Washington University in St. Louis

JAMES MCKELVEY SCHOOL OF ENGINEERING

Manual Drill with Flywheel

Throughout this project we aimed to create a functional and effective flywheel hand drill. The hand drill that we made requires no electrical input and functions solely on the grip above the flywheel. There is also a functional break to stop the chuck from spinning. Once the morphology charts were made and the final design was established, an engineering analysis was conducted. Gyroscopic loads, the flywheel work/energy and critical speeds were found by hand and through MATLAB.

MEMS 3110: Machine Elements, Spring 2021

Contents

List of Figures

List of Tables

Introduction

Drilling holes is an essential operation in nearly all woodworking projects. Electric hand drills are a common way to make holes, but a variety of manually powered tools also exist, including the bit brace and "eggbeater" hand drill. Manual drills can be a safer alternative for young woodworkers, and can also give the woodworker a more intuitive "feel" for the material. There are instances where professional carpenters may prefer a manual drill to an electric one.

One problem with manual drills is that they generally require the user to apply power while making the hole. For example, the classic eggbeater drill requires the user to crank the handle in a vertical plane while they try to keep the bit aligned and apply an appropriate amount of axial force. It would be easier if the user could power-up the drill first and then make the hole by simply pushing the spinning drill bit into the material. This requires some method of mechanical energy storage.

For this project, the goal is to design a manual drill that can make small pilot holes in wood without requiring the user to simultaneously power the drill while making the hole. This functionality is enabled by an appropriately designed ***flywheel***.

Problem Understanding

The first step in the design process is to become familiar with existing designs as well as relevant patents, codes, and standards that could influence the design. Interviewing potential customers to identify their wants and needs for the product is also essential.

Existing Devices

It is important to know what similar devices already exist so that you can compare the advantages and disadvantage of each, and avoid "reinventing the wheel." In MEMS 411 (Senior Design), you and your group would identify 3 existing devices to use as benchmarks. You would show photos of each device, provide a link to information about them, and describe them in your own words.

For this course, here is a list of existing devices that perform a similar function:

- Power drill/driver (battery or corded)
- Bow drill
- Pump drill
- Bit brace
- Hand drill ("eggbeater")
- Push drill
- Spinning top (toy)
- Manually powered flash lights

Patents, Codes & Standards

In MEMS 411 Senior Design, your group would identify patents, codes, and standards that are relevant to your project.

User Needs

An interview was conducted with an intended user to elicit the most important customer needs. From the qualitative needs, some quantitative metrics will be established in the next section.

Customer Interview

Interviewee: Dr. J. Jackson Potter

Location: Online (via Zoom)

Date: March 31^{st}, 2021

Setting: Dr. Potter used a webcam to transmit audio and video. He demonstrated some existing manual drills and talked about their advantages and disadvantages.

Interview Notes:
Here is an example question?

- Here is the customer's answer.

Here is an example question?

- Here is the customer's answer.

Here is an example question?

- Here is the customer's answer.

Here is an example question?

- Here is the customer's answer.

Interpreted Customer Needs

Based on the interview with Dr. Potter, a list of customer needs for the Manual Drill with Flywheel (MDF) was created, and each need was rated on a 1 (least important) to 5 (most important). These needs and rankings are displayed in Table 1.

Table 1: Interpreted Customer Needs

Need #	Interpreted Customer Need	Importance
1	The MDF is lightweight	4
2	The MDF makes holes quickly	5
...	...	...

Design Metrics

To address each of the interpreted customer needs in Table 1 above, specific design metrics were established. Ideal and acceptable specifications are shown in Table 2.

Table 2: Target specifications

Metric #	**Assoc. Need**	**Metric**	**Units**	**Acceptable**	**Ideal**
1	1	Total weight	lb	< 3	< 2
2	2	Time to drill 1/8” hole through cheap 2x4	sec	< 3	< 2
3	2	Rated (intended) rotational speed of chuck	RPM	> 600	> 900
4	2	Flywheel kinetic energy at rated speed	J (N·m)	> 12.5	> 20
			in·lb	> 110	> 165

Concept Generation

Function Tree

A function tree for the manual drill is shown in Fig. 1. The primary function in this tree is to design a device that will drill a hole using stored energy. The device should not have a crank or rotational method to continuously use the device. Each branch on the tree represents a specific function in each part of the device.

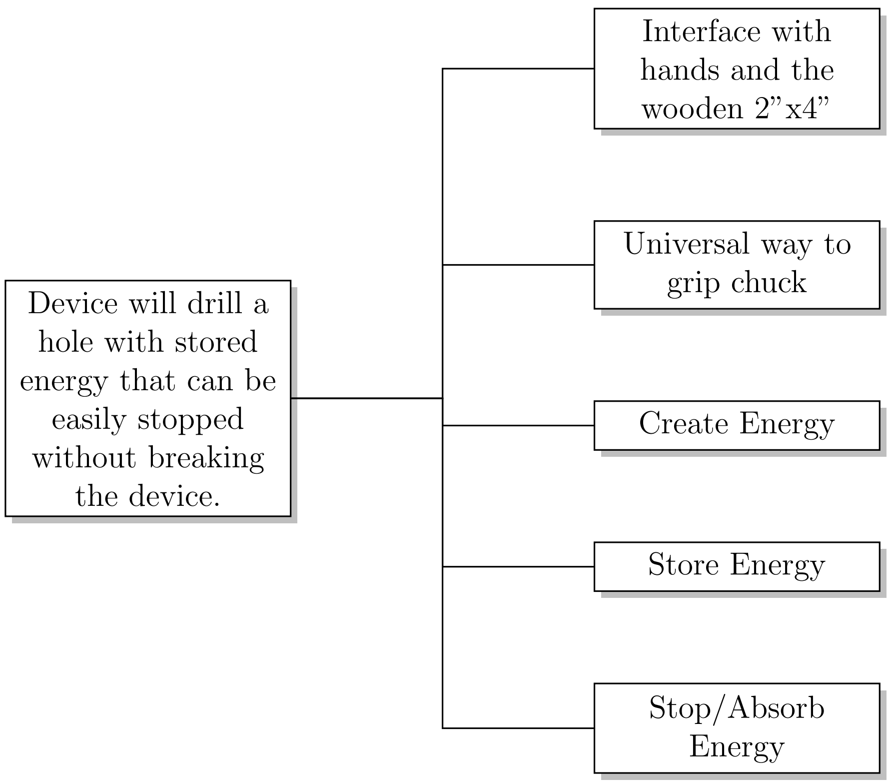


Figure 1: Function tree for a manual drill that uses stored energy

Morphological Chart

The morphological chart is a collection of different designs for a specified function. As shown in Fig. 2, there are rows that correspond to each function on the function tree shown above in Fig. 1. There are four columns that have different options for each design needed for that function.

