DESIGN OF BALL LOCK MULTI-SPEED TRANSMISSION SYSTEM

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Abstract— The SAE Mini Baja team requires a custom, multispeed transmission for their vehicle. Concurrent engineering with the Baja design team created a working model. The overall purpose of this project was to fabricate a fully functional three speed [10:1 and 7:1 and 6:1] transmission for a 10 HP vehicle. The product was designed using decision matrices and house of quality. Then, it was drawn up on SolidWorks and a finite element analysis was done on the shafts in order to optimize the design. Lastly, some of the designs were sent to a manufacturer and the rest were machined by the team using Tech's facilities. The finished product was integrated into the vehicle that will race in future.

Keywords— SAE Mini Baja, Multispeed Transmission, Three Speed Transmission, Ball Lock.

I. INTRODUCTION

The Society of Automotive Engineers sponsors an engineering design competition every year called the Mini Baja competition. The design for this particular transaxle was determined through a series of decision matrices, house of qualities, and comparisons with designs from previous years. Two speeds were originally chosen to provide a lower ratio for speed as well as a higher ratio for better torque for the sled pull. Based on hypothetical calculations of the vehicle climbing a hill, the speeds were narrowed. The final design incorporates two gear ratios: 10 to 1 and 7 to 1 in order to provide the needed speed and torque requirements for the most versatile Baja vehicle.

Based on manufacturing and availability constraints, spur gears were chosen to use and the rest of the transmission was design around their properties. The most innovative part in this design that will set the team apart from the rest of the teams is the shifting mechanism. This design utilized a ball lock shaft, which enables the entire case width to be cut in half as well as reduce weight. This mechanism allows a smooth transition between gear reductions, making it desirable in a race setting. Rather than use clips like a traditional transmission, the ball lock relies on ball bearings within the input shaft to lock the respective gears into place.

The concept is better understood as shown in Figure 1.

Lastly, the design incorporates a case specially designed to house the needed gears, shafts, differential, and bearings while leaving little unused space.

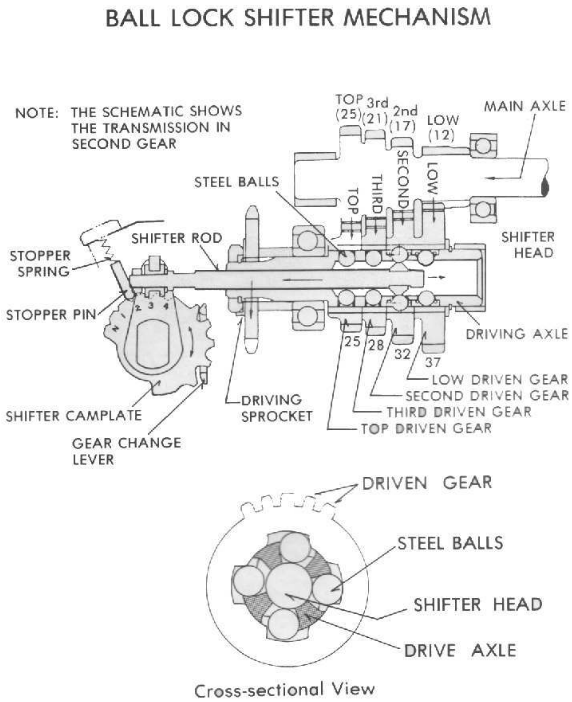

Figure 1. Ball Lock Shifter Mechanism [1]

Before the design was sent out to get manufactured, finite element analysis of the shafts were done. Each shaft was analyzed under a torsional loading in order to determine where the piece would fail and how likely it is to fail under maximum possible loading from the motor.

II. DESIGN

The most important aspect of this project was ensuring a working SolidWorks model of the design to send to the fabricator. Each component (case, shafts, bearings, c-clips, differential, and gears) needed to be created and combined in a feasible layout that would optimize the space. The first parts of the design were the differential because we started with that part and needed to design around it. We calculated the ratios needed and SolidWorks allows us to find and use standard size gears. The shaft sizes were based on the gears given and the case was formed around the parts. Once that was all said and done, there was room on the shaft due to the differential being so wide. In order to better our design, we added another gear ratio of 6:1, making this transmission a three speed and making our max speed go from 35pmh to 39mph. It only added a little over 1 pound to our 29.16lb design. This year's design is 6 pounds lighter than the transaxle that was used last year that had one speed and reverse.

