Improving the Drive-Train for ELBA

ELBA - Car competing at Shell-Eco Marathon

August 2016

KTH ROYAL INSTITUTE OF TECHNOLOGY

SHELL ECO-MARATHON

MF2020

Improvement of existing Drive-Train on ELBA

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SUMMARY

Shell Eco-Marathon is a competition conducted by Shell Corporation. The ELBA car built by KTH Royal Institute of Technology, competed in the Urban-Concept Car category, where ethanol was used as fuel. In this competition each team was given 4 attempts, in each of which there was a time limit of 45 minutes for the car to complete specified number of laps around the track. The team to complete these laps within the given time frame, with the least amount of fuel consumed was declared the winner of the competition.

ELBA is a car that was developed for the aforementioned competition by the students of KTH in the year 2015. Although the car was well made, like any other product,it had a lot of problems. The students from the batch of 2016 were to refine this car. The Shell-Eco Marathon team from KTH has 3 major teams - (1) Mechatronics, (2) Internal Combustion Engine(ICE) and (3) Machine Design. The main objectives of the mechatronics team are to design a system in order to compute an optimum drive cycle and to control elements like the clutch, engine ignition, lights. While the ICE team had to develop an ignition controlled engine that runs on ethanol. Finally, the Machine Design team has to improve the existing drive train and incorporate a better clutch mechanism so as to make the system more efficient.

The clutch mechanism that was being used was inefficient and the parts used were worn out. One of the main reasons for the inefficiency of the clutch in the previous design was that, the actuators were exerting more force than necessary and also this force was being exerted even after the needed part was engaged. So the idea was to have a clutch mechanism that wouldn't need the actuators to exert a force after the necessary parts were engaged. It was decided to retain as many parts as possible from the previous drive train model and come up with a new clutch that could be accommodated into the existing drive-train model.

The new clutch mechanism makes use of balls and springs that are inserted into the hole drilled through the shaft at appropriate positions. A bushing with a grooved profile is made so as to slide axially along the shaft. The grooves were made in order to accommodate the balls that pop out once the clutch is fully engaged or dis-engaged. The spring force pushes the ball against the face of the groove thus locking the clutch in position i.e. not letting the clutch slide axially until the force is exerted by the actuator. Although the clutch mechanism proved to be efficient, the drive train as a whole did not prove to be highly efficient owning to the minor misalignment in shaft and the high amount of friction at the bearing shaft interface.

Keywords : Shell-Eco Marathon, Ethanol, Mechatronics, Machine Design, Internal Combustion Engine, Clutch, Drive-Train

ACKNOWLEDGEMENT

*We take this opportunity to thank **Mr.Mikael Hellgren** who gave us a chance to be a part of building ELBA and also guided us through the process. We would like to thank **KTH Royal Insitute of Technology** for extending the necessary funds to participate in Shell-Eco Marathon at London and to obtain the necessary accessories to build the car. We shall remain indebted to **Thomas Östberg** for machining the parts needed for the drive train on time. We would also like to thank **Per Risberg** for his whim and wit even at tense moments at the paddock. Last but not the least, we would like to thank the members of the **Mechatronics** and the **IC engines** team, whose assistance at crucial times helped us deliver our goals.*

TEAM MACHINE DESIGN

Contents

Chapter 1

INTRODUCTION

This report discusses at length the efforts made to improve the existing drive-train by the Machine Design team. This section in particular gives a brief description of the basic functioning of the old drive-train and it's disadvantages. In the subsequent sections the new drive train design will be dealt with in detail.

1.1 Previous Drive-Train

In this section a brief description of the layout of the old drive train and it's working is discussed.

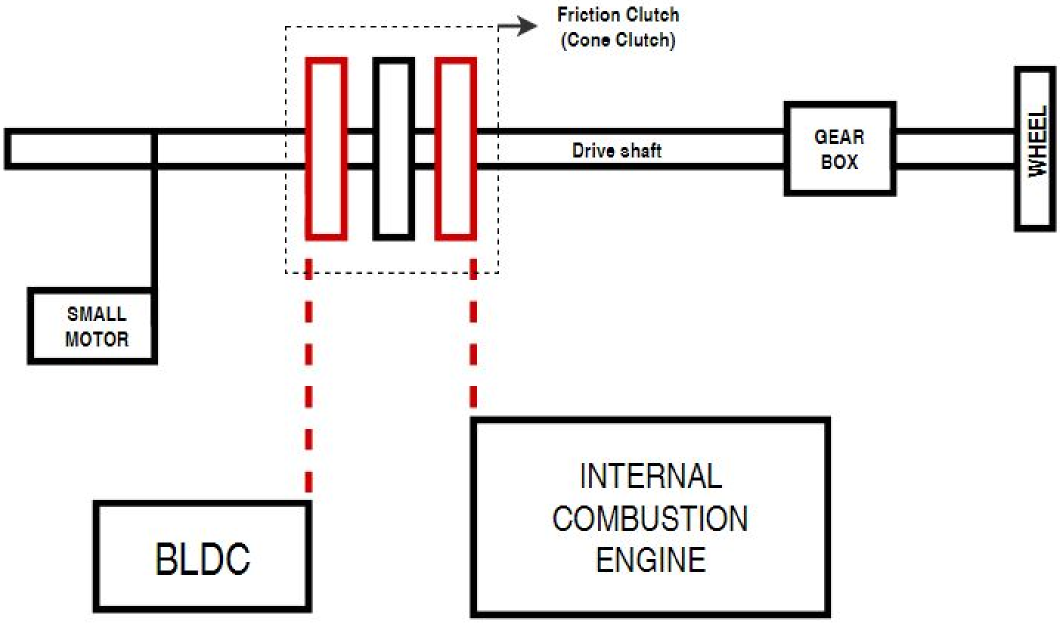


Figure 1.1: Layout of the old-drive train (A rough schematic)

Figure 1.1 shows a simple schematic representation of the layout of the old drive train. The components shown in red indicate that they are not always connected to the drive shaft. They are engaged and disengaged at will. However, the other components are always connected. The small motor is always connected to the drive-shaft. While the power from the BLDC (large electric motor) and Internal Combustion Engine(ICE) is drawn only when the respective clutches are engaged/mated with the center disc that is always rotating (indicated by the black rectangle in between the two red rectangles in **figure** 1.1) with the drive shaft.

