University of California, Berkeley

ME H194 Final Report

INSTAR RP-1

Load and Safety Considerations in the Design of Flywheel Kinetic Energy Recovery Systems for Electric Vehicles

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Abstract

Flywheel technology has novel applications in electric vehicles as the core component of a kinetic energy recovery system. Flywheels have quick charge and discharge rates, and can be used to recapture the energy that is generally lost using current regenerative braking technology or traditional friction brakes. One challenge to implementing these systems is mechanically connecting the flywheel to the vehicle chassis. This project focuses on the development of a robust flywheel mounting system that minimizes vibration transmission from the chassis, reacts loads under extreme driving conditions, and protects the driver in the event of a catastrophic failure.

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1 Introduction

INSTAR, or INertial STorage And Recovery, is a research group at UC Berkeley that focuses on development and testing of electric vehicles and cost-effective flywheel energy storage systems. While the main focus has been designing the flywheel, over the past several years the lab has developed and built an electric go-kart as a platform for this research. Since the flywheel spent a significant amount of time in the design phase, the scope of the project shifted to include improvements on all areas of the kart. Some of the projects in recent years include high-density batteries, traction control, an electronic differential, and a drive-by-wire system. However, after the first prototype flywheel was finally completed, the project returned to its original focus and I was tasked with coming up with a way to attach the flywheel to the kart.

2 Prototype Flywheel Mount

2.1 Objective

The initial flywheel mount was designed with the following objectives in mind:

1. Support the flywheel under extreme driving loads (cornering, braking, accelerating)

2. Damp vibrations through the use of rubber isolators

2.2 Design and Manufacturing

The mount is made of 6061-T6 aluminum, and was designed to be manufactured almost entirely on a waterjet machine. The mounting pillow blocks are all 2 dimensional profiles that were easily cut out of billet stock by the machine to save on manufacturing time. The plate was waterjet as well, and holes were postdrilled on a drill press, as the waterjet machine sometimes leaves a taper on the insides of holes. Rubber isolators were used to decouple the flywheel from the chassis. The parts that attach to the top of the plate were designed to constrain the flywheel from longitudinal and lateral forces, and were cut from angle stock, and the holes drilled on a mill. The mount bolts onto the chassis tubes using pillow blocks, which are blocks with semicircles cut out of them to clamp onto the tubes. The mount also contained extra holes for attaching the second flywheel when it was completed. Images of the prototype mount are shown below in Figures 1 - 4.

