MEEN 404 - 905

Experiment 2

The effects of thickness and material on the spring constant of 3D printed spiral torsion springs

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Abstract

This experiment tested the effects of spring thickness and printing material on the torsional spring constant of 3D printed spiral torsion springs. Spiral springs, typically made from rolled steel, provide a radial deflection and are used in a variety of applications. Current springs are often used in corrosive, or other, environments where metal is not ideal so the group explored the possibility of replacing the metal springs with 3D printed ones. The springs were printed using three different materials which consisted of acrylonitrile butadine styrene (ABS), high impact polystyrene (HIPS), and polylactic acid (PLA). Three springs were printed with each material with three different thicknesses consisting of 2, 3, and 4 mm for a total of 9 springs for the experiment. In order to test the springs, an angle meter coupled with a torque wrench was used to twist the springs, fixed to a board at the center and free end, counter-clockwise. Using a form of Hooke's Law, the spring constant for each spring can be calculated by dividing the torque by its corresponding angle. As expected, the 4 mm PLA spring had the highest spring constant but it was much lower than expected in numerical value at 2.59 $\frac{N \cdot m}{rad}$. The HIPS 2 mm has the smallest spring constant at 0.25 $\frac{N \cdot m}{rad}$ as was expected, however, the 2 mm PLA and 2 mm ABS weren't much larger at 0.27 $\frac{N \cdot m}{rad}$ for both. All the measurements followed a positive linear trend, however, there were some discrepancies caused by the torque wrench uncertainty. The overall uncertainty for the spring constant was 0.018 $\frac{N \cdot m}{rad}$ or about 3.60 $\%$. It was also found that the spring constant values did not follow the predictor model used with metal springs. This is thought to be due to the 3D printing of these springs. Their resulting material properties were different than what they would have been if they were made of solid plastic by no longer being isotropic.

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Glossary Table

A	Arbor diameter (see diagram in Appendix for clarification)
ABS	Acrylonitrile Butadiene Styrene
$ANOVA$	Analysis of Variance, a statistical analysis tool
b	Material width $[mm]$
E	Youngs Modulus $[MPa]$
$FMEA$	"Failure Modes and Effects Analysis"
$HIPS$	High Impact Polystyrene
κ	Hookes law constant $\left[\frac{N\cdot m}{rad}\right]$
$\bar{\kappa}$	Average Hookes law constant $\left[\frac{N\cdot m}{rad}\right]$
K_B	Bending Stress Correction Factor
L	Length of active material within spring (in mm)
M	Moment created by spiral torsion spring
m	Meters
mm	Millimeter
N	Newtons
Nm	Newton-meter
Nm/rad	Newton-meter per radian - units for spring constant
π	Mathematical constant pi ≈ 3.14
PLA	Polylactic Acid
PMT	"Provide Means To"
ODF	Approximate minimum outer diameter $[mm]$
R^2	Coefficient of determination
RPN	Risk Priority Number
STL	Stereolithography
t	Material thickness $[mm]$
τ	Torque exerted by a spring $[N \cdot m]$
$\bar{\tau}$	Average torque exerted by a spring $[N \cdot m]$
θ	Angle of twist of spring from equilibrium position $[rad]$
$\bar{\theta}$	Average angle of twist of spring from equilibrium position $[rad]$

1 Introduction & Objective

Spiral torsion springs, unlike compression and extension springs, provide a radial deflection. They are typically produced with flat steel that is rolled and are typically characterized by coils that do not contact during operation. Currently, there are little to no springs that are ideal for corrosive, or other, environments where metal is not ideal. This may include underwater applications where a spring may be necessary, or medical devices [1], such as magnetic resonance imaging (MRI), where magnetic materials can not be used for the equipment.

The team intends to design and test springs of various diameters printed using polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and high impact polystyrene (HIPS). A torsion test will then be conducted to determine if the spring constant is affected by the thickness of the spring coils and/or the material. This will help determine the optimum material and diameter to achieve a desired spring constant given that a correlation is found.

Objective: To determine how closely 3D printed spiral torsion springs follow the Hookian relationship shown by metallic spiral torsion springs.

2 Theory

Springs are an integral part of many underwater applications such as on a universal joint on an exposed drivetrain. Zinc plated metal springs are typically used, but due to wear, this coating is eventually compromised and the interior metal is exposed to water allowing for corrosion to begin. The goal of this experiment is to determine what 3D printed material and at what thickness a new torsion spring should be designed to replace this zinc plated version. With this new design, spring corrosion would no longer be an issue in this application. There is an additional issue that is created by using plastic springs, which is the finite fatigue life. Smithers Rapra Technology showed that plastic springs typically lose 50% of failure strength in 10^7 cycles [2]. However, due to the nature of the torsional springs as designed, the effective stress on the spring is significantly lower than this failure strength of plastic at 10^7 cycles. This can be calculated by using equation 1 from Lee Spring [3]. Therefore, the durability of plastic springs will not an issue as they essentially have infinite life.