1.1.1 Working

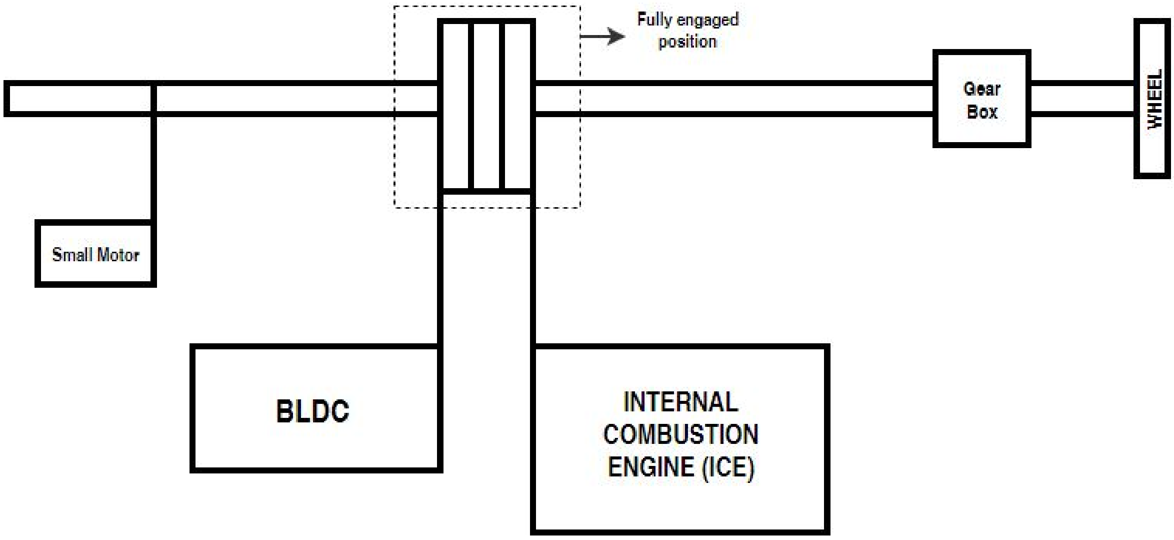
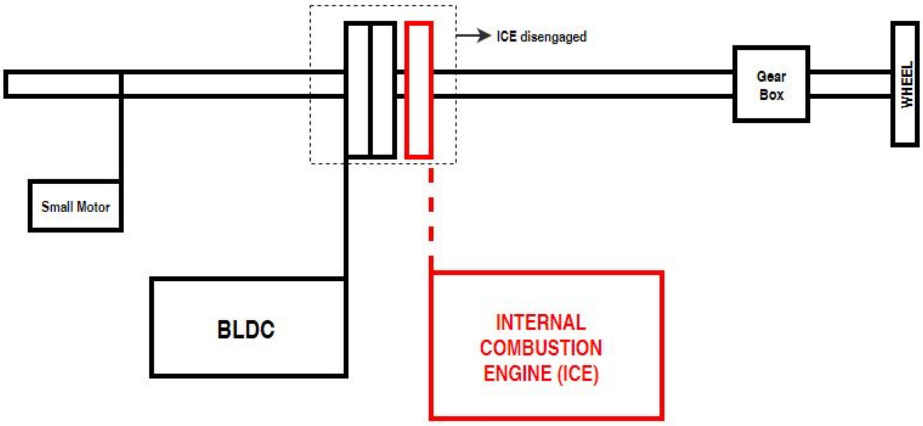


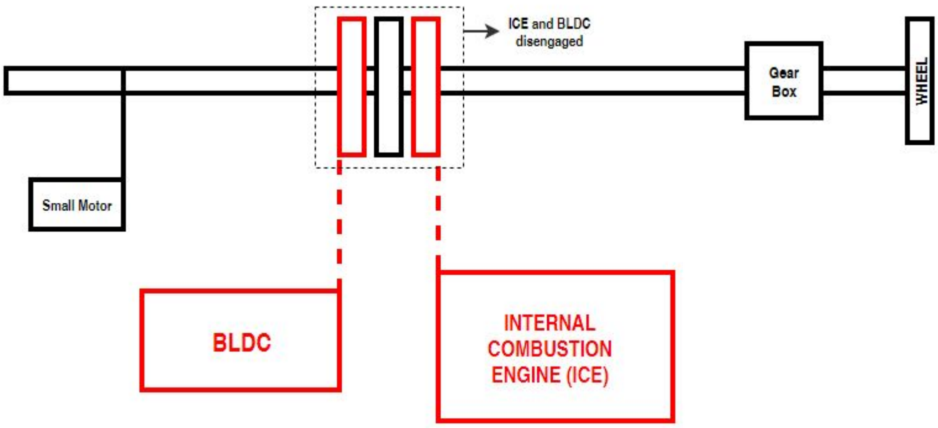
Figure 1.2: Start position of the drive (A rough schematic)