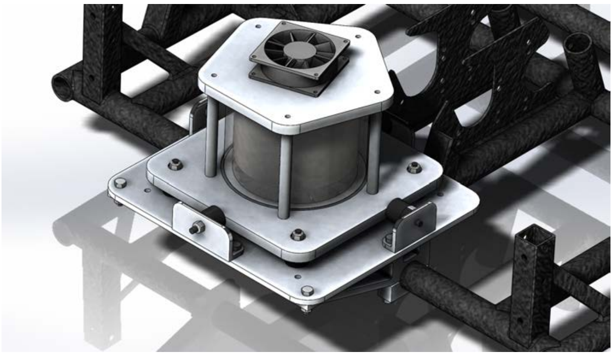

Figure 1: The prototype flywheel attached to the chassis

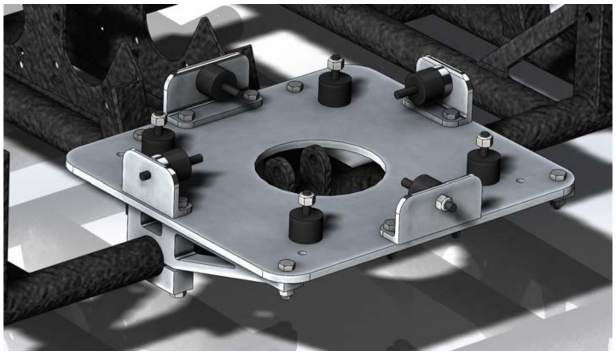

Figure 2: Rubber isolators exposed

Figure 3: Pillow blocks on underside of mount

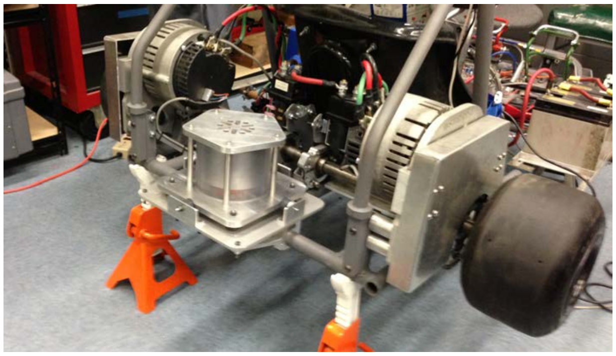

Figure 4: Photo of the assembly

2.3 Assembly and Testing

The assembly process for the prototype flywheel mount was very smooth, due to the fact that the CAD model was precise and included all of the mounting hardware. There were no unexpected issues, and the entire assembly fit onto the kart perfectly the first time it went together. Initial testing showed that the prototype mount would fully support the flywheel under normal driving conditions. At the time we were not able to spin up the flywheel on the kart, but our torque calculations showed that this was a weaker loading case than a sudden acceleration or breaking event, which we had already tested.

At this point the flywheel mount remained untouched for around a year, as our efforts were redirected towards developing and manufacturing the second (and final) flywheel. In 2014 after this flywheel was finished it was assembled onto the prototype mount, which required no additional machining because the plate was designed with a second set of holes to accommodate the new flywheel. The new flywheel was completely qualified and tested on the new mount, both on the kart and using the mount to attach to a table in the lab. Ultimately this design was very successful, and the initial prototype mount performed perfectly both on and off the kart.

2.4 Safety Concerns

Initial testing showed that the prototype mount would fully support the flywheel under normal driving conditions. However, after further analysis I realized I had not designed for a potentially catastrophic load case. One way for a flywheel system to fail is for the flywheel to "seize", or stop spinning very quickly due to a broken bearing, or some other object interfering with rotation. This failure imparts a massive torque from the flywheel to the mount, which it was never designed to handle. The issue lies in the rubber isolators — the bolts on each end of the isolators are not directly connected, but rather are each embedded in a rubber structure as shown in Figure 5. Consequently, the isolators are rated only in compression and can be pulled apart quite easily in shear. The mount contained eight isolators to counteract this, but I failed to consider that in an extreme in-plane torque event, all eight isolators would be loaded in shear and the mount would fail.

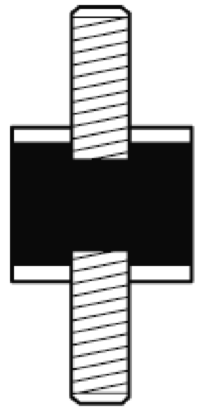

Figure 5: A cross-sectional view of the damper

3 Seizure Containment Flywheel Mount

After the realization that the initial prototype mount was potentially unsafe, I went to work redesigning the mount to contain the flywheel in the event of a seizure. While the majority of the redesign was completed by myself, Jason Cheung and Menglong Guo both made significant contributions to the analysis and calculations behind the design work.

3.1 Objective

The second flywheel mount design had an additional objective to cover any event that would transmit a large amount of torque to the mount in a short period of time, called a "massive torque event":

1. Support the flywheel under extreme driving loads (cornering, braking, accelerating)

2. Damp vibrations through the use of rubber isolators

3. **Safely contain flywheel in the event of a failure or massive torque event**

3.2 Concept

The team came up with two main concepts for modifying the design to add seizure containment. Both concepts rely on "seizure blocks," or large blocks that essentially form a protective cage around the base of the flywheel. The blocks do not touch the flywheel baseplate in normal operation to reduce vibration transmission, but catch the plate if a massive torque event occurs.

The two concepts are shown below. The first concept in Figure 6 relies on a bolted connection between the blocks and the baseplate of the mount, while the second in Figure 7 relies on a clamping mechanism.