The equation used in this experiment is Hookes Law for a torsion spring, equation 2. τ is the torque being applied to a spring which in this experiment is applied and measured by a torque wrench. is the angle that the torque wrench travels as it applies the torque to the spring and is measured by an angle meter attached to the wrench. With both of these other values being able to be determined, the spring constant of a spring can be determined via $\kappa = \frac{\tau}{\theta}$. Each spring's spring constant can be determined using this method. Each spring will also provide multiple points of data as each incremental angle change will result in a new torque value, thus another spring constant value can be calculated. These constants can then be averaged for each spring to determine a mean spring constant value. From the Handbook for Spring Design: Spiral Torsion Springs [4], an estimate for the expected torque can be computed using equation 3, and an estimate for the minimum outer diameter for the spring can be computed using equation 5. Therefore, the predicted spring constant can be found using equation 4.

$$S = \frac{32\tau}{\pi OD^3} K_B \tag{1}$$

$$\tau = \kappa \cdot \theta \tag{2}$$

$$M = \frac{\pi E b t^3 \theta}{6L} \tag{3}$$

$$\kappa = \frac{\pi E b t^3}{6L} \tag{4}$$

$$OD_F = \frac{2L}{\pi \left(\frac{\sqrt{A^2 + 1.27L \cdot t - A}}{2t} - \theta \right)} \tag{5}$$

Using equation 3, it is possible to optimize the dimensions of the tested springs to use the full range of the torque wrench. Relevant material properties for the materials used are outlined in table 1. The arbor diameter was first defined due to size constraint from the socket attachment. 3D printers generally cannot effectively print walls thinner than 2mm, so thicknesses of 2, 3, and 4 mm were chosen [5]. From there, an assumption of a length of 100 mm and a θ of 45° were made to begin the iteration process. The final dimensions are outlined in Appendix E. The resulting predicted κ values from the dimensioned parts and equation 4 are summarized in table 2

Table 1: Plastic material Properties

Material	Young's Modulus [GPa]
ABS	2.3
HIPS	1.9
PLA	3.5

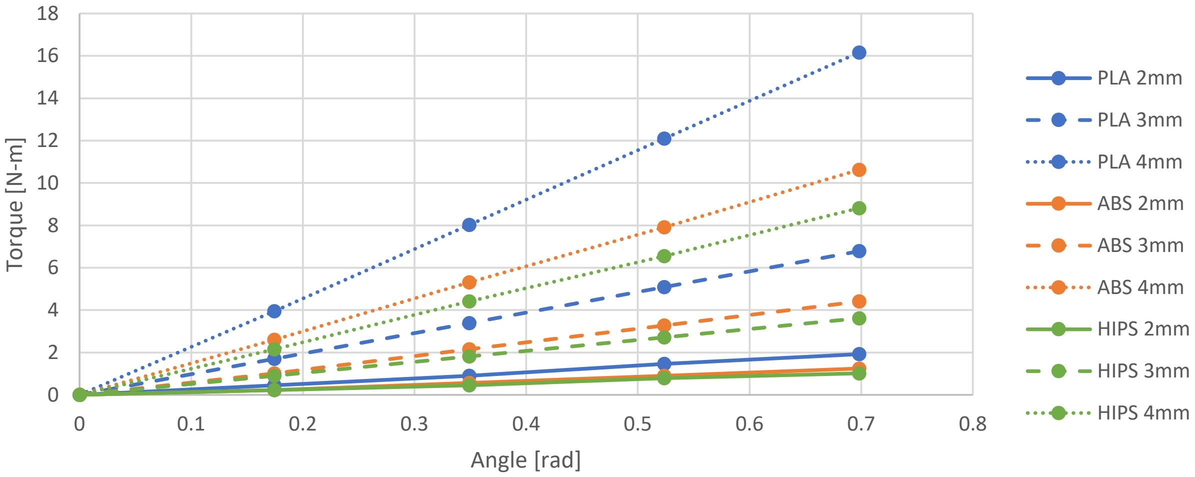


Figure 1: Predicted Torsion Values

Table 2: Predicted Spring Constants in $\frac{N \cdot m}{rad}$

	Thickness [mm]		
Material	**2**	**3**	**4**
ABS	1.91	6.46	15.31
HIPS	1.58	5.34	12.65
PLA	2.91	9.83	23.30

3 Experimental Apparatus

This experiment required 3D printing spiral torsion springs which were then mounted onto a piece of wood. A nail was used to hold the center of the spring and the free end of the spring in place so that there is only torsional motion and not any lateral movement. Figure 2 below shows the spring and the location of the nails relative to the board. A torque wrench coupled with an angle meter can then fitted in the socket at the center. Figure 3 shows how the experiment was conducted.