Figure 1.2 shows the schematic of the drive train when the car begins to move. Here, the BLDC is in fully charged condition, and all the components are engaged. So, the power from the BLDC is used to fire the ICE. This power from the ICE is used to propel the car forward. Now, the BLDC has utilized some power to start the ICE and this has to be replenished. So, the power is no longer supplied to BLDC, and the car is propelled by the ICE. During this the power from the ICE is also used to charge the BLDC. Once the BLDC is charged to 48 volts (fully charged state) the ICE is disengaged. After this there are two possible scenarios:

- SCENARIO 1 - when the car has to accelerate
- SCENARIO 2 - when acceleration is not needed



(a) SCENARIO 1 (A rough schematic)



(b) SCENARIO 2 (A rough schematic)

Figure 1.3: Drive Train layout for Scenario with acceleration and without acceleration

Scenario 1 - Acceleration

Figure 1.3a shows the acceleration scenario in the drive train setup. In this case both the small motor and the BLDC are used to run the car, the BLDC in addition to the small motor provides the means to accelerate. Once the power from the motors are used up, then the ICE is again engaged and the motors are recharged.

Scenario 2 - No acceleration needed

In this scenario, as seen in **Figure** 1.3b both the BLDC and the ICE are disengaged and the power from the small motor is enough to drive the car at a constant speed. Once the charge drains from the small motor, the ICE and the BLDC are engaged again and the power from the ICE is used to charge the motors.

It can be seen that, whenever the ICE is running the BLDC is engaged as well, however the converse need not be true. So, the point of using the ICE is mostly to charge the

BLDC whenever it runs out of charge. The usage of ICE is limited to just charging the motors because the main objective of the competition is to cover larger distances with less consumption of fuel.

1.2 Disadvantages of the old drive train

The existing drive train did not perform to it's potential. The reasons for that were analyzed by making observations of the functioning drive train and by taking it apart to see if all the components were intact. The following observations were made:

- The clutch mechanism was not functioning. The reason being, excessive force applied by the actuators. Due to this excessive force, the clutch plate stuck very hard to the center plate and could not be deactuated easily. Also, the force being applied on the bearings, to actuate the clutch, caused some friction losses on the bearing elements. So, it was necessary to come up with a new clutch mechanism where force would be required to just move the clutch plates towards the center plate, but not to perpetually hold them against the center plate.i.e there must be other means of locking the clutch plates in position.
- The small motor was always connected to the shaft. Due to this, when driving down a slope the car went on slower speeds than it would have without the small motor. So, there had to be a means to disengaging the small electric motor from the drive train.
- Most of the parts like bearings were worn out due to continuous use during the race.
- The center plate of the clutch was worn out and had to be re-made
- There was misalignment in the shaft due to improper mounting.

Based on the above observations, certain solutions were discussed and implemented. These shall be discussed in the subsequent sections

Chapter 2

NEW DRIVE TRAIN

This chapter elucidates the clutch design solution that has been implemented in the final working model of the car. It must be noted that the layout of the previous drive train was deemed reliable and a decision was made to use the same layout. But, it was decided to improve the efficiency of the existing arrangement by re-manufacturing the worn out components and coming up with a new clutch mechanism.

2.1 Description of new clutch solution

When engaging the ICE or the BLDC, the power flow in the previous clutch mechanism went from the actuator through the rotating ball bearings and into the conical clutch. When an axial force was applied on a rotating ball bearing, friction losses occurred. Therefore, a solution that made use of a spring loaded ball to lock the clutch in the engaged position (to avoid the friction force in the bearings, when the clutch is engaged) was used. **Figure** 2.1 is an illustration of how the power flow was in the old clutch mechanism. It

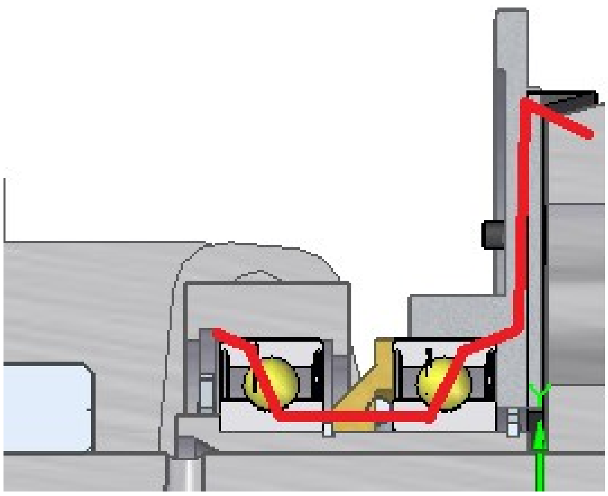


Figure 2.1: Power flow in the old clutch mechanism (red line indicates power flow)

can be seen that the power flows through both the bearings in the fully engaged position.

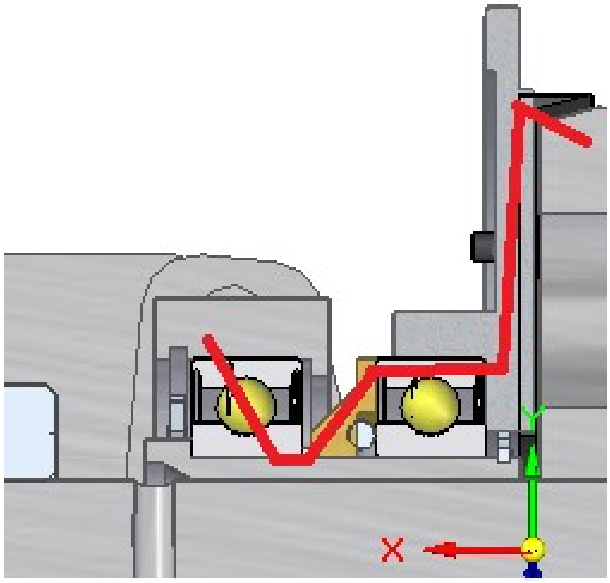


Figure 2.2: Power flow in the new clutch mechanism (red line indicates power flow)

Figure 2.2 illustrates the force flow in the new clutch solution. It can be seen that the power flows through one rolling element only (during the engagement phase).