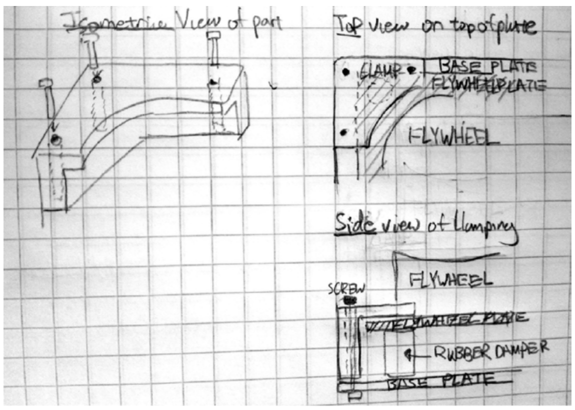

Figure 6: The bolted concept

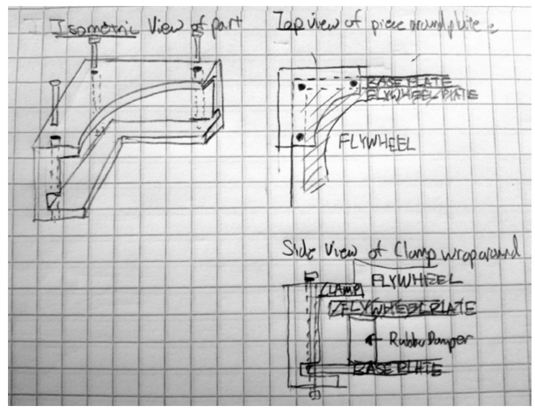

Figure 7: The clamping concept

Ultimately we chose to go with a version of the bolted concept, as machining the internal features on the seizure block for the clamping concept would be far too difficult.

3.3 Design

The new mount has the same basic design as the prototype mount, and uses the same pillow block setup to mount to the chassis. This saves on design and manufacturing time, and brings the overall cost of the project down. The initial concept had a lip that extended over the flywheel, but to make the parts more manufacturable this was changed into two separate components, a top plate and an L-shaped bracket. This change means that all parts can be made on a waterjet, and no CNC is necessary. We decided to make the inner walls angled slightly as shown in Figure 10 so that when the bottom plate rotates, it strikes the "seizure block" face to face, rather than point to point.