The next step in confirming a safe design was to conduct finite element analyses on the shafts. The input shaft was analyzed by fixing one end and loading 15 ftlb/in on the end connected to the motor. The shaft weighed 1.4lbs, had a safety factor of 43 and the most stress occurred at the bearing holes with a magnitude of 8.14MPa. Figures 2 and 3 show the Stress and Factor of Safety, respectively.

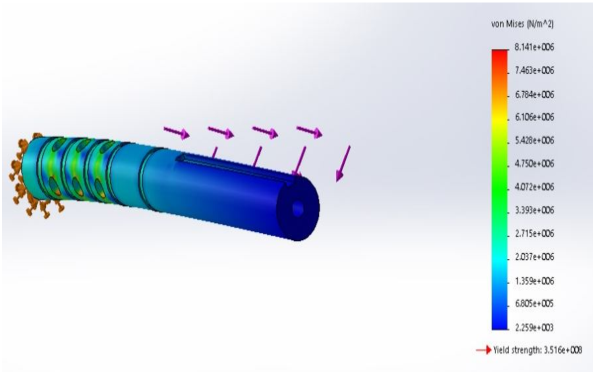

Figure 2. Stress on the Input Shaft

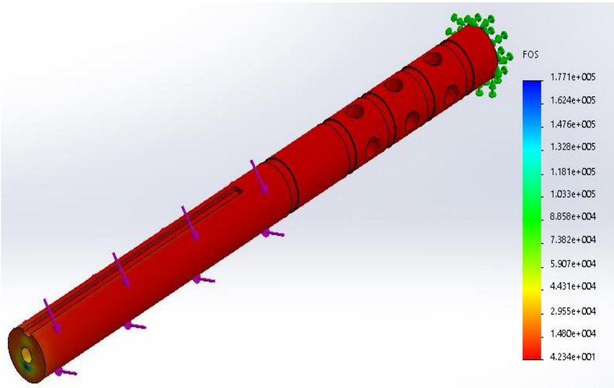

Figure 3. Factor of Safety of the Input Shaft

The 2nd shaft was going to be under more loading than that provided by the motor, so we used the following equation to determine the maximum loading of the vehicle based on the motor torque and lowest gear ratio provided [2].

$$Motor\ torque * gear\ ratio = 15\frac{ftlb}{in} * 2.53 = 37.95\frac{ftlb}{in}$$

Therefore, the analysis loading constraints were 40 ftlb/in of torque and fixed both ends of the second shaft. This weighed 0.61lbs, resulted in a safety factor of 110 and the maximum stress occurred at the thinnest parts with a magnitude of 3.16MPa. The stress image (Figure 4) of the finite element analysis has been greatly exaggerated to show the accurate magnitude of forces on the shaft. The metal will not actually behave in such a way, but the software allowed the team to see where the most stresses were put on the shaft.

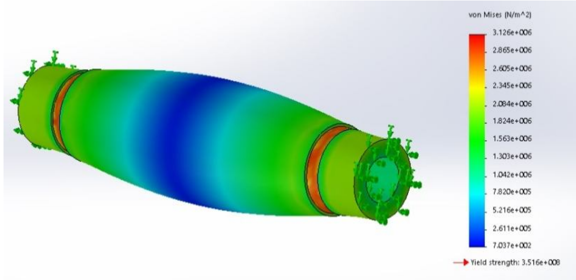

Figure 4. Stress on 2nd Shaft

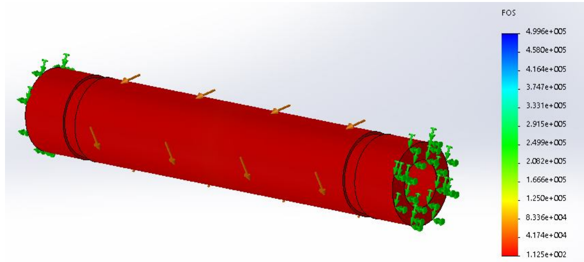

Figure 5. Factor of Safety of the 2nd Shaft

From this FEA, we can conclude that the shafts were designed larger than they needed to be. However, because they have to be a specific diameter to accommodate the gears, the only alteration made was machining material out from the center of each shaft to decrease the thickness.

The next area of optimization occurred with the case design. After a meeting with the manufacturer [3], the team decided to simplify the case structure in order to better utilize manufacturing time. Figure 6 shows the optimized case design that was sent for manufacturing.