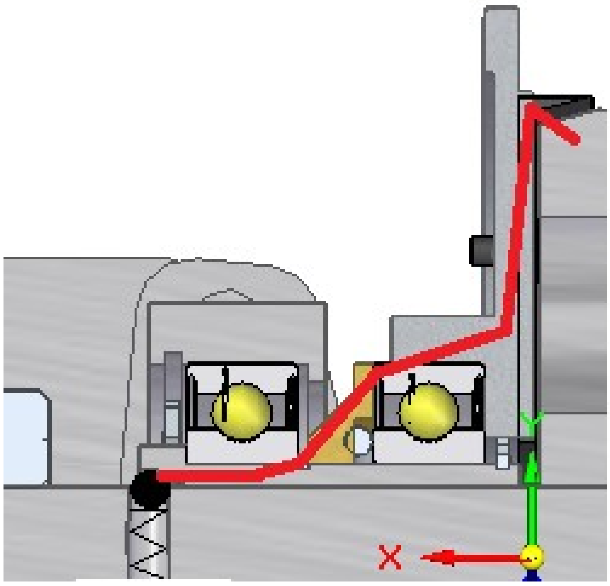


Figure 2.3: Power flow in the new clutch mechanism (red line indicates power flow)

Figure 2.3 illustrates how the spring and ball arrangement in the shaft ensures that no force is transmitted through the balls of the bearing.
This was the concept that was finalized. The next step was to make calculations so as to decide the wedge angle for the spring and ball locking mechanism.

2.2 Calculation

The calculations were made to compute the wedge angle needed. These calculations were not done with very high precision. However, care was taken to accommodate all the operating conditions with some simplifications that would not affect the result largely.

According to [1], as seen in **Figure** 2.4 with the reaction force at the wedge (N_1) due to the spring (P) and ball acting as a function of the wedge angle (α), the force N_2 on the ball can be calculated using **equation** 2.1. This force N_2 is nothing but the force with which the clutch is engaged.

$$N_2 = P * \frac{sin\alpha}{cos\alpha - \mu * (1 + sin\alpha)} \tag{2.1}$$

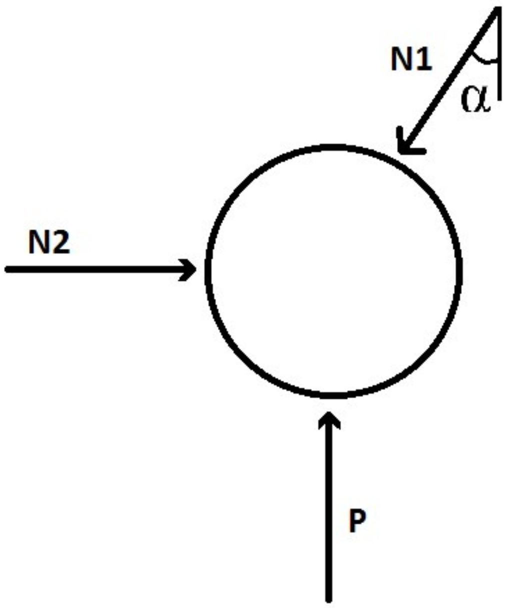
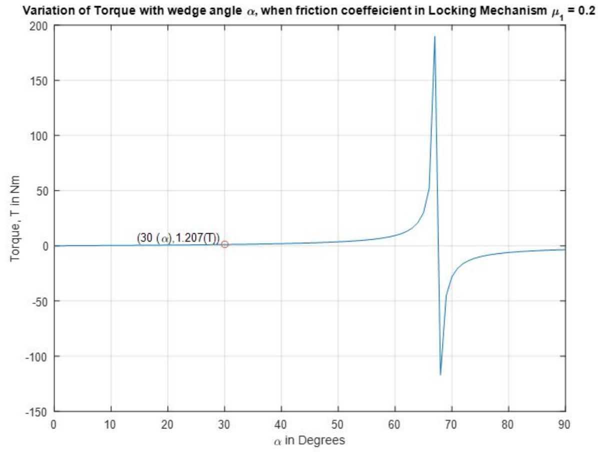


Figure 2.4: Free body diagram of the ball in the locking mechanism

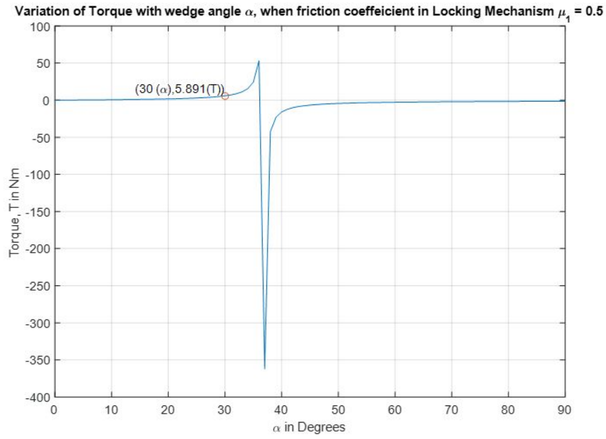
The amount of torque to be transmitted was estimated to be 3-4Nm. This estimate of torque was given by the ICE team. According to [2] the torque to be transmitted by the clutch can be estimated by **equation** 2.2

$$T = \frac{\mu R_m N_2}{sin\beta + \mu cos\beta} \tag{2.2}$$

- $\alpha = 0 - 90°$, tested angles on the locking mechanism
- $\mu_1 = 0.2, 0.5$; friction coefficient of the locking mechanism (Steel-Steel)
- $\mu_2 = 0.6$, friction coefficient of the conical clutch
- $R_m = 0.0955m$, the mean radius of the conical clutch
- $\beta = 15°$, angle of the conical clutch.
- $P = 20N$, minimum force from the spring according to the data sheet given by the supplier