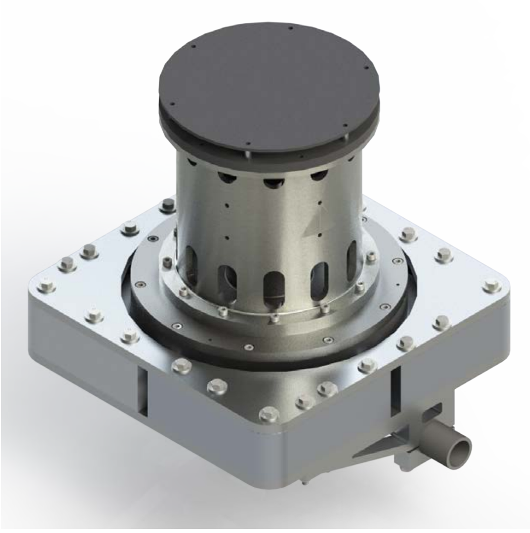

Figure 8: The full assembly

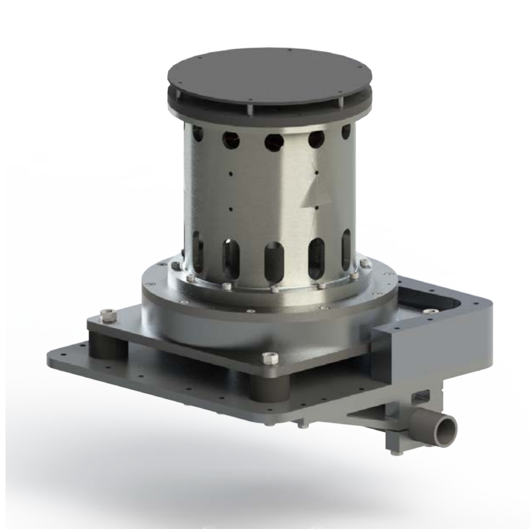

Figure 9: Rubber isolators and containment

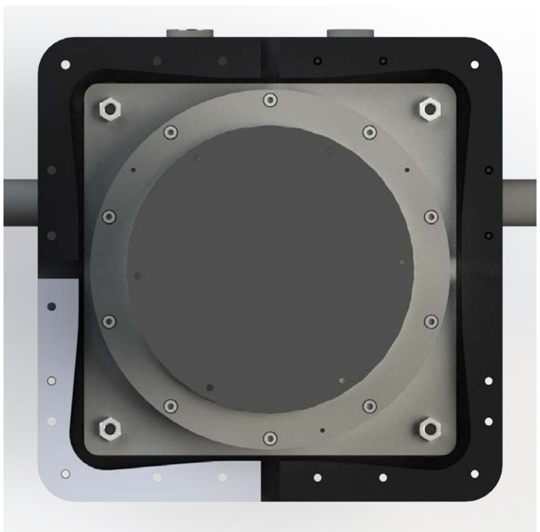

Figure 10: Top view of angled impact walls

Figure 11: Containment/flywheel interface

The seizure block is extremely bulky so it can stop the flywheel assembly from rotating in the event of a seizure. Under normal conditions it never touches the flywheel attachment plate, as there is a 3/16" gap between the two parts. However during seizure the plate will begin to rotate, where it will promptly hit the containment piece, which will deform but prevent the flywheel assembly from escaping its enclosure. The final change in the design from the prototype was to thicken the mount base plate from 1/4" to 3/8". This was done for reinforcement purposes, as the thickness of the plate needed to match that of the containment pieces or else the plate would be the "weakest link" in the chain between the flywheel and the chassis. Figures 8-11 show the flywheel mount and its subcomponents.

3.4 Manufacturing and Assembly

Design of the box was completed and all parts were in hand with around 3 weeks remaining in the Fall 2015 semester, and the team was on track to have the project completed by the last week of classes. However, at the end of the semester student projects get priority over research on the waterjet machine. Because the new mount is almost entirely manufactured on this machine, unfortunately the manufacturing was not completed by the time this report was written. At the time of writing all the raw material is in the shop, and the request has been quoted by the machine shop and approved by the lab. Once the manufacturing is done, this section will be updated and the report will be sent out with additional information.

Figure 12: Stock at the waterjet

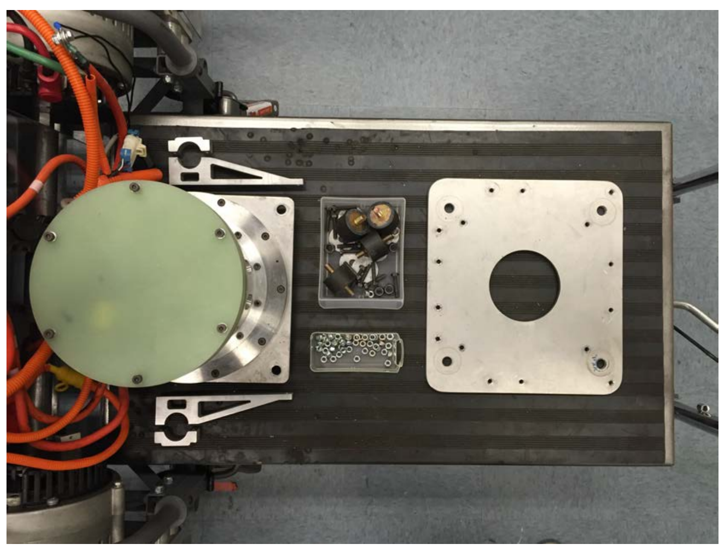

Figure 13: Prototype flywheel mount disassembled

3.5 Analysis

3.5.1 Force Calculations

The team decided to analyze how much torque would be generated at the mount for different ”spindown times”, or the time it takes the flywheel to go from theoretical maximum speed (25000 rpm or 2618 rad/s) to stopped. This spindown time determines how quickly the energy is released into the mount, and as a result how much force is generated on the mount.

The following symbols and values were used in our calculations:

Table 1: Force Analysis Terms

Name	**Symbol**	**Value**
Flywheel Mass	m_f	5kg
Flywheel Radius	r_f	0.1016m
Flywheel speed	ω_f	2618 rad/s
Spindown Time	Δt	variable
Damper Shear Force	F_{shear}	40 lbs
Number of Mounts	n	4

In order to make the hand calculations possible, we had to make several assumptions about what happens during a massive torque event.