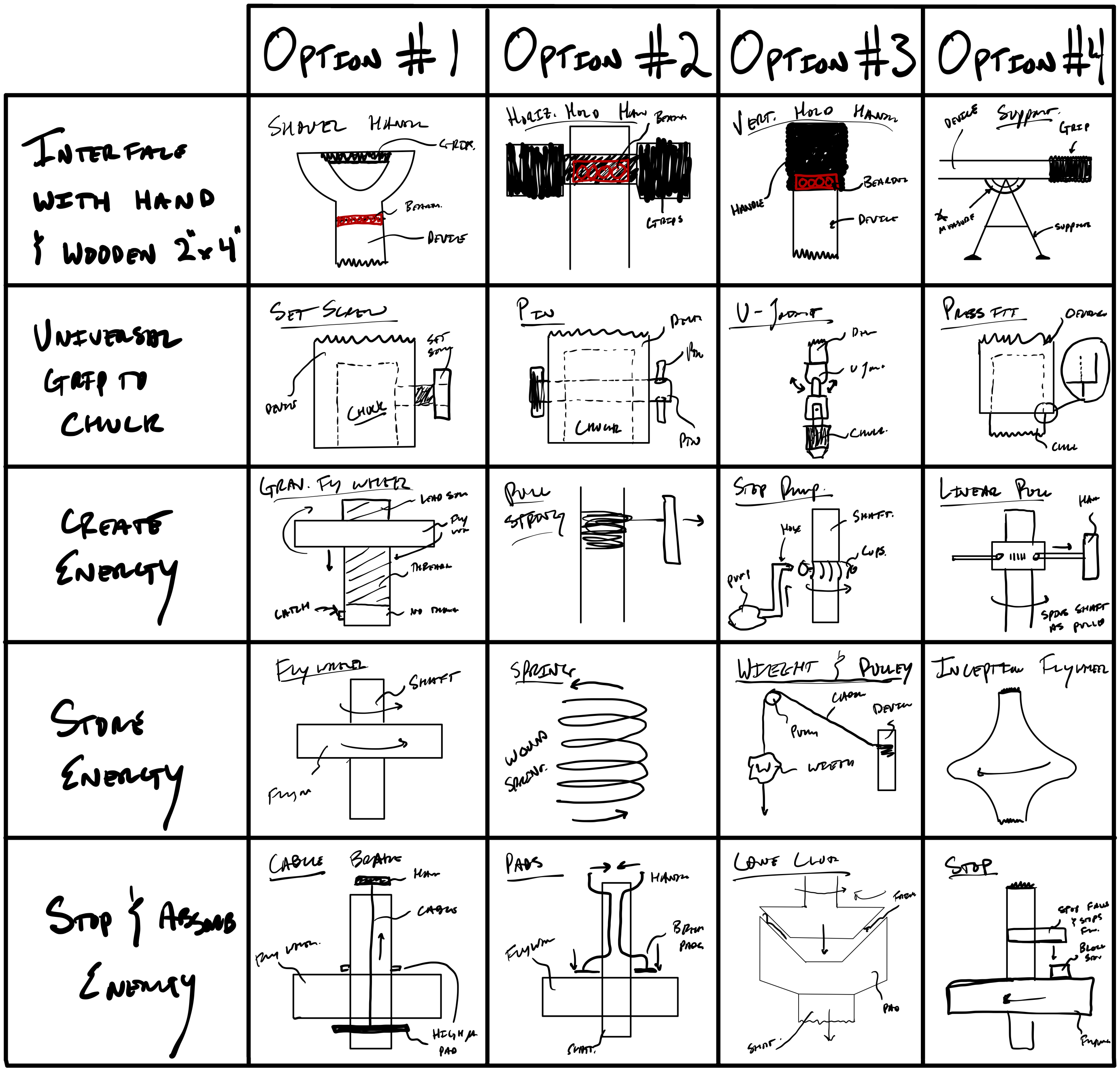


Figure 2: Morphological chart for the manual drill

Design Concept #1: Pedal Pump, Blade Brake Pad

Illustrations

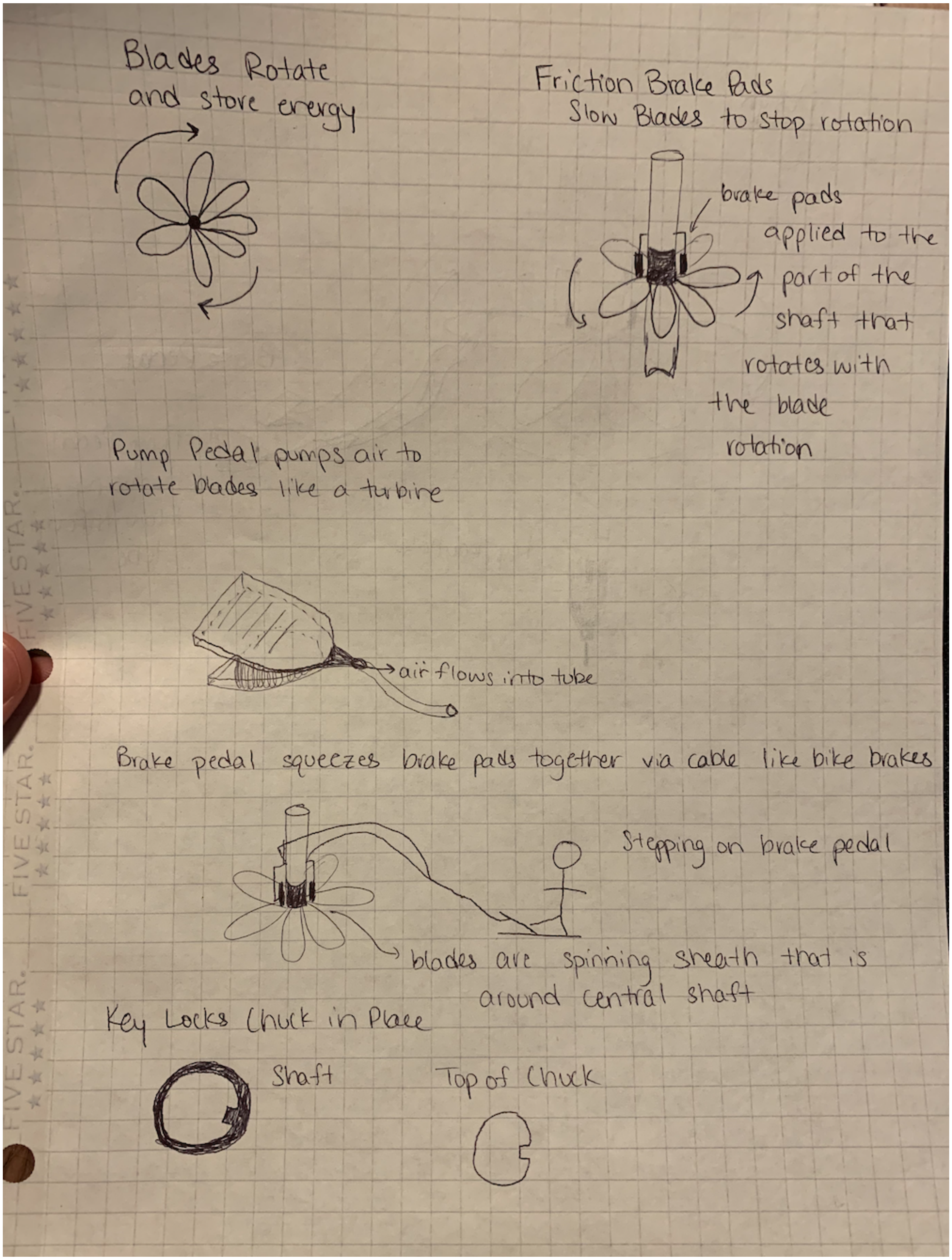


Figure 3: Pedal Pump, Blade Brake Pad scratch work and breakdown

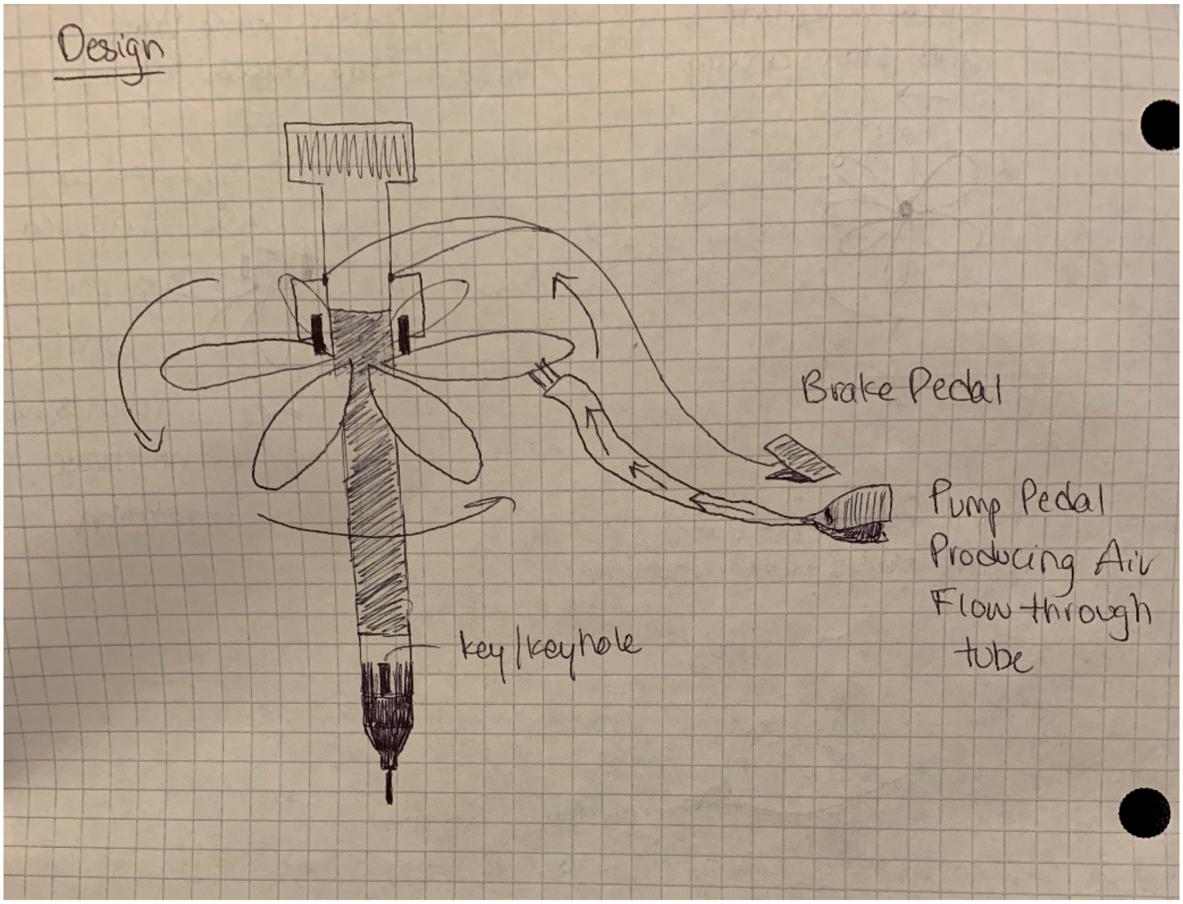


Figure 4: Pedal Pump, Blade Brake Pad design

Solutions from Morph Chart

- Handle interface with wood
- Pump Pedal inputs rotational energy
- Brake Pedal engages brake pads to slow rotating blades
- Rotating blades store energy
- Key locks the chuck in place

Description

This concept is based partly on the fireplace air pedal machine, which serves a very similar purpose in inputting mechanical work to a foot pedal to create airflow. In this case the airflow then leads to rotational energy through the use of blades. As shown in Fig. 4, it uses a foot pedal and airflow to create rotational energy, and uses a brake pedal that creates tension in a cable to squeeze the brake pads. This is a lot like the hand brake pedals on a bike. There is also a simple key and keyhole match up between the chuck and the shaft to attach the chuck to the shaft.