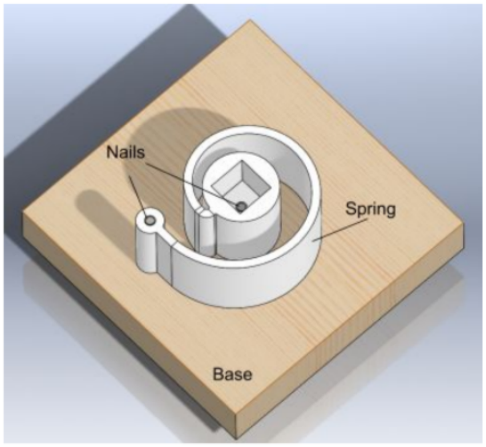


Figure 2: Experimental Apparatus

Figure 3: Actual Experiment Setup

According to the failure modes and effects analysis (shown in Table 5 in the Appendix), delamination and stripping the wrench socket have the highest risk priority number(RPN). This means that those to mechanisms of failure are more likely to occur, would have severe repercussions on the experiment, and are not easy to detect. When conducting the experiment, it is important to take caution to these situations and attempt to ensure they do not occur. Printing impurities, mounting point slippage, and a failure to print are also potential issues that may occur, however, their RPN value is lower. This implies that they are either not as severe, not as likely to occur, or easy to detect.

This is a relatively safe experiment so there are no major safety concerns. The most dangerous part of the experiment is nailing the mounts into the wood. Additionally, it is important to be careful of splinters from the mounting board or the spring material after it has yielded.

Table 3 shows the uncertainties for the measurement devices used in this experiment. These uncertainties were used to calculate the uncertainty in the spring constant which came out to 0.018 $\frac{N \cdot m}{rad}$ or 3.60 % of the average value.

Table 3: Instrumentation Uncertainty

Instrument	**Range**	**Uncertainty**	**Units**	**Average Measurement**	**Percent Uncertainty**
CDI Torque Wrench [6]	18	0.113	Nm	0.427	26%
Empire Angle Meter [7]	6.28	0.00873	rad	0.436	2.0%

4 Experimental Procedures

1. Print the parts
    - Using the generated 3D models, print the parts at a resolution of 200 microns, with 100% infill.
    - Allow the parts to cool completely and check for any surface defects
2. Setup the Experimental Apparatus
    - Vertically mount the experimental board for testing
    - Check that the board is plumb using the angle meter
3. Collect Data
    - Mount the test spring onto the pegs
    - Insert the torque wrench and zero the angle meter

- Turn the wrench in 10° increments, recording the data at each point
- Repeat for each test spring

5 Results

Once the experiment was conducted, the measured torque values were plotted against their corresponding angle. Figures 4, 5, and 6 show the plots with linear regression fits added for each material. Each plot consists of three data sets which represent the three thicknesses tested in the experiment.