(a) Variation of transmitted torque with wedge angle. ($\mu_1 = 0.2$)



(b) Variation of transmitted torque with wedge angle. ($\mu_1 = 0.5$)

Figure 2.5: Variation of transmitted torque as a function of wedge angle and coefficient of friction of the locking mechanism

In **Figure** 2.5a where the coefficient of friction of the locking mechanism is 0.2, the variation of torque with the wedge angle can be observed. It can be seen that it would be advantageous to have a wedge angle (α) of 60° as the torque transmitted is higher at this value of α and is closer to the given torque requirement. However, when the coefficient of friction of the locking mechanism is higher i.e $\mu_1 = 0.5$ the case is different.

As seen in **Figure** 2.5b, for a higher coefficient of friction of the locking mechanism, the torque transmitted is nearly zero at larger wedge angles (α) i.e. for $\alpha > 40°$. Also, for $30° < \alpha < 40°$ the locking mechanism appears to go on to a self-locking mode. This means that a high force would be necessary to separate the clutch. This made it necessary to make a trade off in deciding the wedge angle. It was decided to have a wedge angle (α) of 30°. Although the torque transmitted initially will be low, eventually with the increase in friction of the locking mechanism the torque transmitted will be higher and shall reach the required level.

NOTE: The MATLAB code for one of the cases is attached in the appendix. The actual and clearer plots of the code are also available in the appendix.

2.3 Manufacturing

The bearings, springs, balls and sprockets were bought from companies, while the other parts were made at the machine shop at KTH with the help of **Thomas Östberg**. The parts that were made in the machine shop were :

- the shaft
- the conical center plate
- the clutch plates
- keys

The bearings needed for the shafts were bought from **SKF** and the planetary gear from the previous setup was used as such. Once the parts were obtained, they were all assembled and manually tested several times. Due to time constraints an integrated testing was not carried out until the race at London.

NOTE : The drawings for all the parts have been attached in the appendix.

Chapter 3

PROBLEMS AND CONCLUSIONS

The drive train was completely assembled and fit into the car a week before the race at London. Once the car arrived at the paddock in London, the drive train team did not have much to do with the drive train itself. Various systems were fixed and the engine was made to fire before the technical inspection. On the race day, **KTH Royal Institute of Technology**, in spite of completing the technical inspection did not finish the race. The car could run only one lap successfully after which the actuators failed to disengage the clutch.

While preparing for the race, the drive train team encountered some problems. These shall be outlined in this section.

3.1 Problems

- The first and foremost problem was encountered during the assembly of the drive train. Once assembled, it was seen that the drive train was pretty heavy and that it wobbled when rotated. The reason for wobbling was unclear initially, but later was attributed to improper balancing during mounting of all the parts. The weight of the drive train can be reduced either by using lighter materials or by reducing the number of bearings (there are currently 5 bearings on the shaft).

- Once the clutch was tested at the integrating stage, it worked fine for the first few runs. But after continuous usage the clutch plates stuck very hard to the center plate and had to be plied open using a crow bar. This problem was thought to be because of the excessive force exerted by the actuators i.e. the actuators exerted more force than necessary on the clutch plates, thus making the clutch plate stick to the center plate with increased adhesive friction (as it is a steel-steel contact).

- The center plate of the clutch moved a minute amount from it's original position after repeated cycles of operation. This is a major issue as it could potentially damage the spring-ball locking mechanism. A better way has to be found to lock the center plate axially to it's original position.

3.2 Conclusion

With the above mentioned problems and suggestions taken into consideration a better drive train can be produced. Also, the force estimates were not given as input to design the shaft. So, the previous inputs were taken and the same shaft was redone. However, it would be better to have the force output from the engine and the motors. With those estimates a shaft can be conventionally designed.

One of the most valuable lessons learnt from this year's race is to always carry out all the testing before going to the paddock. Especially the integrated testing. Sometimes systems might function well independently, but when combined with other systems might not function well. This was a major set-back for team ELBA. Nevertheless, the same car can be modified and made race-ready, for it has cleared the technical inspection.

Bibliography

[1] Kjell Melkersson. Övningsexempel med lösningsförslag i konstruktion fk. *Chalmers*, 2009.

[2] Rober L Mott. *Machine Elements in Mechanical Design*, chapter 22, page 855. Prentice Hall , Pearson Education South Asia Pte Ltd, 2006.