Design Concept #2: Cone-Clutch Flywheel

Illustrations

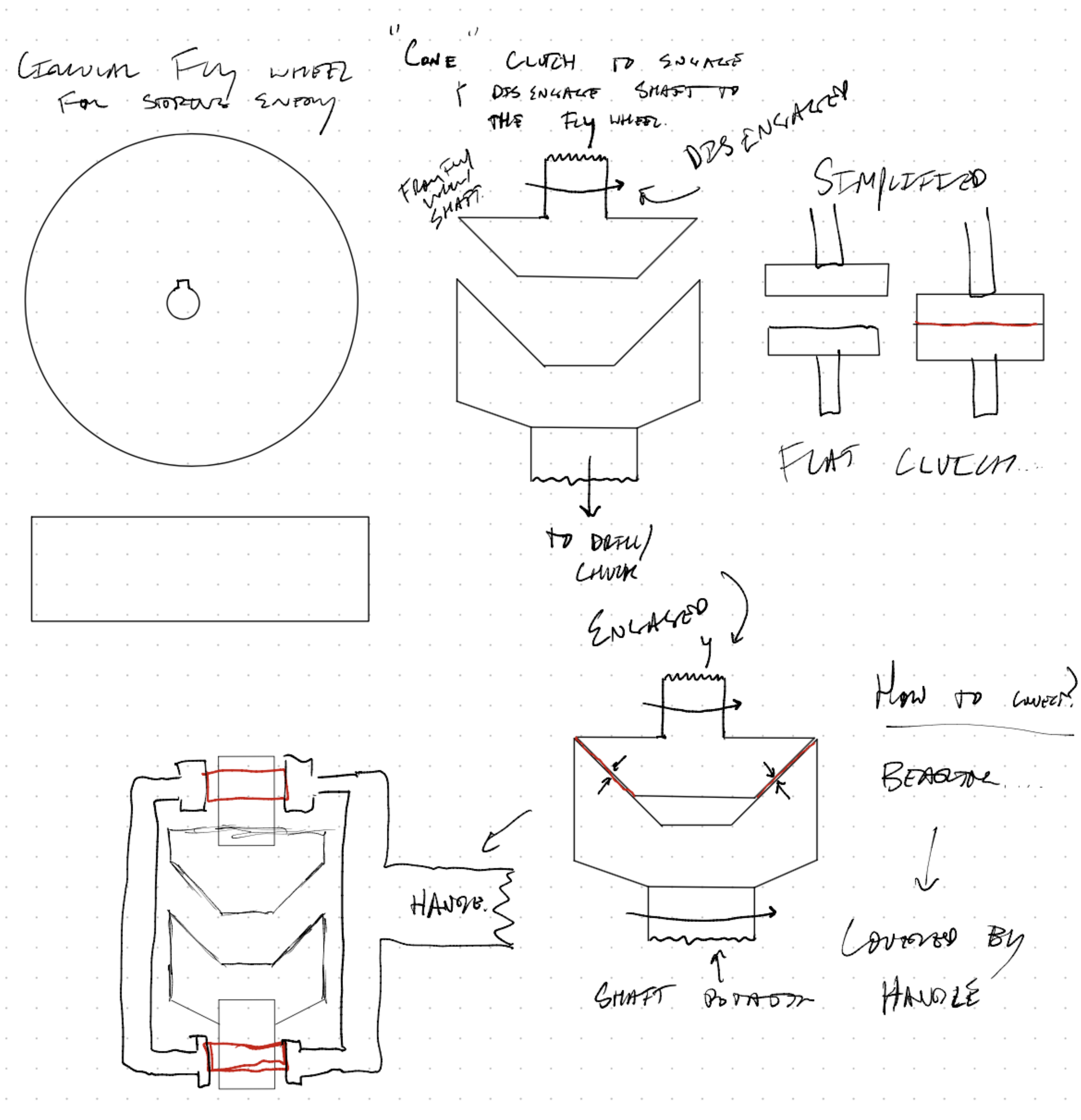


Figure 5: Scratch Work for the cone-clutch

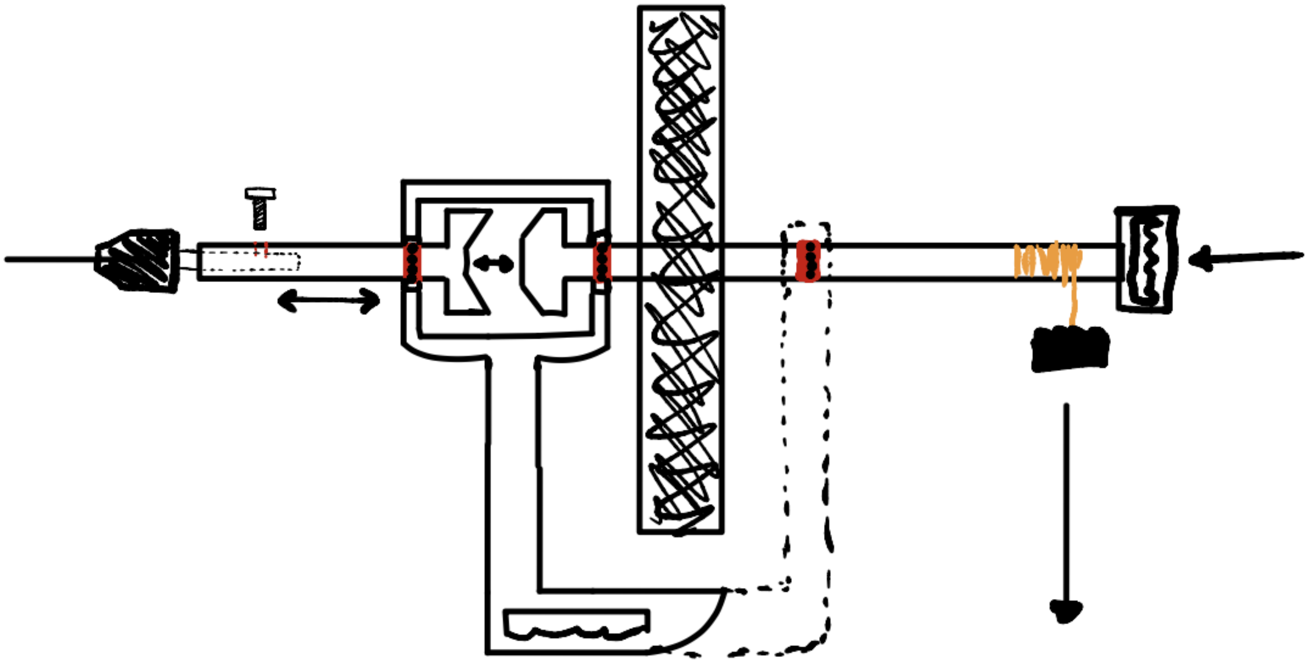


Figure 6: Cone-Clutch Flywheel Design

Solutions from Morph Chart

- Handle Interface with wood, provides stability to device
- Cone clutch Disengages the chuck and drill bit from rotating
- Pull String Creates rotational energy
- Flywheel Stores and continues energy created
- Set Screw Universal way to grip the chuck

Description

This concept is inspired partly of Dr. Potters example when the drill bit broke due to misalignment. To increase stability and reduce the chances of this happening, there is a handle that has been added right below the flywheel as pictured in Fig. 6. There is an option to add another support above the flywheel for increased stability. Shown in Fig. 5, a "cone clutch" is being used to transfer rotational energy generated by the shaft to the chuck and drill bit. The pull string will generate rotational energy to the shaft, which is stored by the flywheel. When the user would like to begin drilling, they can apply a light force to the top of the shaft. This will push the shaft down, and engage the chuck and drill bit. The beauty of this design is in it's stability due to the user interface. Additionally, due to the cone clutch, the chuck and drill bit can be engaged and disengaged quickly.