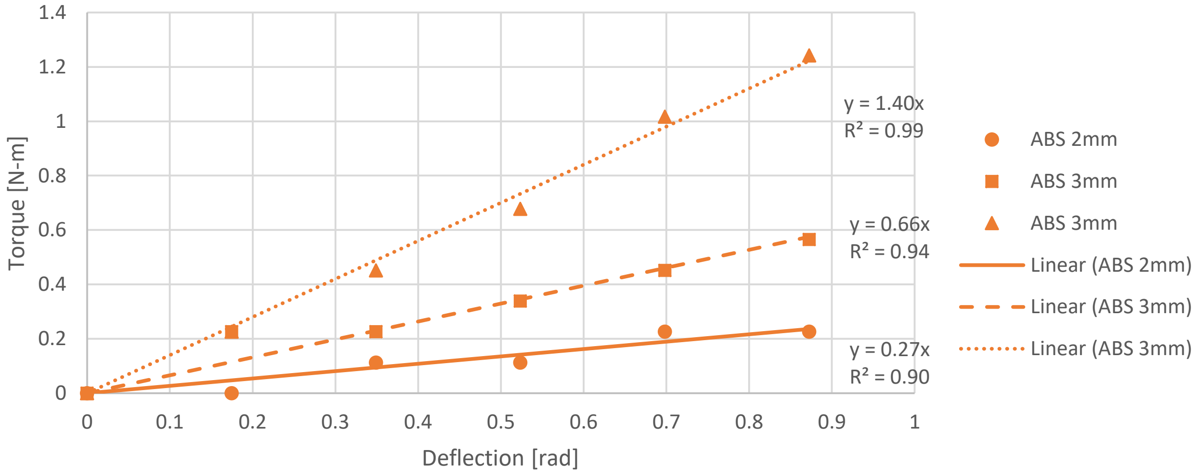


Figure 4: Experimental Results for ABS

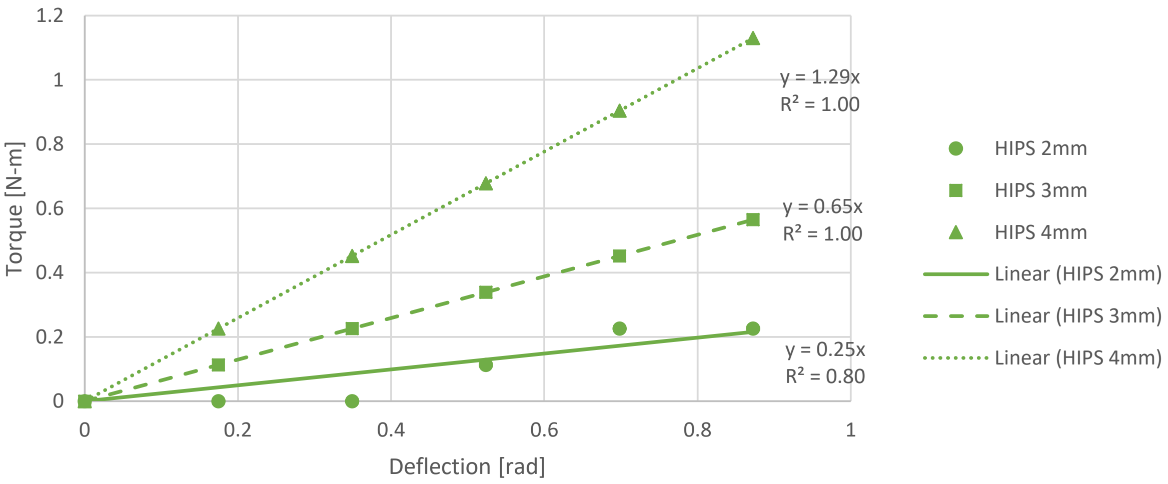


Figure 5: Experimental Results for HIPS

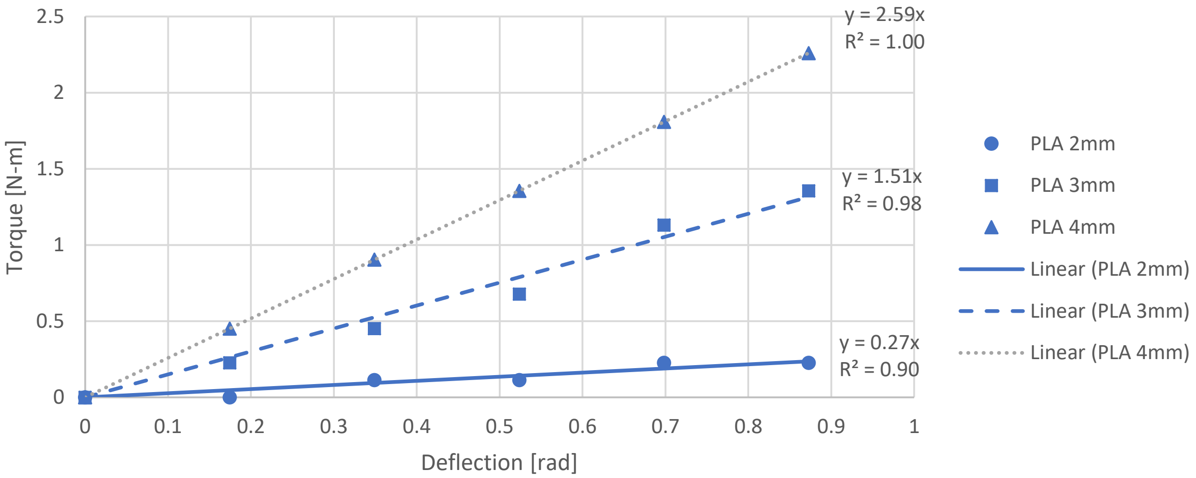


Figure 6: Experimental Results for PLA

Table 4: Experimental Spring Constants in $\frac{N \cdot m}{rad}$

	Thickness [mm]		
Material	**2**	**3**	**4**
ABS	0.27	0.66	1.40
HIPS	0.25	0.65	1.29
PLA	0.27	1.51	2.59

6 Discussion of Results

From these results, linear regression models were fitted to all nine 3D printed torsion springs. As can be seen in Table 6 of Appendix C, all of these models had R^2 values of at least 0.80 with eight out of the nine springs having a value greater than or equal to 0.90. These values indicate that the linear regression models fit the data well. This is what the team expected as the relationship between the angular displacement and torque of a torsion spring should be linear with a multiplier of the spring's κ value. In addition to this, an ANOVA was run on the data and the results can be seen in Figure 7 of Appendix C. The F-value's from this analysis are 94.16 for material selection and 392.18 for thickness. When comparing this to the table F-value of 3.26 for both material selection and thickness, it is clear that the null hypotheses for the effects of both material selection and the thickness on the spring constant's value can be rejected. As for the interaction between material selection and thickness, the F-value of the data for this interaction of 27.84. Because this value is greater than the table F-value for this interaction of 2.63, the null hypothesis can be rejected.

As a result of these analysis tools, it can be determined that there is a significant difference between the material selection, the thickness, and the interaction between them on the effect on the torsion springs κ value. This means that the team's hypothesis was correct in that by choosing a different material and/or a different thickness, one can accurately predict and attain the desired κ value of a spring. However, compared to the predicted values calculated from equations 3 and 4, the spring constants measured in this study were lower by, on average, a factor of 8.7. It is thought that the 3D printing process affects the material properties of the plastic springs. Due to the layer by layer process for manufacturing the springs, it is possible the samples were not isotropic, reducing the degree to which they would follow the predictor model used with metal springs.