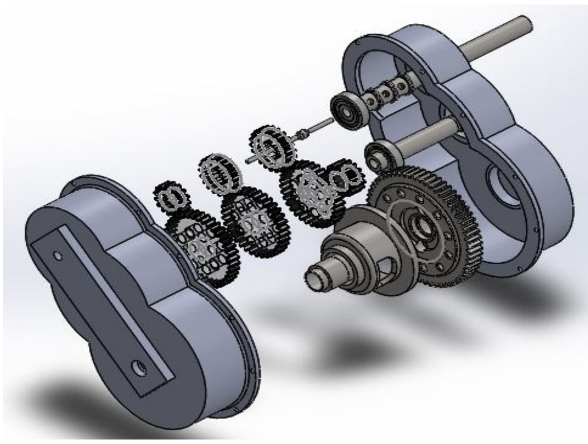

Figure 6. Optimized Case Design

Another suggestion was to use contoured shapes to make it simpler and easy to machine. The main tip stressed was to put dowel pins along the linear axis of the bearing holes of the case as shown in Figure 7. These dowel holes gave points to start from when the manufacturer had to flip or move the part in the machine. The other use of the dowel pins was to align the cases up perfectly when the team began to assemble the transmission.

The main requirement that the machinists asked for was to have hard copies of the drawings and to have them dimensioned properly. They wanted to see all three views and an isometric view. The reason for the hard copies of the drawing was that when the machinist out on the floor got the part, he only receives flat drawings to go off of. This is a standard practice that was not previously known about. The experience of working with the machinist to make the part manufactural has been a good method to get the part done.

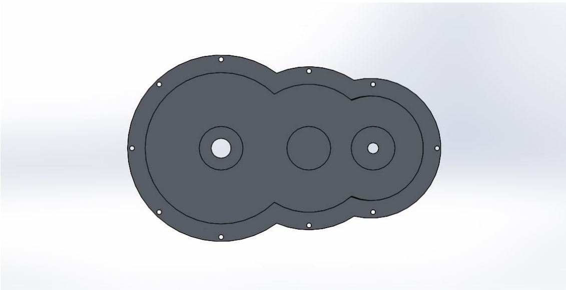

Figure 7. Side View of Case

The gears were the next area of concern and they were designed on SolidWorks. Figure 8 shows the drawings of one stationary gear and one of the ball lock gears. The gears were designed to allow the ball bearings to punch outward and grab hold inside the half-moon shapes cut into each gear. In terms of manufacturing, the gears were cut using the method wire electrical discharge machining (EDM). The desired teeth were to be cut by sending electrical discharges through a wire.

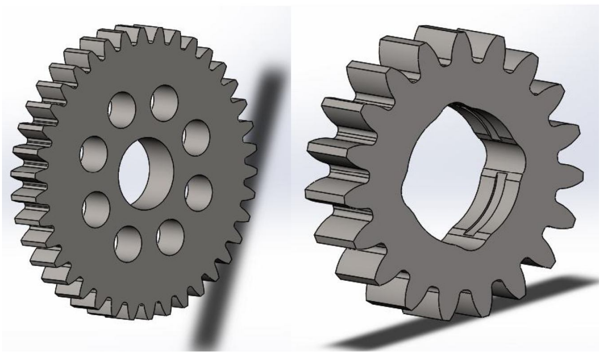

Figure 8. SolidWorks Drawing of the Gear Design

In order to determine the material used for the gears, the mechanical properties of several different steels were compared and contrasted to the following calculations. The maximum transmitted load on the gear tooth face was found using the maximum bending tooth stress (S), the face width of the gear (F), the diametral pitch (D_p), and the Lewis factor (L). The following equation was used [4]:

$$W_t = \frac{S*F*Y}{D_p}$$

The manufacturer had suggested several metals depending on whether heat treating capabilities were available. The ones suggested were ASTM A36, AISI 8620, and Hardox 400. The A36 was not a viable option because the material is not heat treatable and would be too soft for gears [5]. The Hardox material seemed more advantageous because of its high tensile strength, but based on the mechanical properties (Table 1) after case hardening, the 8620 was chosen. Table 2 shows the gear tooth strength results.

Table 1. Mechanical Properties of AISI 8620 Steel and Hardox

	AISI 8620 Steel [7]	Hardox [6]
Yield Strength	785 MPa	1000 MPa
Tensile Strength	1270 MPa	1250 MPa

Table 2. Gear Tooth Strength Calculations [4]

Gear Tooth Strength Calculator	
Design Variables	
Maximum bending tooth stress (taken as 1/3 of the tensile strength) (S) =	60785.320
Face width of gear (in.or mm) (F) =	0.500
Diametral Pitch, 1/module (for equation only) (D_p) =	10.000
Lewis Factor (Y) =	0.289
Results	
Maximum transmitted load (N or lbs) =	878.3479

Based on these results, verification of the material chosen was conducted using the following equation, given the torque of the motor (14.25lbft), maximum gear ratio (7:1), and the gear radius (1.7in).

$$Max\ Torque = Torque\ from\ motor * \frac{Max\ Gear\ Ratio}{Gear\ Radius} = 14.25 * \frac{7}{.1417} = 703.95ftlb$$

After the design and verifications were completed, the drawings were sent out to the respective companies to be manufactured.