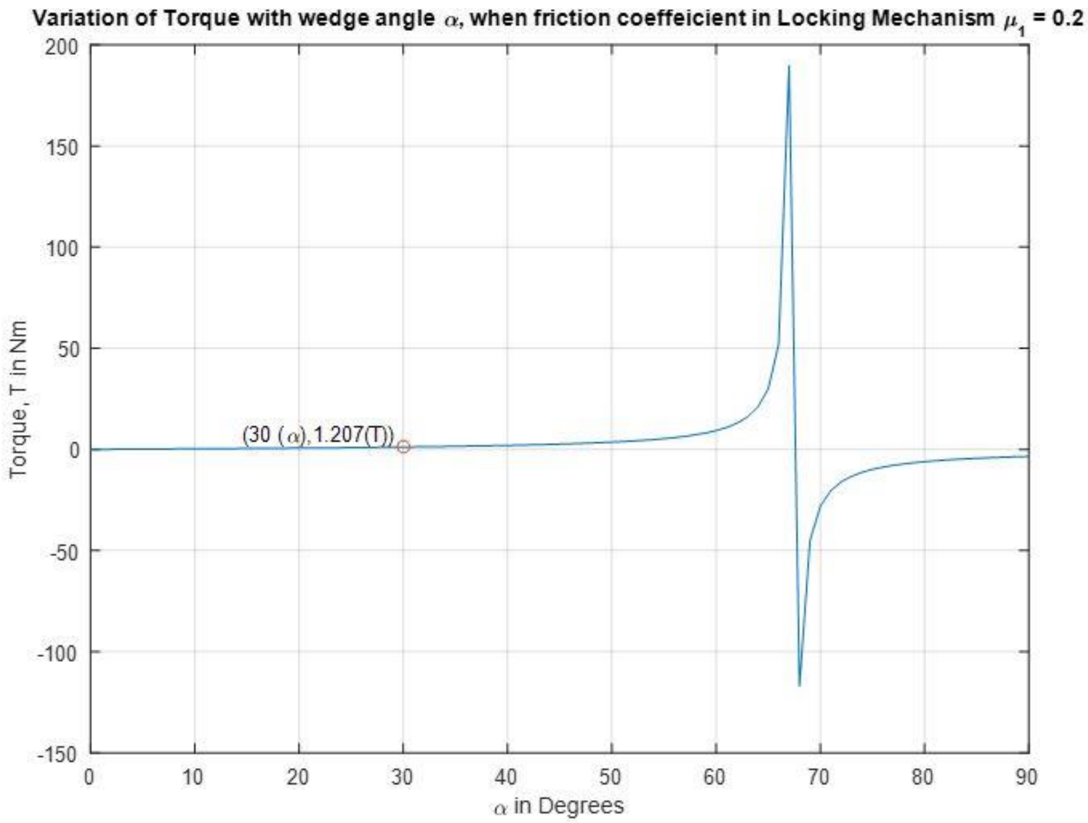
APPENDIX

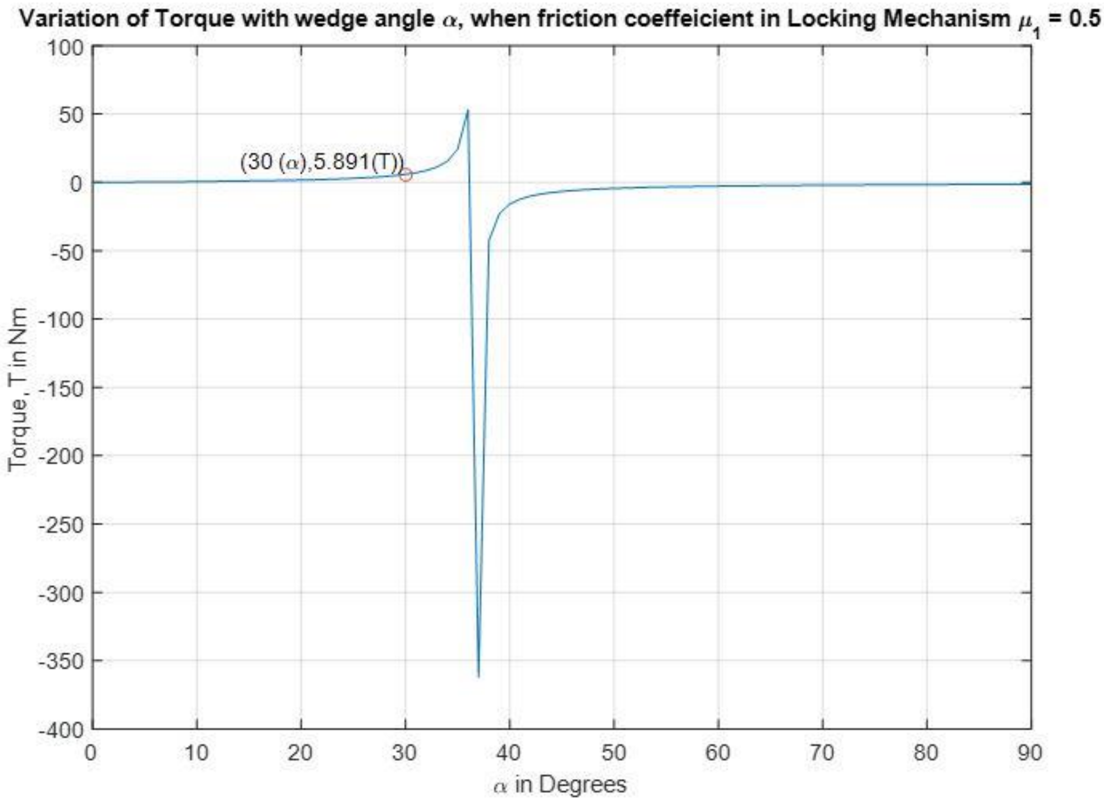
MATLAB code - Variation of Torque with wedge angle α

```
%% Introduction
%This code plots the variation of torque with the change in wedge angle

%Maadhav Padmanabhan, Daniel Hallberg , Parsa Broukhiyan
%KTH Royal Institute of Technology
%% Initialization
clc;clear all;
alpha = 0:1:90; %wedge angle in degrees
mu1 = 0.2; %friction coeff in locking mechanism
mu2 = 0.6; %friction coeff in conical clutch
Rm = 0.0955; %mean radius of the clutch
beta = 15; %angle of the clutch in degrees
P = 20; %minimum force that the spring can exert. (Data sheet - supplier)

%% computation
numerator1 = sind(alpha);
denominator1 = cosd(alpha)- (mu1*(1+sind(alpha)));
N2 = P * (numerator1./denominator1);
numerator2 = mu2 * Rm .* N2;
denominator2 = sind(beta) + (mu2*cosd(beta));
T = numerator2./denominator2;
%% plot
str31 = '(30 (\alpha),1.207(T))';
xmarker = alpha(31);
ymarker = T(31);
figure(1);
plot(alpha,T,xmarker,ymarker,'o');
grid on;
text(alpha(31),T(31),str31,'HorizontalAlignment','right','VerticalAlignment','Bottom');
xlabel('\alpha in Degrees'); ylabel('Torque, T in Nm');
title('Variation of Torque with wedge angle \alpha, when \mu_1 = 0.2');
%%mu_1 is the friction coeff of locking mechanism
```