7 Summary

- There is a constant linear relationship between torque and angular displacement
- PLA 4mm has the highest spring constant at 2.59 $\frac{N \cdot m}{rad}$
- HIPS 2mm has the smallest spring constant at 0.25 $\frac{N \cdot m}{rad}$
- Spring constant tends to increase with an increase in thickness

- The ANOVA indicates that there is a statistical difference between spring constants based on the material, thickness, and the combination of the two
- While still obeying Hooke's Law, the experimental spring constant values were below the predicted values, likely due to the 3D printing process and anisotropic properties

8 Conclusions

- There is an increase in spring constant with increasing thickness
- PLA has a higher spring constant than ABS which has a higher spring constant than HIPS for each respective thickness, as was expected due to their moduli of elasticity.
- The metallic model used to predict the results of the experiment was not a good representation
- One can use these results to predict a spring constant based on material and thickness
- The 3D printed springs would be a good application for moment correcters in underwater universal joints because of their effective infinite life, corrosion resistance, and linearity as torsion springs

9 Recommendations

While this experiment did acquire significant results, it does have room to improve upon in future iterations. For instance, pieces of equipment with higher precision than what was used here should be considered. The torque wrench and angle meter used in this experiment were both analog and accurate to ±0.113 Newton-meters and ±0.00873 degrees respectively. If tools with higher precision and digital readouts are used in the future, perhaps better torque data points for each angular displacement will be gathered. This could then result in even more statistically significant data than what was gathered in this first iteration of the experiment. In regards to the discrepancy between the predictor model and the results, it is thought the manufacturing process affected the properties of the 3D printed springs. However, it is also possible that this model used to predict torque values is not valid for plastic spiral torsion springs. To be able to determine this, another experiment is suggested using injection-molded springs of the same material and dimensions. This would eliminate the confounding variable of additive manufacturing and could determine if plastic spiral torsion springs follow the model when not 3D printed.

References

[1] Lee Spring Company. Plastic springs: A revolutionary breakthrough in spring technology! *Lee Spring Company*, 2018.

[2] Smithers Papra Technology Ltd. Why plastic products fail. *A Smithers Group Company*, 2010.

[3] Lee Spring. Torsion spring design theory. *Spring-I-Pedia*, 2011.

[4] Spring Manufacturing Institute. Handbook for spring design: Spiral torsion springs. *Spring Manufacturing Institute*, 2018.

[5] Richie Tran. Recommended wall thickness for 3d printing. *Fictiv*, 2016.

[6] CDI. *CDI Torque Products Catalog*. Industry, CA., 2018.

[7] The Home Depot. *Empire Polycast Magnetic Protractor*, 2018.

A FMEA

Table 5: Failure Modes and Effects Analysis

Item	Severity	Occurrence	Detection	RPN
Delamination	7	6	3	126
Strip the wrench socket	7	6	3	126
Print impurities	3	2	9	54
Mounting point slips/breakage	9	5	1	45
Failure to print	10	4	1	40

B Uncertainty Analysis

Percent Uncertainty Calculations:

$$\frac{\Delta\tau}{\bar{\tau}} = \frac{0.113\frac{N\cdot m}{rad}}{0.427\frac{N\cdot m}{rad}} = 26\%$$

$$\frac{\Delta\theta}{\bar{\theta}} = \frac{0.00873rad}{6.28rad} = 2.0\%$$

Uncertainty of spring constant calculation:

$$\frac{\partial\theta}{\partial\kappa} = -\frac{\tau}{\theta^2}$$

$$\frac{\partial\tau}{\partial\kappa} = \frac{1}{\theta}$$

$$\Delta\kappa = \sqrt{(\frac{\partial\theta}{\partial\kappa}\Delta\theta)^2 + (\frac{\partial\tau}{\partial\kappa}\Delta\tau)^2} = 0.018\frac{N\cdot m}{rad}$$

Relative Uncertainty for the spring constant:

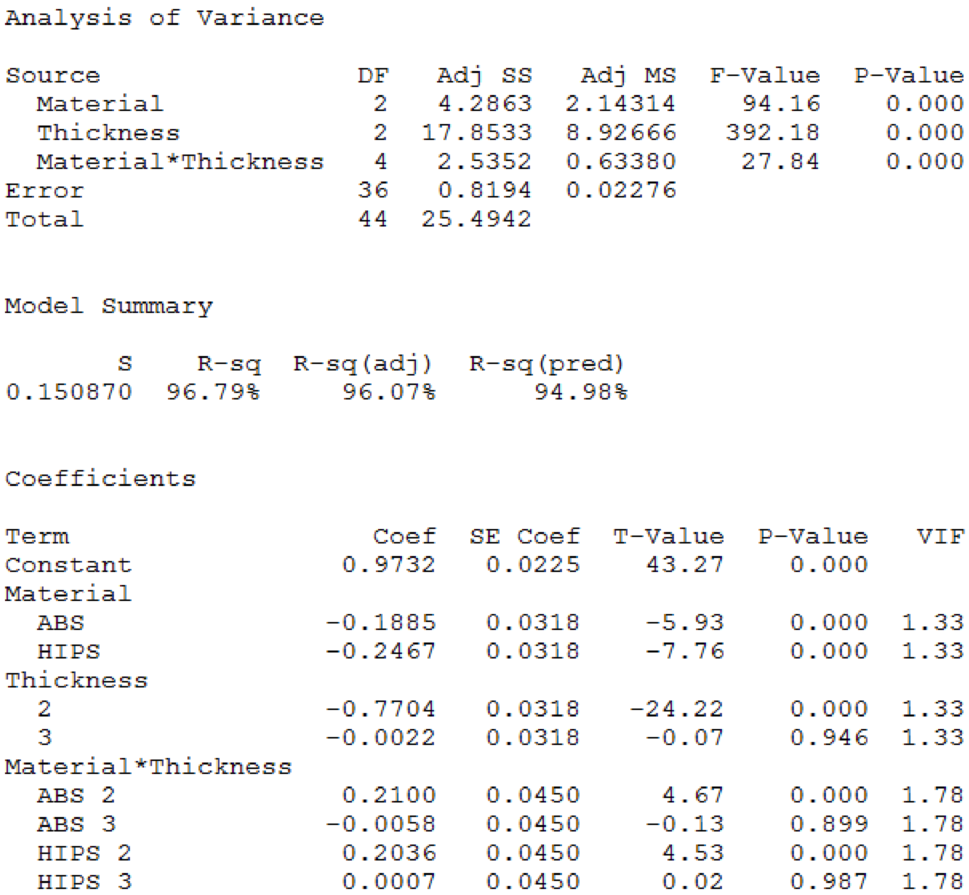
$$\frac{\Delta\kappa}{\bar{\kappa}} = \frac{0.018}{0.512} = 3.60\%$$

Relative Uncertainty for the spring constant:

C Statistical Analysis

Table 6: R^2 Values for all Linear Regression Models

	Thickness [mm]		
Material	**2**	**3**	**4**
ABS	0.90	0.94	0.99
HIPS	0.80	1.00	1.00
PLA	0.90	0.98	1.00



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Analysis of Variance

Source                     DF   Adj SS   Adj MS  F-Value  P-Value
  Material                  2   4.2863  2.14314    94.16    0.000
  Thickness                 2  17.8533  8.92666   392.18    0.000
  Material*Thickness        4   2.5352  0.63380    27.84    0.000
Error                      36   0.8194  0.02276
Total                      44  25.4942


Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.150870  96.79%     96.07%      94.98%