Design Concept #3: Push handle thingy

Illustrations

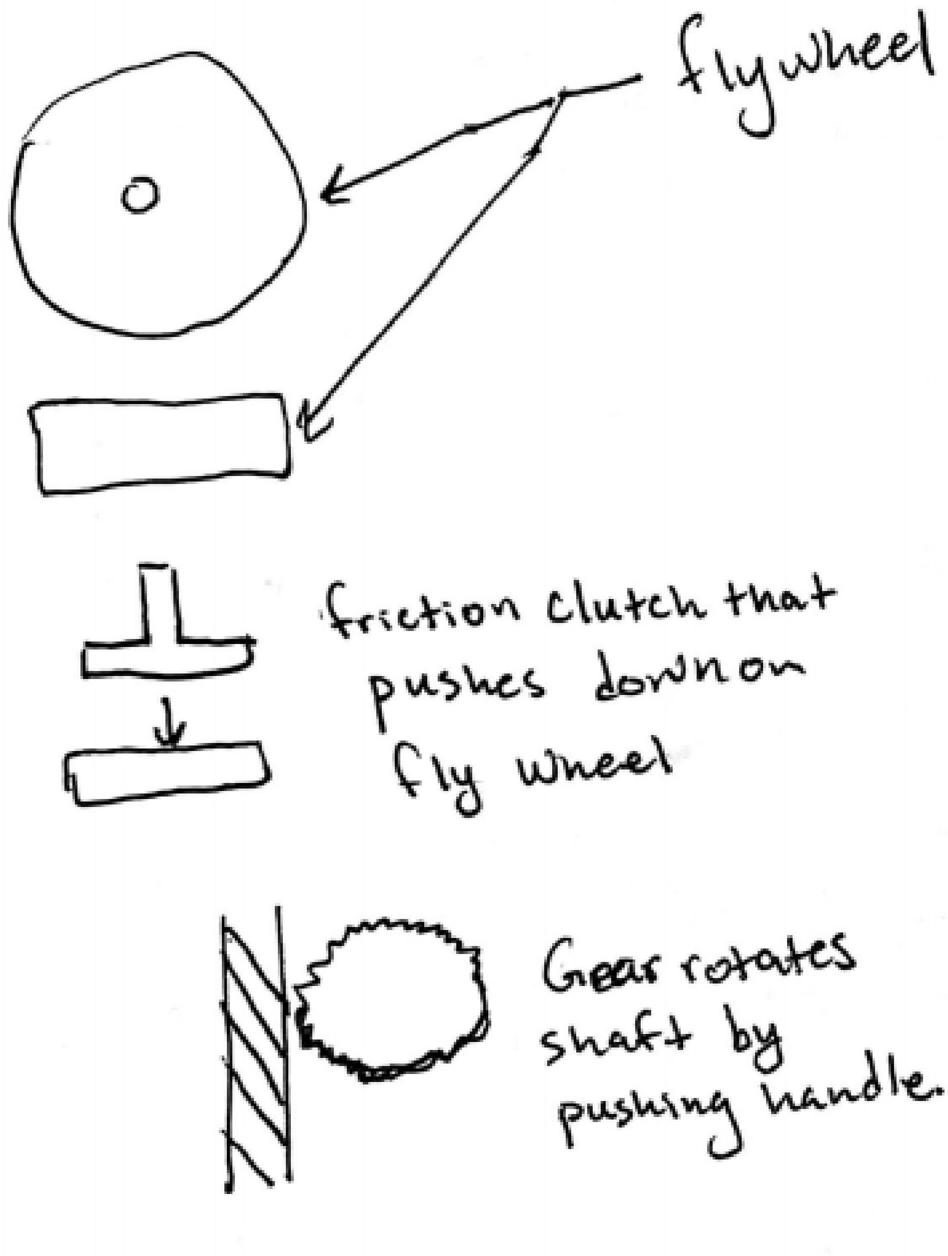


Figure 7: Break down of push handle thingy design

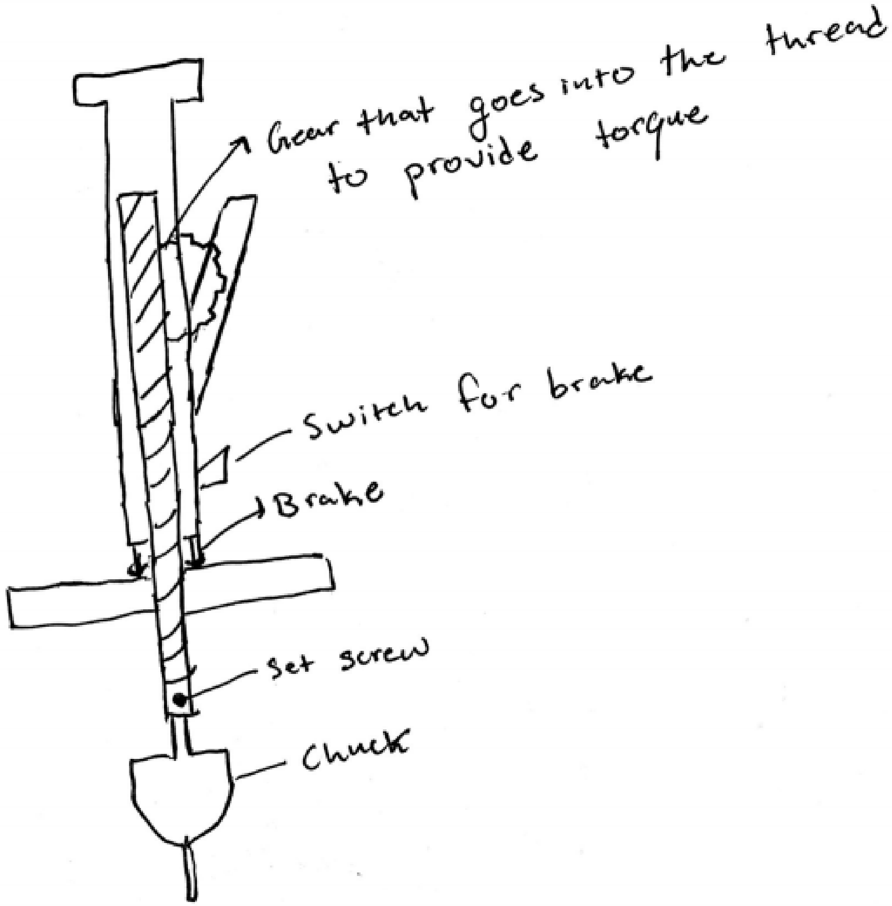


Figure 8: Push handle thingy design

Solutions from Morph Chart

- Handle To grip the device.
- Main Gear Handle Used to supply the torque to the shaft in the handle.
- Flywheel Stores rotational energy.
- Friction Clutch Attached to the flywheel from the top to stop the shaft when brake switch is applied
- Set Screw To attach the chuck to rotating shaft

Description

The handle at the top is used as grip and to initiate downward force. The push leaver as seen in As shown in Figure 8 is used to initiate rotation and provide torque to the system.The switch at the bottom of the shaft is used to apply the breaking force by initiating a friction clutch acting downward on the fly wheel as seen in Figure 7. The flywheel provides a means to store rotational energy. The chuck is attached to the shaft using a set screw.