III. MANUFACTURING

The focus of this project was the fabrication of the design made before. There were two approaches to the fabrication: doing everything with the machines the school provides, or sending our CAD drawings to a company, having them machine the specialized parts, and put all the components together at school. Table 3 shows a breakdown of the cost for each option.

Table 3. Cost Breakdown of Manufacturing Options

CNC- 40 hrs at \$70/hr	Machining- 80-100 hrs at \$35/hr
Labor- 6 hrs at \$35/hr	Labor- 12 hrs at \$35/hr
Outside shop= \$3010	Ourselves= \$3920

Based on the time and monetary constraints the team faced, the best option was to send the designs out to a fabricator. The team met with the manufacturer to determine whether they could fabricate what we needed, timeframe, and what they needed to have in our CAD drawings.

The case drawing was sent to be machined and the gears were sent to be wire EDMed. Copper bushings were made to hold the shafts in place and the bearings were purchased. The lathe machines at the school were used by the team to create the two shafts as designed. After the pieces came back from each place, the gears were welded onto the secondary shaft and the ball bearing gears were placed on the input shaft separated by washers with bearings. After mounts were made on the frame, the transmission parts were assembled and integrated into the Baja buggy design.

Figure 9. Machined Case

Figure 10. Shafts and Ball Lock Gear Assembly

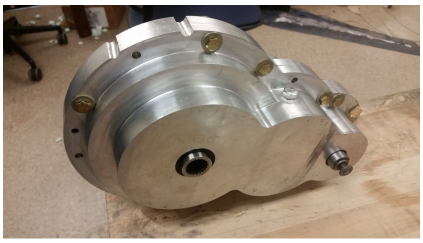

Figure 11. Final Product

CONCLUSION

This project served as a great way to learn about the engineering design process and the final product was a functioning, efficient, well-designed multi-speed transaxle. Some valuable lessons about time management, working in a team, and the design process were learned along the way. Another important skill gained from this experience was effective, professional communication with manufacturers and businesses. Proper contact and communication allowed for the team to spend a lot less money and gain important contacts for the future.

In learning this design process and seeing how it benefited the final product, the team will bring this process to the SAE Baja Team as a whole. The entire buggy can only benefit from being designed the proper way with a schedule, analysis, and more testing. This product also provided a working model for many years to come. The SAE Baja team will be able to design around this product or even modify it depending on the design constraints of that year's vehicle. Overall, the product was exactly what the team required and following the design process allowed the team to make educated and engineering-based decisions.

REFERENCES

[1] "GEAR SHIFTERS." Dan's Motorcycle. Web. <http://www.dansmc.com/gearshifters.htm>.

[2] Stonecypher, Lamar. "Drive Shaft Design Concept for Combined Bending and Torsional Loading." Brighthub Engineering. 22 Aug. 2010. Web. <http://www.brighthubengineering.com/machine-design/45105-drive-shaft-design-concept-for-combined-bending-and-torsional-loading/>.

[3] "Design Meeting with Manufacturers." Personal interview. 22 Jan. 2015.

[4] "Gear Tooth Strength Calculator" Engineers Edge. Web. <http://www.engineersedge.com/calculators/gear-tooth-strength-calculator.htm>.

[5] "ASTM A36 Steel, Plate." MatWeb Material Property Data. Web. <http://www.matweb.com/search/datasheet.aspx?matguid=afc003f4fb40465fa3df05129f0e88e6&ckck=1>.

[6] "Hardox 400: Mechanical Properties." Hardox. SSAB, Web. <http%3A%2F%2Fwww.ssab.com%2FGlobal%2FHARDOX%2FDatasheets%2Fen%2F151_HARDOX_400_UK_Data%2520Sheet.pdf%3Fepslanguage%3Den>.

[7] "8620 Case Hardening Steel." Engineering Steels and Alloys. Interlloy, Web. <http%3A%2F%2Fwww.interlloy.com.au%2Four-products%2Fcase-hardening-steels%2F8620-case-hardening-steel%2F>.

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