1. Flywheel seizes up
2. 100% of energy is transferred from flywheel into flywheel enclosure
3. Deceleration is linear
4. Radius of contact on seizure blocks is r = 4in

The following basic equations were used in our analysis:

$$\tau = I\alpha \tag{1}$$

$$\alpha = \frac{\Delta\omega}{\Delta t} \tag{2}$$

$$I(disk) = \frac{1}{2}mr^2 \tag{3}$$

$$\tau = Fd \tag{4}$$

And finally, here is the solution to solve for Force in terms of spindown time:

$$\tau = I\alpha \tag{5}$$

$$Fr = \frac{1}{2}mr^2 \cdot \frac{\Delta\omega}{\Delta t} \tag{6}$$

$$F = \frac{1}{2}mr \cdot \frac{\Delta\omega}{\Delta t} \tag{7}$$

$$F = \frac{1}{\Delta t}\left(\frac{1}{2}mr \cdot \Delta\omega\right) \tag{8}$$

$$F = \frac{1}{\Delta t}\left(\frac{1}{2} \cdot 5 \cdot 0.1016 \cdot 2618\right) \tag{9}$$

$$F = \frac{1}{\Delta t} \cdot 665 \ \ \text{N} \tag{10}$$

The results are shown below in Figure 14:

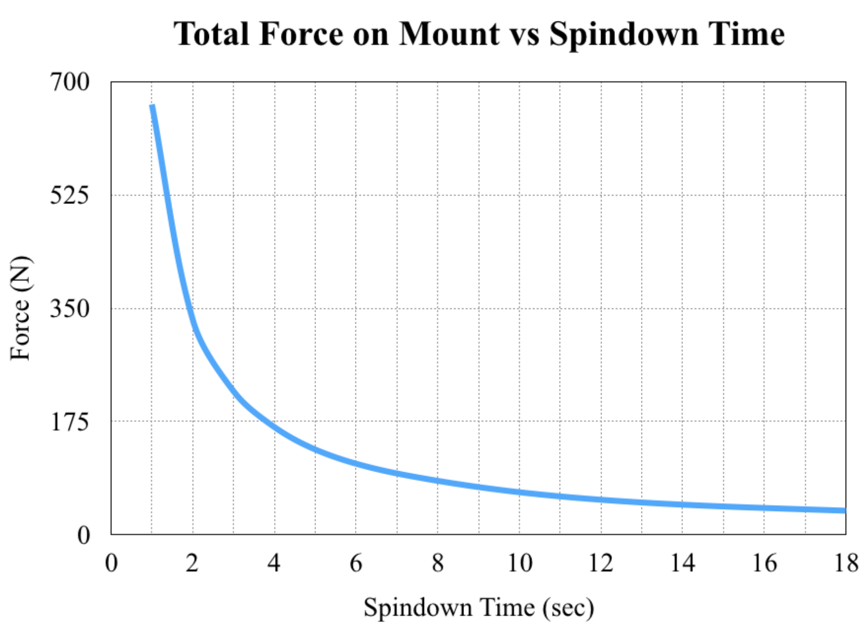

Figure 14: A visual representation of force versus spindown time

Given that the the mounts only have 4 dampers, which each provide 40 lbs of shear resistance, the mount can only withstand $F_{shear} \cdot n = 40 \cdot 4 = 160$ lbs of force! So if the flywheel had ever spun down in under 4 seconds, the first mount could have failed!

3.5.2 Finite Element Analysis

After calculating the forces for different spindown times, we took the results and plugged them into Solidworks Simulation to get an idea of how stiff the design is. We used basic fixed constrains on the bottoms of the pillow blocks. We placed the load approximately where the flywheel base-plate would meet the seizure block, and split it between the four contact planes as shown in Figures 15 and 16.