Design Concept #4: Push-to-Charge Flywheel Drill by

Illustrations

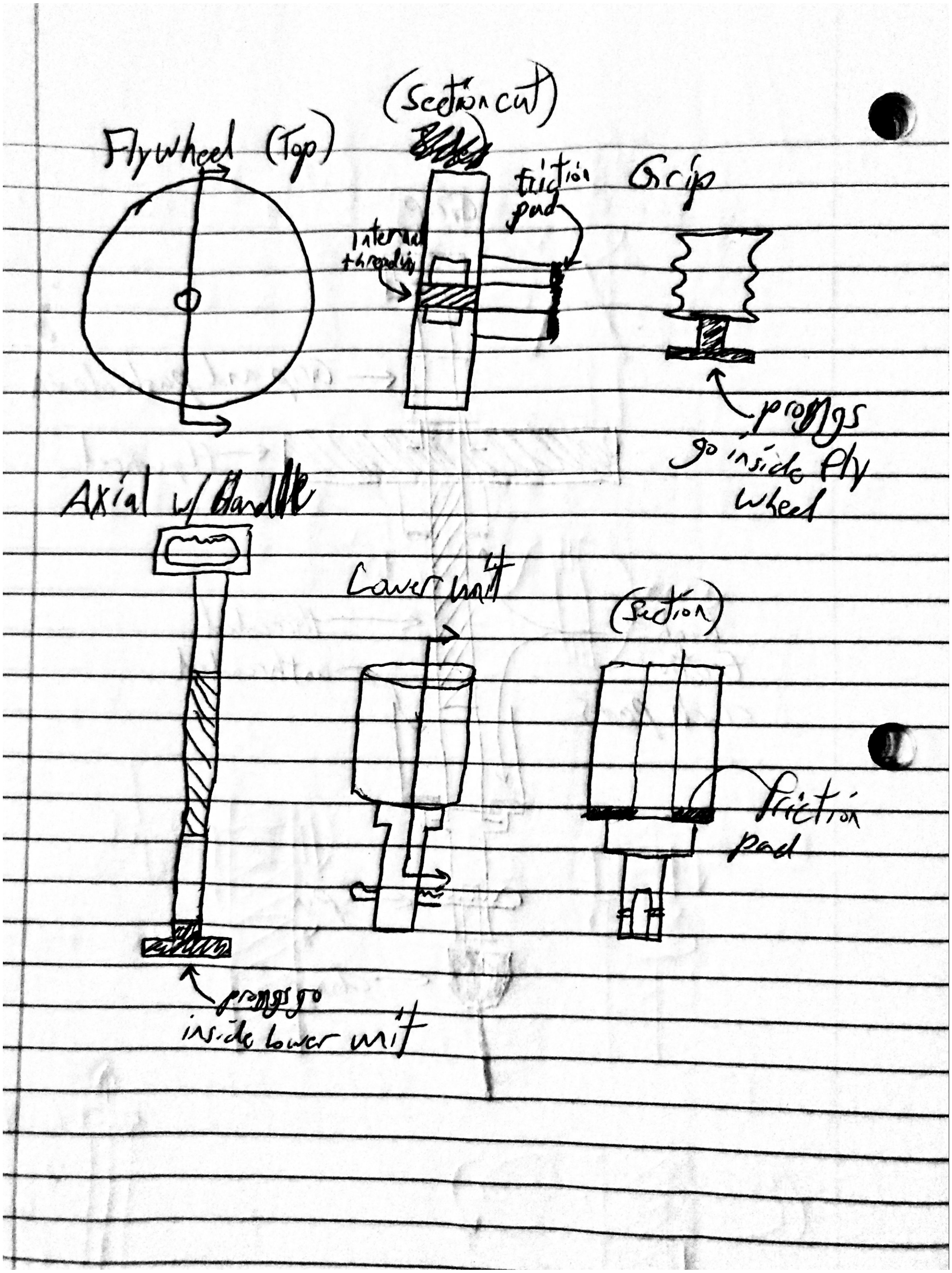


Figure 9: Push-to-Charge Flywheel Drill design

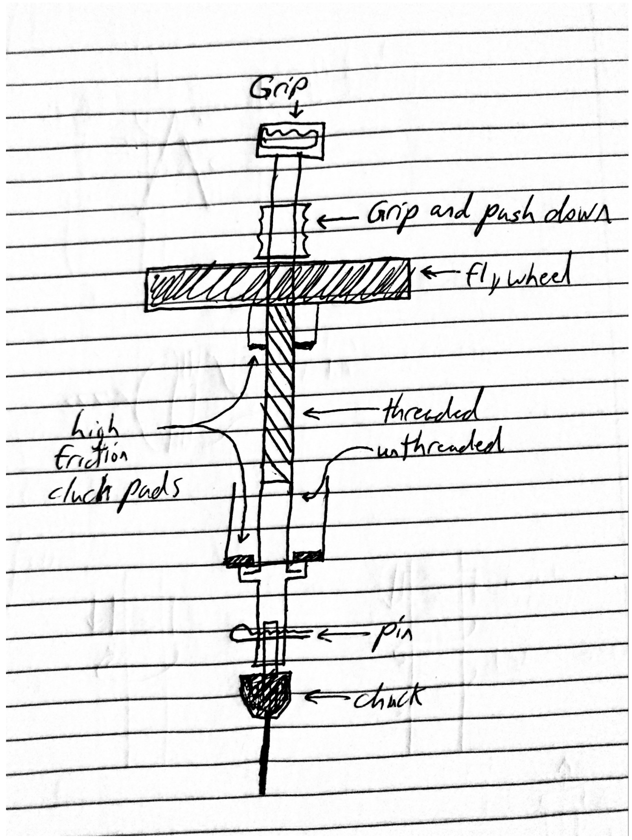


Figure 10: Push-to-Charge Flywheel Drill breakdown

Solutions from Morph Chart

- Handle To grip the device.
- Lead Screw Within the flywheel that converts axial motion to rotational energy.
- Flywheel Stores rotational energy.
- Friction Clutch Attached to the flywheel and the mechanism holding the clutch to transfer energy
- Pin To attach the chuck

Description

The handle and grip in this device are used similarly to how grips are used when opening an umbrella, but as the grip slides down the axial, it causes a flywheel to start spinning. As shown in Figure 10, it uses a threaded axial to force the flywheel to spin as the grip pushes it along the axial, until it reaches an unthreaded region. When the friction pads attached to the bottom of the wheel are pushed into making contact with the corresponding pads, the lower unit of the drill rotates. The lower unit is connected to the chuck by a pin causing the two to spin together. Figure 9 more clearly shows how the grip connects to the flywheel, controlling it's axial movement, and how the main axial will attach to the lower unit of the device.

Concept Selection

Table 3: Weighted scoring matrix

		Alternative Design							
		Pedal Pump Blade Brake Pad		Cone-Clutch Flywheel		Push Handle Thingy		Push-to-Charge Flywheel Drill	
Selection Criteria	**Wt. (%)**	**Rtg**	**Wt.**	**Rtg**	**Wt.**	**Rtg**	**Wt.**	**Rtg**	**Wt.**
Safety	20	1	0.20	3	0.60	3	0.60	3	0.60
Drilling Time	30	1	0.30	5	1.50	2	0.60	5	1.50
No. of Parts	10	5	0.50	3	0.30	4	0.40	3	0.30
Size & Weight	25	3	0.75	3	0.75	5	1.25	3	0.75
Simplicity	15	3	0.45	3	0.45	4	0.60	4	0.60
	Total score	**2.200**		**3.600**		**3.450**		**3.750**	
	Rank	**4**		**2**		**3**		**1**	

Scoring Results & Discussion

Using a results oriented mindset, we decided that drilling time was the most important criterion for the drill. The size and weight was a close second and safety was third. Behind those criteria were simplicity and number of parts in terms of importance weighting. Our winning design was the Push-to-Charge Flywheel Drill which converts easily input translational energy into rotational energy. Among the losing designs, the pedal pump design was creative and offered a unique design, but would take a very long time to drill the desired hole. Additionally this design was not safe, which led to its poor score. The cone clutch fly wheel was the most similar to our winning design, but was more complicated to build and loss the simplicity category. The Push Handle Drill was not far behind, and was the most ergonomic design, but ultimately lost due to taking a long time to drill the hole.

The Push to Charge Flywheel Drill, which we have decided to call the ”PC Flywheel Drill”, was our best design. For safety, this design received a 3 out of 5. This was the maximum safety score for any design because all of these drills have exposed metal threading and screws which could cause cuts. In addition, no guards are used to protect from coming in contact with the rotating flywheel. This design was significantly safer than the pedal pump which has exposed blades. The PC Flywheel drill received a 5 out of 5 for drilling time. This was a relative score, as it was our fastest drill time amongst out designs. The PC Flywheel also received at 3 for number of parts and a 3 for size and weight. This was the average score for these two categories across all designs, however the parts are simple to design and make, so these mediocre scores are not detrimental to the design. Finally, the PC Flywheel Drill received a 5 out of 5 for simplicity. This drill was easier to design than the cone clutch flywheel because it has an external brake pad as opposed to needing to design internal clutches. Pushing the handle to input energy is also a far easier input mechanism for the user than pumping a pedal.