Coefficients

Term                      Coef  SE Coef  T-Value  P-Value   VIF
Constant                0.9732   0.0225    43.27    0.000
Material
  ABS                  -0.1885   0.0318    -5.93    0.000  1.33
  HIPS                 -0.2467   0.0318    -7.76    0.000  1.33
Thickness
  2                    -0.7704   0.0318   -24.22    0.000  1.33
  3                    -0.0022   0.0318    -0.07    0.946  1.33
Material*Thickness
  ABS 2                 0.2100   0.0450     4.67    0.000  1.78
  ABS 3                -0.0058   0.0450    -0.13    0.899  1.78
  HIPS 2                0.2036   0.0450     4.53    0.000  1.78
  HIPS 3                0.0007   0.0450     0.02    0.987  1.78
```

Figure 7: ANOVA Results

D Raw Data

Table 7: 2 mm Raw Data

Material	ABS		HIPS		PLA	
Color	Black		White		Blue	
Test	Angle [deg]	Torque [in-lbs]	Angle [deg]	Torque [in-lbs]	Angle [deg]	Torque [in-lbs]
1	0	0	0	0	0	0
2	10	0	10	0	10	0
3	20	1	20	0	20	1
4	30	1	30	1	30	1
5	40	2	40	2	40	2
6	50	2	50	2	50	2
7	80	4	94	4	60	3

Table 8: 3 mm Raw Data

Material	ABS		HIPS		PLA	
Color	Black		White		Blue	
