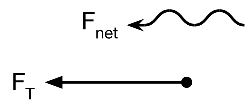

Figure 3: Free body diagram of the rotating stopper

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

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

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

$$F_T = F_c \tag{3}$$

Substituting Equation (2) into Equation (3):

$$F_c = F_{g1} \tag{4}$$

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 trials[2].

It is intuitive that when $f = 0\text{Hz}$, $F_c = 0N$ (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.

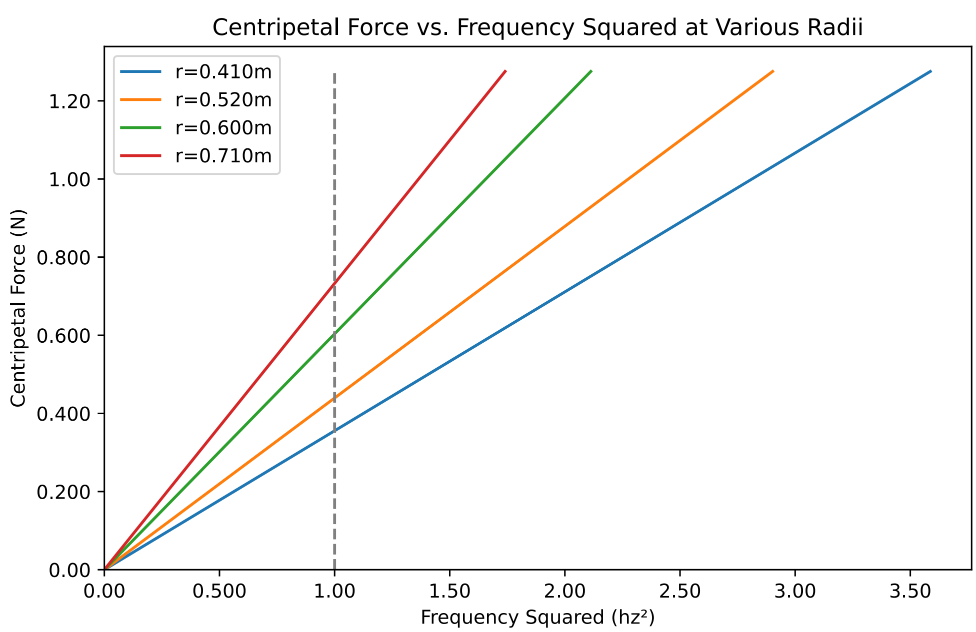

Figure 4: Centripetal Force vs. Frequency Squared at Various Radii

[2]See Appendix C.1. for calculations.

A vertical is then drawn at at 1.00hz². 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

Next, the log-linearization technique can be applied on Equation (1):

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

Substituting $m = 0.0329\text{kg}$ and $f^2 = 1.00\text{Hz}^2$ into the above equation yields:[3]

$$\log(F_c) \approx \log(r) + \log\left(1.30\tfrac{\text{N}}{\text{m}}\right)$$

The remainder of this section will produce an equivalent experimental formula in the form:

$$\log(F_c) \approx n_1 \log(r) + \log(k_1)$$

Ideally, $n_1 = 1$ and $k_1 = 1.30\frac{\text{N}}{\text{m}}$

First, by taking the logarithm of values Table 3, the following table was produced:

Table 4: Extrapolated Centripetal Forces at Various Radii (Logarithms)

#	m_{stopper} (kg)	f^2 (Hz^2)	$\log(r)$	$\log(F_c)$
1	0.0329	1.00	−0.387	−0.450
2	0.0329	1.00	−0.284	−0.358
3	0.0329	1.00	−0.222	−0.220
4	0.0329	1.00	−0.149	−0.135

[3] See Appendix C.2. for calculations.

The data from Table 4 has been plotted below in Figure 5. An r-value[4] of 0.985 indicates a very strong positive correlation between these two variables.