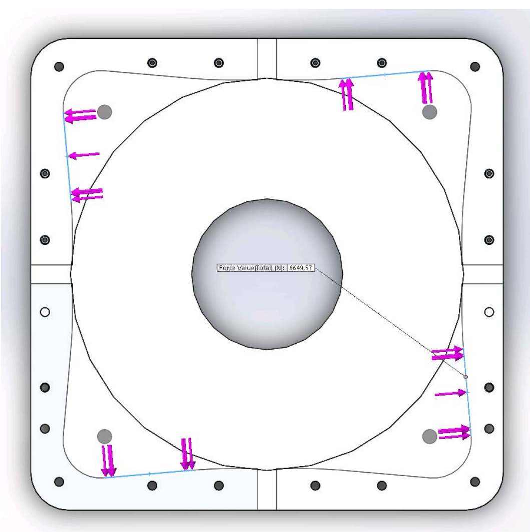

Figure 15: Angled load faces

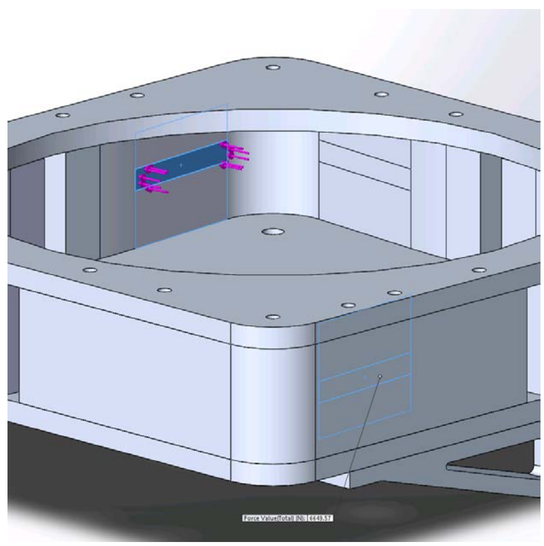

Figure 16: Load Location

Figure 17 shows the results from a simulation with a force corresponding to a spindown time of 5ms. With a minimum factor of safety of 3.5 it technically passes but I am not confident enough in the setup of the FEA constraints to trust that number. Realistically the only way to really know how strong the new mount is would be to destructively test it. Unfortunately, we don't have the budget for such tests so we must rely on hand calculations, rudimentary FEA analysis, and engineering intuition.

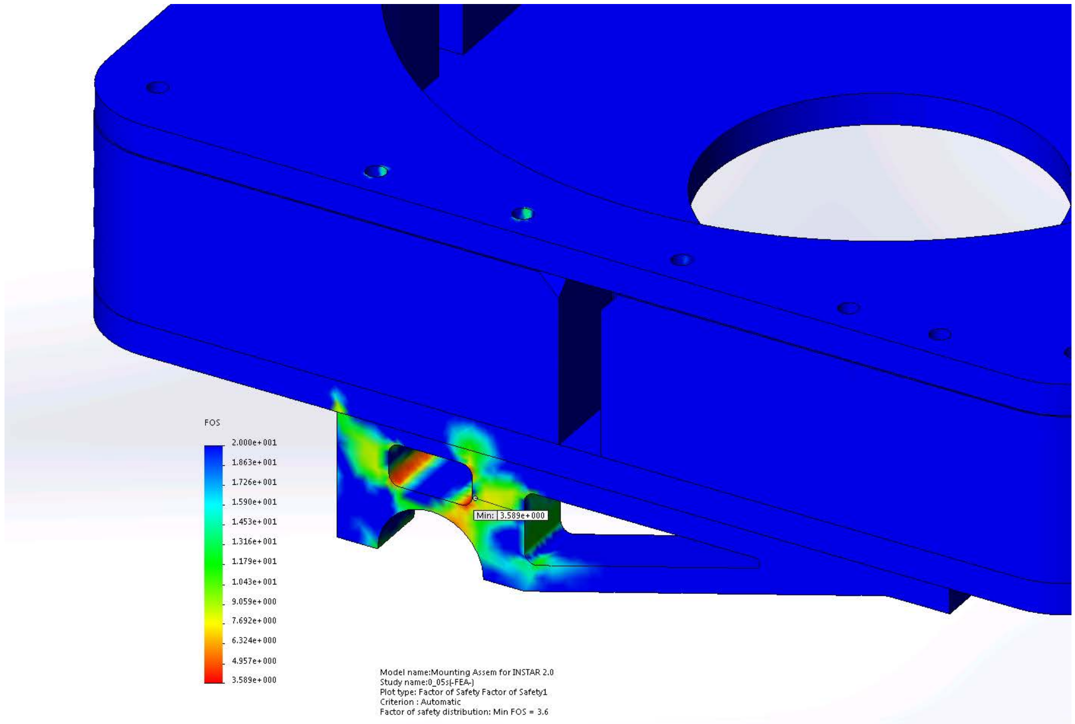

Figure 17: Factor of safety plot from a spindown time of 5ms

4 Conclusions

Over the course of this semester, I have gained a much better understanding of how to create strong designs for complicated mechanical systems. I have also learned more about leading small design teams. Discovering and the issues with my initial flywheel mounting design was a great learning experience for me, and I was able to use it to help define what I needed to fix for the new version. I had to look closely at what my requirements were the first time around, why they were flawed, and what I could do the second time to account for new information I had about the flywheel seizure failure mode. I am looking forward to getting the parts back from the shop and putting them together!