Concept Embodiment

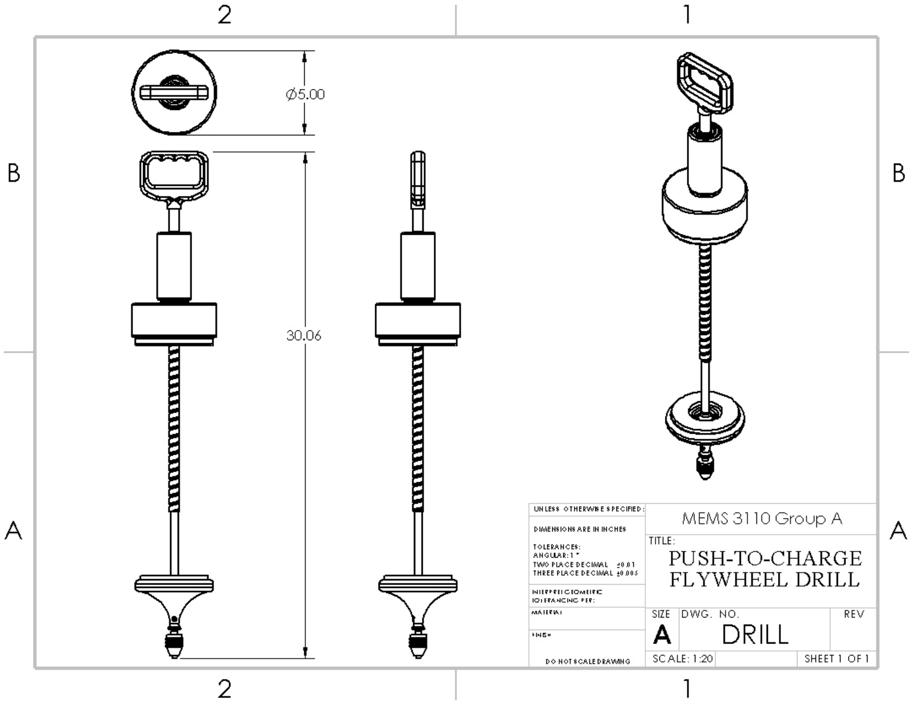
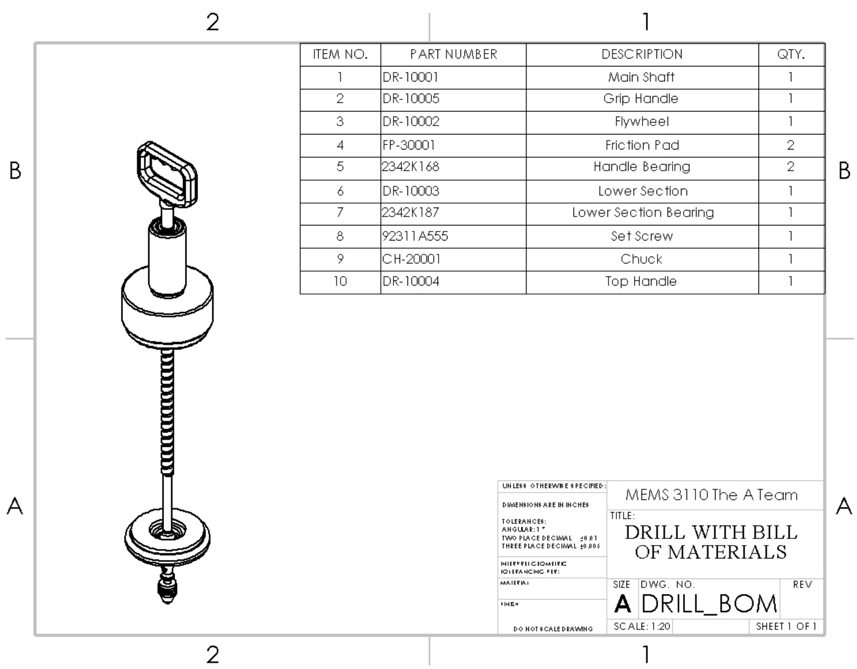


Figure 11: Assembled projected views with overall dimensions



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	DR-10001	Main Shaft	1
2	DR-10005	Grip Handle	1
3	DR-10002	Flywheel	1
4	FP-30001	Friction Pad	2
5	2342K168	Handle Bearing	2
6	DR-10003	Lower Section	1
7	2342K187	Lower Section Bearing	1
8	92311A555	Set Screw	1
9	CH-20001	Chuck	1
10	DR-10004	Top Handle	1

Figure 12: Assembled isometric view with bill of materials (BOM)

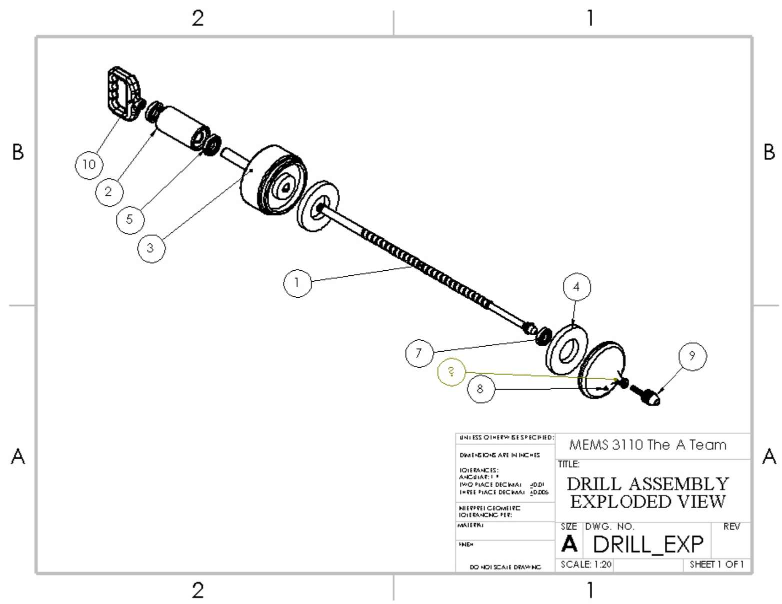


Figure 13: Exploded view

Figure 12 shows the assembled view of the PC Flywheel. The components of this drill are shown and labeled in Figure 13. The main construction of this flywheel is on a partially threaded shaft in which a flywheel is able to rotate around. Other components included are sealed ball bearings, friction pads, and set screws.

This drill is powered by the users "push". The top handle is convenient for holding the flywheel in place while the other grip handle, located above the flywheel, can be used to apply force toward the base of the drill. The grip handle is attached to the flywheel by using bearings allowing it to rotate freely. This allows the users hand to stay in the same position while applying force.

The flywheel moves down a threaded portion, causing it to rotate. The angular velocity of the flywheel increases as it moves down the shaft. At the end the end of the threaded portion the flywheel is able to rotate freely. The user is able to use the grip handle to raise or lower the flywheel is in this unthreaded section of the shaft. If the user lowers the flywheel then the drill will engage and begin to spin. To stop the drill from spinning all the user will have to do is lift the flywheel.

The energy is transferred from the flywheel to the lower section through frictional pads. There is one located on the flywheel and one located on the lower section, which is shown in Figure 11. When these pads are touching the flywheel will spin the lower section. The lower section is able to spin independently of the shaft by using a sealed ball bearing. The chuck is held into place on the lower section by using a set screw.

Engineering Analyses

Part 1: Flywheel Work/Energy

Flywheel Kinetic Energy

The flywheel has a mass, m, of 2.5 lb and a principle moment of inertia axially, I_{yy}, of 7.724 lb·in^2. Equation 1 can be used to find the kinetic energy, K, of rotating wheel with a moment of inertia, I, at a angular velocity, ω.

$$K = \frac{1}{2} I \omega^2 \tag{1}$$

Isolating ω from Eq. 1 yields eq. 2.

$$\omega = \sqrt{\frac{2k}{I}} \tag{2}$$

For the flywheel to have a kinetic energy of 12.5 J, or equivalently 111 lbf·in, using Eq. 2, the angular velocity must be 105.2 rad/s, or equivalently 1005 RPM.