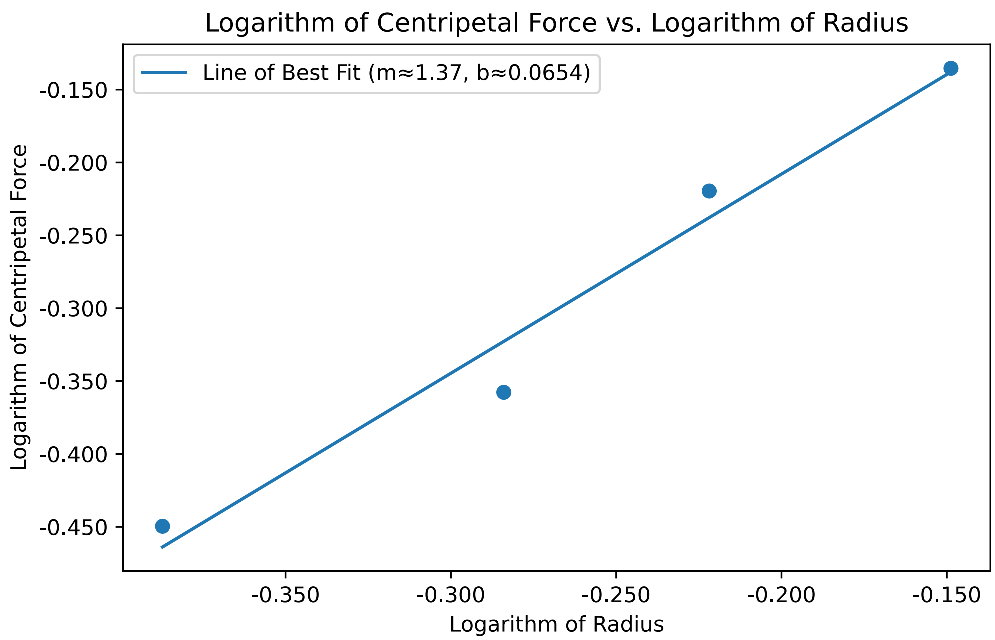

Figure 5: Logarithm of Centripetal Force vs. Logarithm Radius ($r \approx 0.985$)

n_1 is simply the slope in the line of best fit in Figure 5 and k_1 can be calculated as the antilogarithm of the y-intercept, since the relationship between $\log(F_c)$ and $\log(r)$ is linear:

$$\log(k_1) \approx 0.065388416$$
$$k_1 \approx 10^{0.065388416}$$
$$k_1 \approx 1.16 \tfrac{\mathrm{N}}{\mathrm{m}}$$

The following experimental equation for centripetal force arises:

$$\log(F_c) \approx 1.367 \log(r) - \log\left(1.16 \tfrac{\mathrm{N}}{\mathrm{m}}\right)$$
$$\log(F_c) \approx 1.37 \log(r) - \log\left(1.16 \tfrac{\mathrm{N}}{\mathrm{m}}\right)$$

The error in n_1 is 36.7% (by inspection), and the error in k_1 is about 10.5%, which is within experimental error.[5]

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 5.2.2:[6]

[4]Pearson's correlation coefficient. For the formula, please see Appendix B.
[5]See Appendix C.3. for calculations.
[6]See Appendix C.4. for calculations.

Table 5: 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:

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

Substitute $m = 0.0329\text{kg}$:

$$\begin{aligned}
\log(F_c) &\approx -2\log(T) + \log(4\pi^2(0.0329\text{kg})r) \\
\log(F_c) &\approx -2\log(T) + \log((1.30\text{kg})r)
\end{aligned}$$

The goal of the following analysis is to produce a formula in the form:

$$\log(F_c) \approx n_2 \log(T) + \log(k_2 r^{n_2})$$

To compare with this theoretical equation. Theoretically, $n_2 = -2$ and $k_2 = 1.30\text{kg}$.

By simply taking the log of F_c and T from Table 5, the following table is obtained:

Table 6: 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

The following scatter plot and line of best fit can be generated from the data in Table 6:

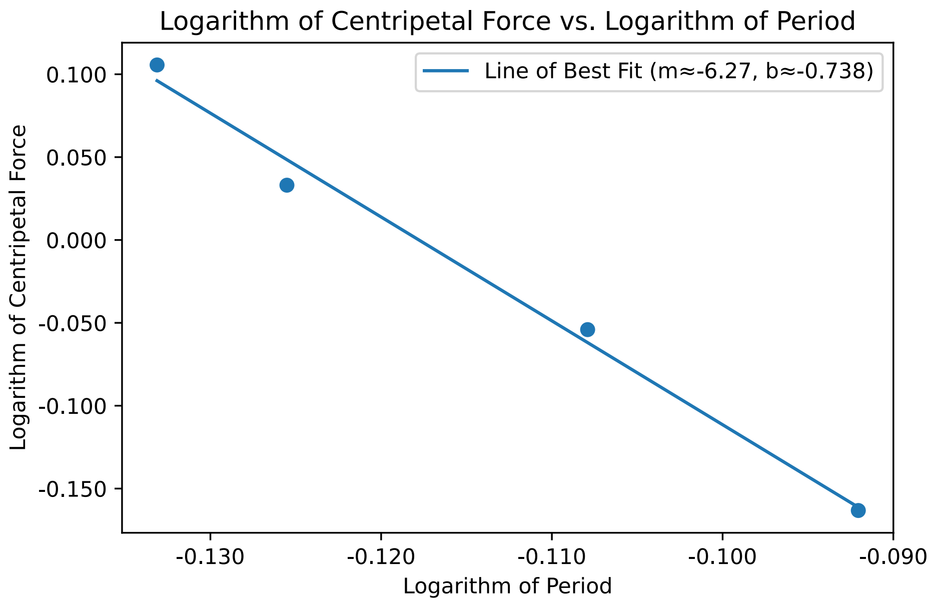

Figure 6: Logarithm of Centripetal Force vs. Logarithm of Period ($r = -0.995$)

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

Using the y-intercept, we can calculate k since $r = 0.500\text{m}$ and $n_1 \approx 1.37$ from Section 6.3:

$$\begin{aligned} \log(k_2 r^{n_1}) &= -0.738113824 \\ k_2(0.500\text{m}^{1.366714833}) &= 10^{-0.738113824} \\ k_2 &= \tfrac{0.182762115}{0.38777243} \\ &\approx 0.471\ \text{kg} \end{aligned}$$

n_2 is simply the slope of the line of best fit in Figure 6 (about -6.27).

The experimental results can now be represented in the log-linearized form of the exponential equation $F_c = k_2 r^{n_1} T^{n_2}$:

$$\log(F_c) \approx -6.27 \log(T) + \log((0.471\text{kg}) r^{1.37}) \tag{5}$$

Both n_2 and k_2 show high levels of deviation from the theoretical values, at 213% and 63.7%, respectively.[7]

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

6.4.2. Relationship Between Centripetal Force & Frequency

Many techniques used in this section will be similar to techniques used in Section 6.4.1. Applying log-linearization, the following relationship is obtained between $\log(F_c)$ and $\log(f)$:

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

Substitute $m = 0.0329\text{kg}$:

$$\begin{aligned} \log(F_c) &\approx 2\log(f) + \log(4\pi^2(0.0329\text{kg})r) \\ \log(F_c) &\approx 2\log(f) + \log((1.30\text{kg})r) \end{aligned}$$

The goal of the following analysis is to produce a respective formula in the form:

$$\log(F_c) \approx n_3 \log(f) + \log(k_2 r^{n_1})$$

Theoretically, $n_3 = 2$ and $k_2 = 1.30\text{kg}$.

First, by taking the log of F_c and f from Table 5, the following table is obtained:[8]

Table 7: 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

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

Using data from Table 7, the below plot was produced:

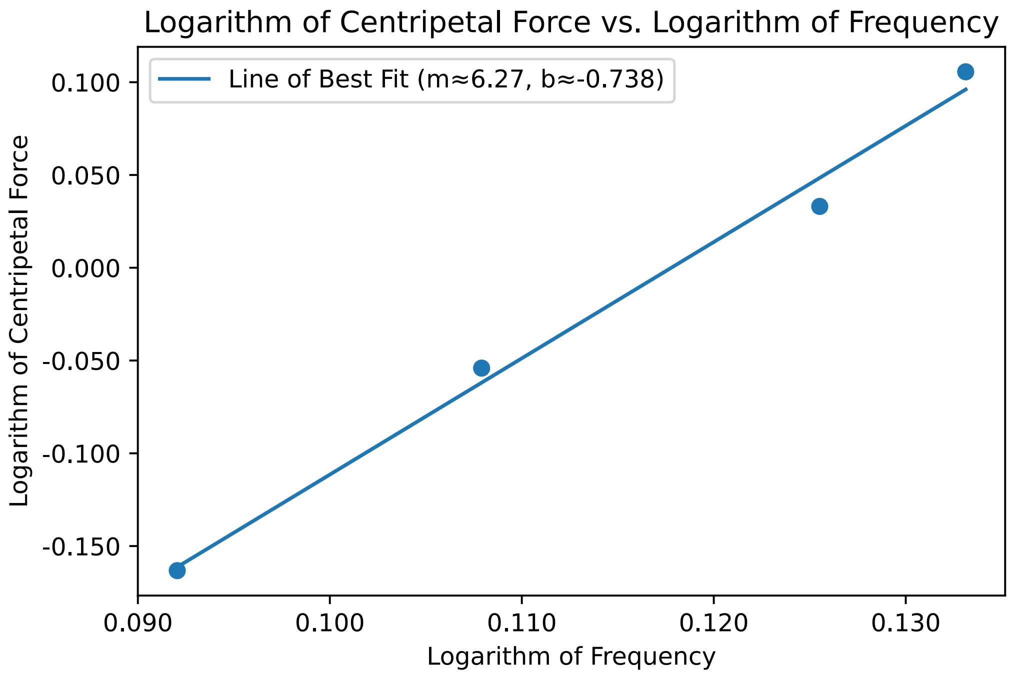

Figure 7: Logarithm of Centripetal Force vs. Logarithm of Frequency ($r = 0.995$)

An r-value of 0.995 indicates a very strong positive correlation between frequency and centripetal force.

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 of the line of best fit is also identical, which is also expected based on the nature of log-linearization. The y-intercept represents the coefficient, which remains constant at $4\pi^2 m$ for both T and f, as in Equation (1).

Since the y-intercept is identical, k_2 must also be identical to the k_2 found in Section 6.4.1 (about 0.471kg).

n_3 is simply the slope of the line of best fit in Figure 7 (about 6.27).

The log-linearized formula for F_c vs. f is therefore:

$$\log(F_c) \approx 6.27 \log(f) + \log((0.471\text{kg})r^{1.37}) \tag{6}$$

However, this also means that the errors for n_3 and k_2 are equally as high as in Section 6.4.1, at 213% and 63.7%, respectively.[9]

[9] See 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 $f = 8.0\text{Hz}$.

Equation (6) was derived in Section 6.4.2:

$$\log(F_c) \approx 6.27\log(f) + \log((0.471\text{kg})r^{1.37})$$

Substitute $r = 1.5\text{m}$ and $f = 8.0\text{Hz}$ into Equation (6):

$$\begin{aligned}
\log(F_c) &\approx 6.266518067\log(f) - \log(0.471311825\text{kg} \times r^{1.366714833}) \\
\log(F_c) &\approx 6.266518067\log(8.0\text{Hz}) - \log(0.471311825\text{kg} \times 1.5\text{m}^{1.366714833}) \\
\log(F_c) &\approx 6.266518067\log(8) - \log(0.82030408) \\
\log(F_c) &\approx 5.65802193 + 0.086025128 \\
F_c &\approx 10^{5.744047058} \\
F_c &\approx 5.55 \times 10^5\text{N}
\end{aligned}$$

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

Relevant equations:

$$F_c \approx k_1 r^{n_1} \text{ , from Section 6.3} \tag{7}$$

$$F_c \approx k_2 r^{n_1} T^{n_2} \text{ , from Section 6.4.1} \tag{8}$$

$$F_c \approx k_2 r^{n_1} f^{n_3} \text{ , from Section 6.4.2} \tag{9}$$

The below table summarizes errors found in Section 6 for relevant parameters:

Table 8: Summary of Errors

Parameter	Description	Theoretical	Actual	Error
n_1	Exponent on r in Eqn. (7)	1	1.37	36.7%
k_1	Coefficient of r^{n_1} in Eqn. (8)	$1.30\frac{\text{N}}{\text{m}}$	$1.16\frac{\text{N}}{\text{m}}$	10.5%
n_2	Exponent on T in Eqn. (9)	-2	-6.27	213%
k_2	Coefficient of $r^{n_1}T^{n_2}$ in Eqn. (9)	1.30kg	0.471kg	63.7%
n_3	Exponent on f Eqn. (10)	2	6.27	213%

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

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, $F_{g\text{ stopper}} = (0.0329\text{kg})\left(9.81\frac{\text{m}}{\text{s}^2}\right) \approx 0.323\text{N}$.