Test	Angle [deg]	Torque [in-lbs]	Angle [deg]	Torque [in-lbs]	Angle [deg]	Torque [in-lbs]
1	0	0	0	0	0	0
2	10	2	10	1	10	2
3	20	2	20	2	20	4
4	30	3	30	3	30	6
5	40	4	40	4	40	10
6	50	5	70	8	50	12

Table 9: 3 mm Raw Data

Material	ABS		HIPS		PLA	
Color	Black		White		Blue	
Test	Angle [deg]	Torque [in-lbs]	Angle [deg]	Torque [in-lbs]	Angle [deg]	Torque [in-lbs]
1	0	0	0	0	0	0
2	10	2	10	2	10	4
3	20	4	20	4	20	8
4	30	6	30	6	30	12
5	40	9	40	8	40	16
6	50	11	50	10	50	20

Table 10: Prediction Data

	Torque [N-m]								
Material	**PLA**			**ABS**			**HIPS**		
Thickness [mm]	2	3	4	2	3	4	2	3	4
Angle [rad]									
0	0	0	0	0	0	0	0	0	0
0.174	0.452	1.695	3.955	0.226	1.017	2.599	0.226	0.904	2.147
0.349	0.904	3.39	8.023	0.565	2.147	5.311	0.452	1.808	4.407
0.523	1.469	5.085	12.091	0.904	3.277	7.91	0.791	2.712	6.554
0.698	1.921	6.78	16.159	1.243	4.407	10.622	1.017	3.616	8.814

E Part Dimensions

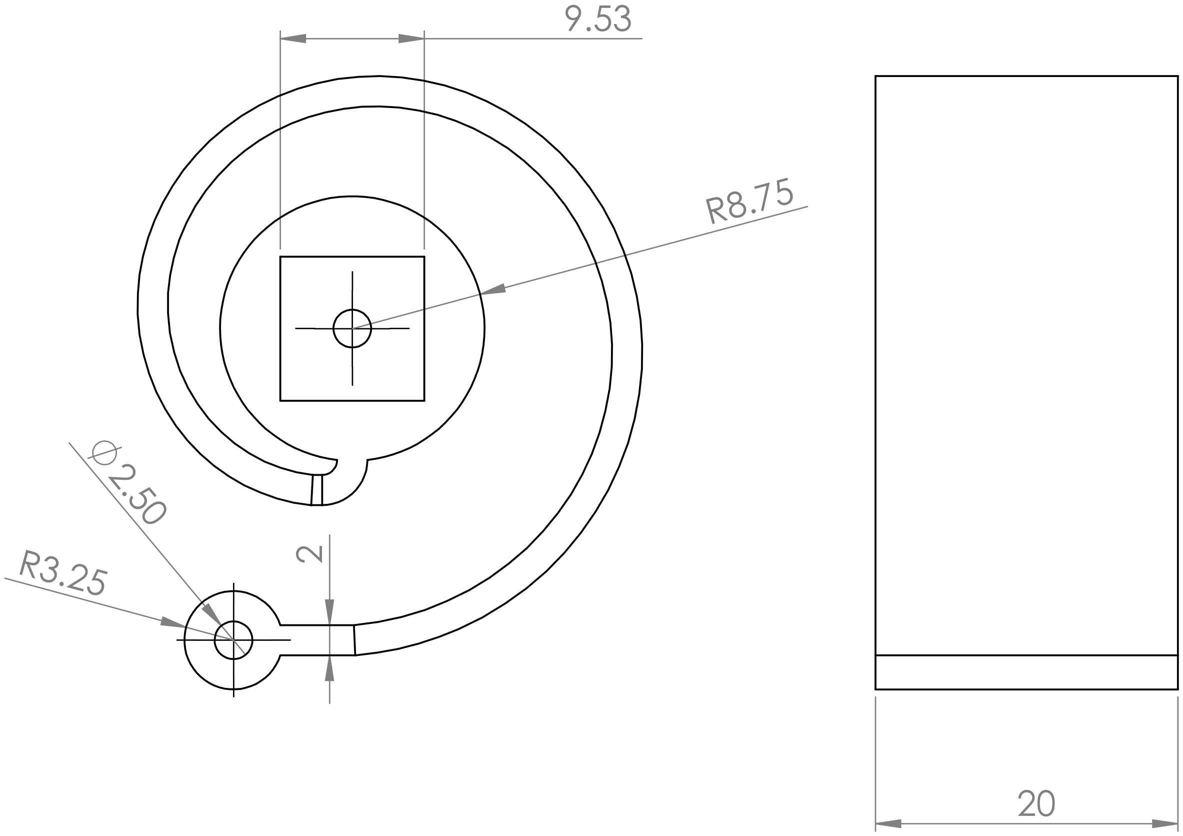

Figure 8: 2mm Part Dimensions

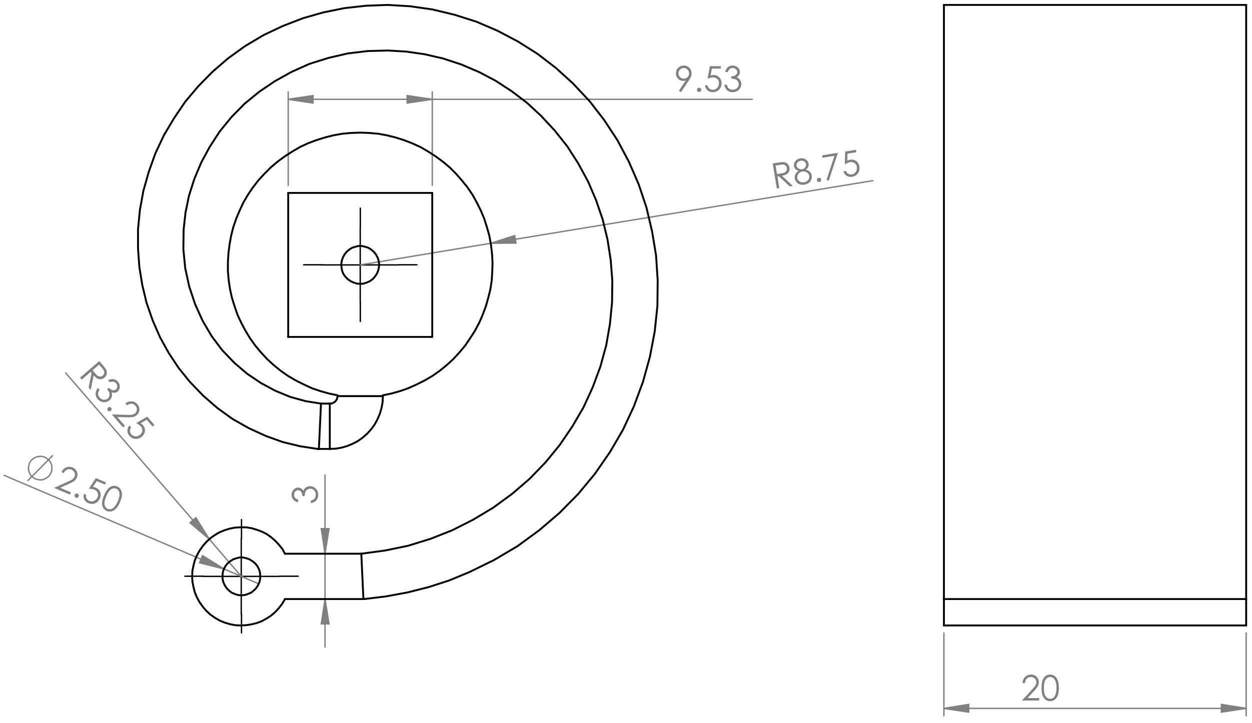

Figure 9: 3mm Part Dimensions

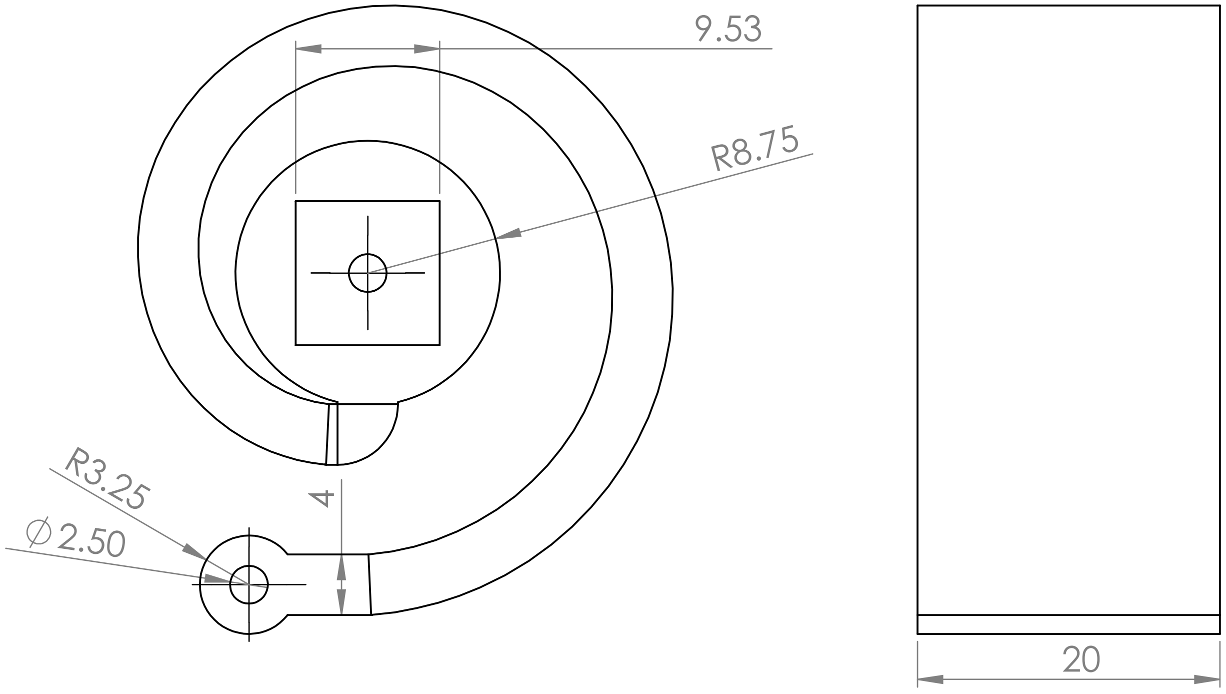

Figure 10: 4mm Part Dimensions