Variation of Torque with wedge angle α, when friction coeffeicient in Locking Mechanism μ_1 = 0.2
Torque, T in Nm
α in Degrees
(30 (α),1.207(T))
200
150
100
50
0
-50
-100
-150
0
10
20
30
40
50
60
70
80
90



Variation of Torque with wedge angle α, when friction coeffeicient in Locking Mechanism μ_1 = 0.5
100
50
0
-50
-100
-150
-200
-250
-300
-350
-400
0
10
20
30
40
50
60
70
80
90
(30 (α),5.891(T))
Torque, T in Nm
α in Degrees

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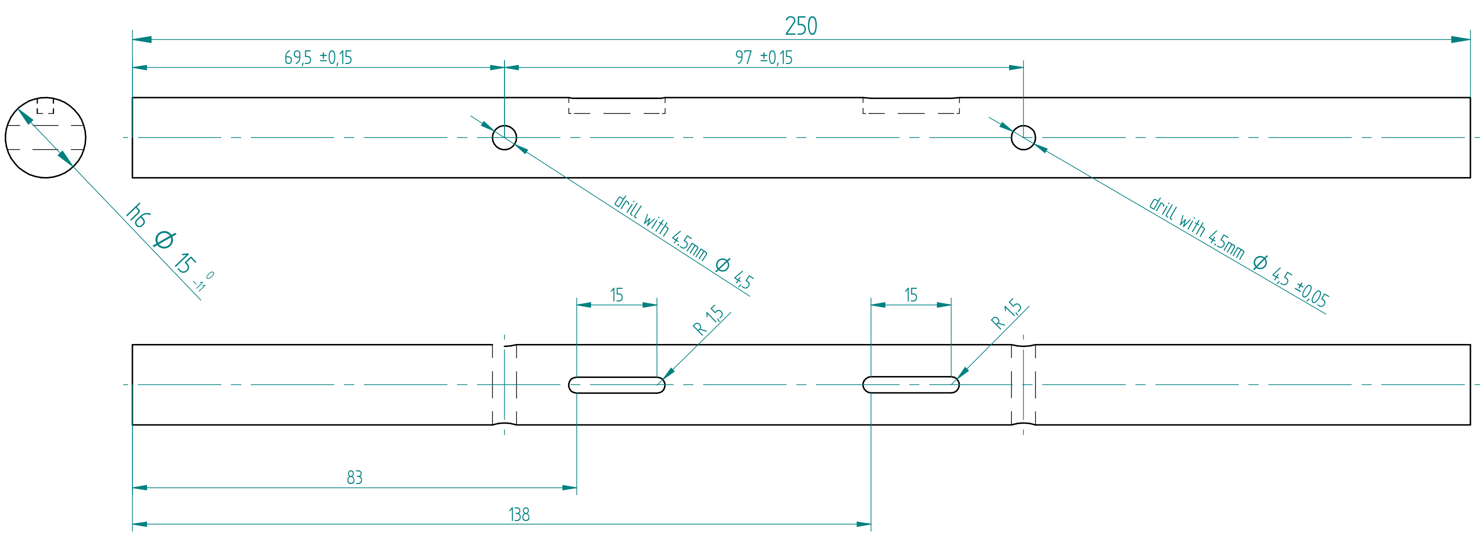

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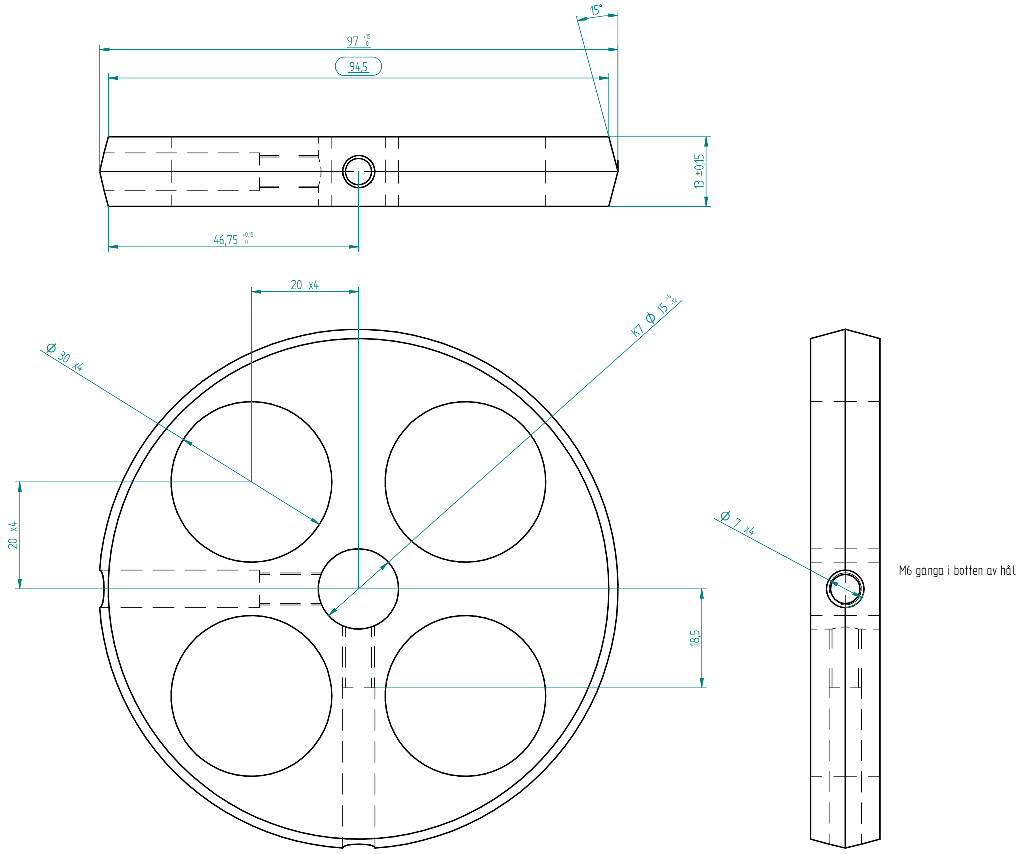