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

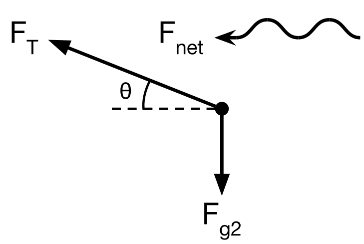

Figure 8: Free body diagram of the stopper, considering gravity

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,

$$F_c = F_{\text{net x}}$$
$$F_c = F_T \cos\theta$$

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.

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

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 $F_{g_1} = F_T \gg F_{g2}$, 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. $F_c \propto \frac{1}{T^n}$
3. $F_c \propto f^n$

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

These conclusions partially verify the hypotheses made in Section 1.3.

However, more work needs to be done to verify the value of n, 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 / $\frac{\mathrm{m}}{\mathrm{s}}$)

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

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

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

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

$r = \frac{\Sigma(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\Sigma(x_i - \overline{x})^2 \Sigma(y_i - \overline{y})^2}}$ (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:

$$F_c = F_g = m_1 g$$

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

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

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

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

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 $f^2 = 1.00\text{Hz}^2$:

$$F_c = 4\pi^2(0.0329\text{kg})r(1.00\text{Hz}^2)$$
$$F_c = (4 \times \pi^2 \times 0.0329 \times 1.00)r$$
$$F_c \approx \left(1.30\tfrac{\text{N}}{\text{m}}\right)r$$

Taking the logarithms:

$$\log(F_c) \approx \log\left(\left(1.30\tfrac{\text{N}}{\text{m}}\right)r\right)$$
$$\log(F_c) \approx \log(r) + \log\left(1.30\tfrac{\text{N}}{\text{m}}\right)$$

C.3. Error for k_1 in Section 6.3

Given: experimental $= 1.162487831\frac{\text{N}}{\text{m}}$, theoretical $= 1.298839939\frac{\text{N}}{\text{m}}$

$$\%\text{ error} = \left|\frac{\text{experimental} - \text{theoretical}}{\text{theoretical}}\right| \times 100\%$$
$$\%\text{ error} = \left|\frac{1.162487831\frac{\text{N}}{\text{m}} - 1.298839939\frac{\text{N}}{\text{m}}}{1.298839939\frac{\text{N}}{\text{m}}}\right| \times 100\%$$
$$\%\text{ error} = \left|\frac{-0.136352107}{1.298839939}\right| \times 100\%$$
$$\%\text{ error} = 0.104979915 \times 100\%$$
$$\%\text{ error} \approx 10.5\%$$

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:

$$F_c = F_g = m_1 g$$
$$F_c = m_{\text{hanging}}\left(9.81\tfrac{\text{m}}{\text{s}^2}\right)$$
$$F_c = (0.110\text{kg})\left(9.81\tfrac{\text{m}}{\text{s}^2}\right)$$
$$F_c = 1.08\text{N}$$

C.5. Error for n_2 in Section 6.4.1

Given: experimental $= -6.266518067$, theoretical $= -2$

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

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

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

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

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

C.6. Errors for k_2 in Section 6.4.1 & Section 6.4.2

Given:

- experimental $= 0.471311824\text{kg}$
- theoretical $= 4\pi^2 m = 4\pi^2(0.0329\text{kg}) = 1.298839939\text{kg}$

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

$$\% \text{ error} = |\frac{0.471311824-1.298839939}{1.298839939}| \times 100\%$$

$$\% \text{ error} = |\frac{-0.827528115}{1.298839939}| \times 100\%$$

$$\% \text{ error} = 0.637 \times 100\%$$

$$\% \text{ error} \approx 63.7\%$$

C.7. Error for n_3 in Section 6.4.2

Given: experimental $= 6.266518067$, theoretical $= 2$

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

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

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

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

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

Bibliography

[1] D. Bruni, M. Digiuseppe, G. Dick, J. Speijer, and C. Stewart, *Nelson Physics 12: University Preparation.* Thomson/Nelson, 2012, p. 136.

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