Input Work from the User

To calculate the work applied to a wheel that moves laterally and rotates, eq. 3 is used. The applied torque, T, can be rewritten using eq. 4. The change in angle, $\Delta\theta$, can be described by the diameter of the threaded shaft, d, the length of the threaded shaft, L, and angle of the threading, α, in eq. 5. The change in position, $\Delta x = L$ is simply the length of the shaft. Substituting this and eq. 4 and eq. 5 into eq. 3 and isolating L, yields eq. 6.

$$W = F\Delta x + T\Delta\theta \tag{3}$$

$$T = F\frac{\mathrm{d}}{2} \tag{4}$$

$$\Delta\theta = \frac{2L}{d\tan(\alpha)} \tag{5}$$

$$L = \frac{W}{F(1 + \frac{1}{\tan(\alpha)})} \tag{6}$$

Given a force of $F = 5$ lbf, and a work of $W = 12.5$ J or equivalently 111 lbf·in, and an angle of $\alpha = 60°$, using eq. 6 the length of the shaft must be $L = 1.169$ ft.

Stopping the Flywheel

The flywheel is given energy simply by apply a axial force to slide it down the shaft. Since the shaft is threaded, the flywheel will begin to spin. At the end of the shaft is a non-threaded section where the wheel can continue to spin freely. On the underside of the flywheel and top of the piece holding the chuck after high-friction disks, which will spin as one when in contact. To make the chuck spin simply push the flywheel to make contact with the corresponding friction pads. To stop the chuck separate the two, but pulling back on the grip, and let the chuck naturally slow down.

Part 2: Gyroscopic Loads

In order to tilt the flywheel's spin axis at $\omega_x = 3$ rad/s a moment of 6.311 lbf·in must be applied. This moment can be found using eq. 7, where ω_y is the expected speed of the flywheel at 105.2 rad/s, and the other terms are the principle moments of inertia.

$$M = \omega_x \omega_y \left(I_{zz} - I_{xx} + I_{yy}\right) \tag{7}$$

Using MATLAB to solve the matrix of equations in equation 8 radial loads were found to be A_x=-83.26 lbf and B_x=83.26 lbf on the bearings.

$$\begin{bmatrix} -L_{AC} & L_{BC} \\ 1 & 1 \end{bmatrix} \begin{Bmatrix} A_x \\ B_x \end{Bmatrix} = \begin{Bmatrix} M \\ 0 \end{Bmatrix} \tag{8}$$

Beam bending diagrams are plotted below. The maximum stress due to bending in the flywheel shaft was found to be approximately 263.3 ksi using eq. 9, where M is the maximum moment, y is the maximum distance on the shaft from the neutral axis equivalent to $d/2$ and I is the moment of inertia of the shaft.

$$\sigma_b = -\frac{My}{I} \tag{9}$$

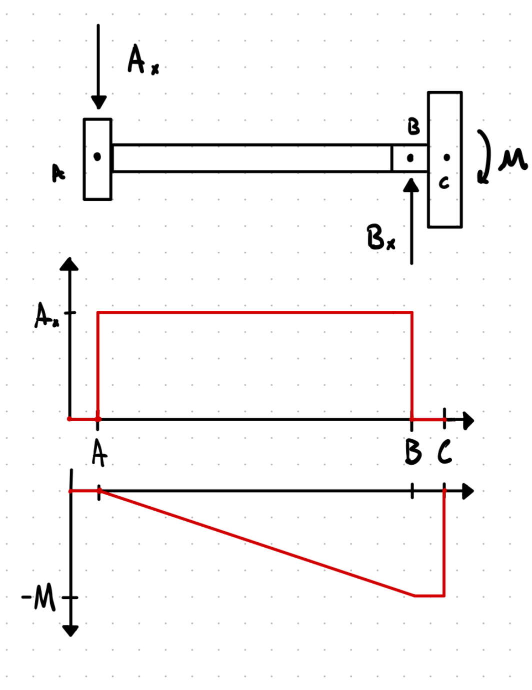


Figure 14: Load, Shear, Bending Moment Diagrams

Part 3: Critical Speed of the Flywheel Shaft

Estimated Critical Speed

The critical speed of the flywheel, ω_c, can be calculated using eq. 10, where $\delta_{\max}$ is the maximum deflection in the shaft, and g is the acceleration of gravity.

$$\omega_c = \frac{30}{\pi}\sqrt{\frac{g}{\delta_{\max}}} \tag{10}$$

The maximum deflection of the shaft happens at the center of mass of the wheel and can be calculated using eq. 11, where P is the weight of the wheel, b is the distance between the wheel and the lower grip, L is the distance between the wheel and the upper grip, E is the elastic modulus of the steel shaft, and I is the moment of inertia of the shaft which for a circular cross section is $I = \frac{\pi d^4}{64}$, where d is the shaft diameter.

$$\delta_{\max} = \frac{Pb^2L}{3EI} \tag{11}$$

Using eq. 11, with a weight of P =2.5 lbf, length $b = 3$ in, length $L = 23.23$ in, elastic modulus of $E_{\text{steel}} = 30 \times 10^6$ psi, and diameter $d = 0.625$ in, the maximum deflection is $\delta_{\max} = 7.754 \times 10^{-4}$ in. Therefore, using Eq. 10, the critical speed is $\omega_c = 6741.25$ RPM, or equivalently 705.9 rad/s.

Comparison to Expected Critical Speed

The expected speed of the wheel, as calculated in an earlier section, given 12.5 J of energy would spin at 1005 RPM, which is over six times slower than the critical speed.

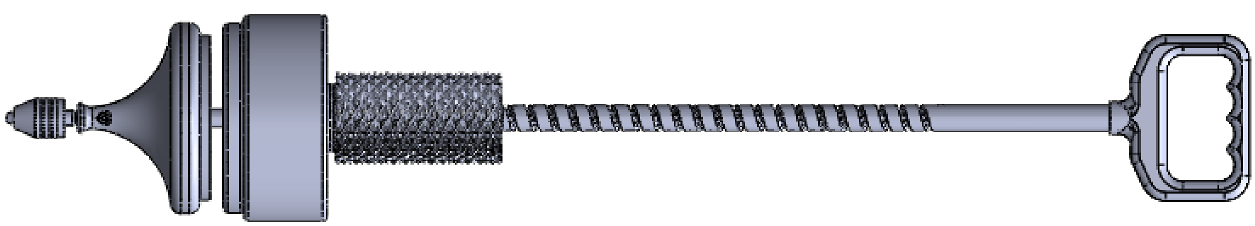


Figure 15: Image of the final rendering of the drill in a compressed state, not engaged with the chuck.

References

[1] J. Potter, GyroscopicLoads.pdf, Washington University, St. Louis, Missouri, 2021, https://wustl.instructure.com/courses/57378/files/2884573?wrap=1

Appendix

A MATLAB Code

```
% Axial load on bearings due to gyroscopic moment

L_AC = 3;          % [m]
L_BC = 23.23;      % [m]
Ixx = 5.3071697;            % [kg*m^2]
Iyy = 7.7243543;            % [kg*m^2]
Izz =  5.3071698;           % [kg*m^2]
w_y = 1004*(2*pi/60);       % [rad/s]
w_x = 3;                    % [rad/s]

A = [-L_AC, L_BC; ...
      1,      1];
B = [w_x*w_y*(Izz - Ixx + Iyy); ...
     0];

X = linsolve(A, B);
Ax = X(1);
Bx = X(2);

M = w_x*w_y*Iyy;

M = M / (32.2 * 12)
```