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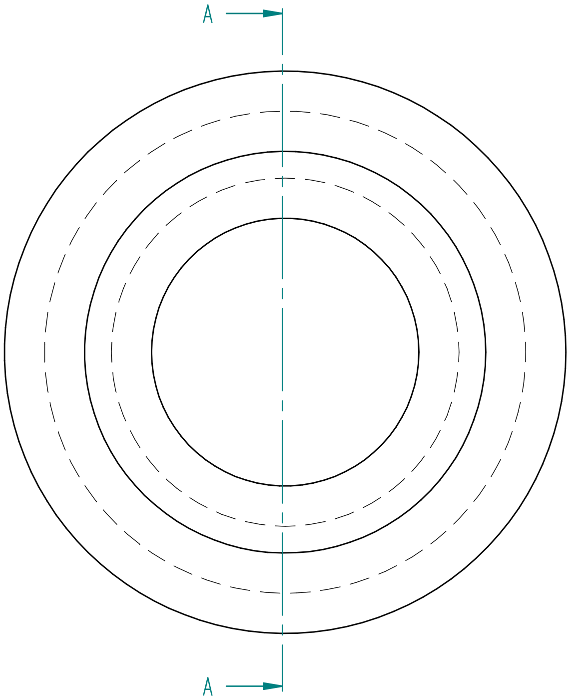

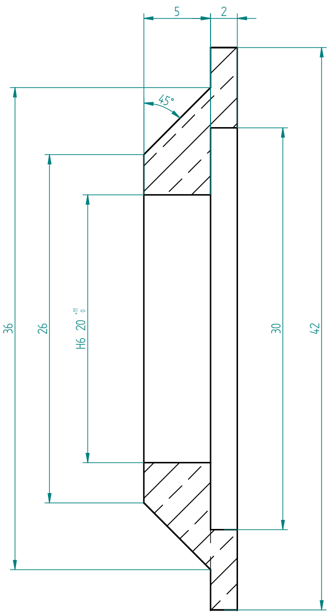

SECTION A-A

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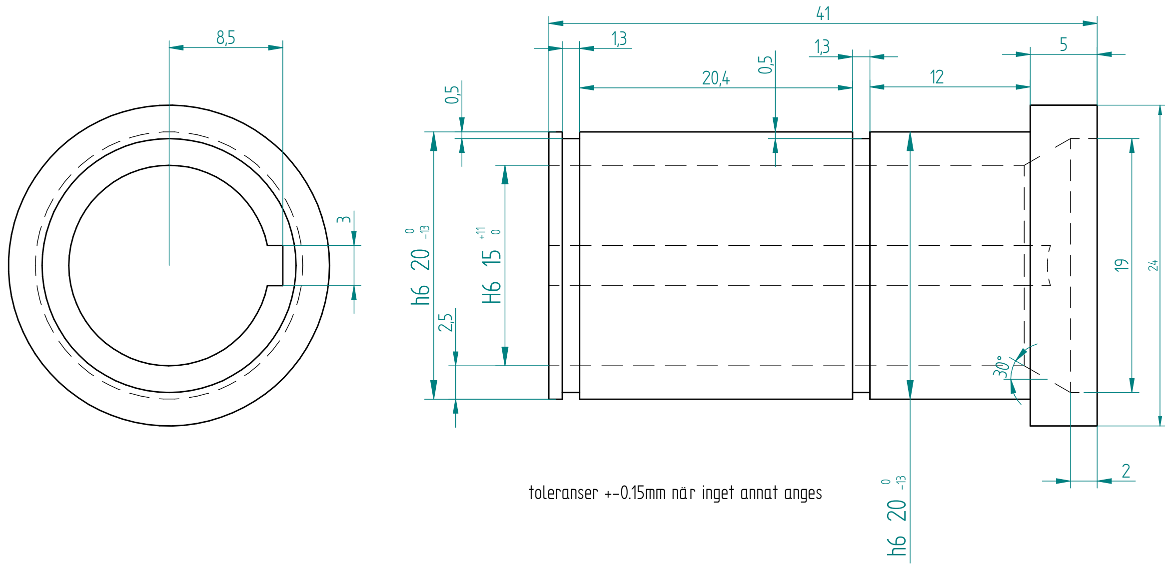

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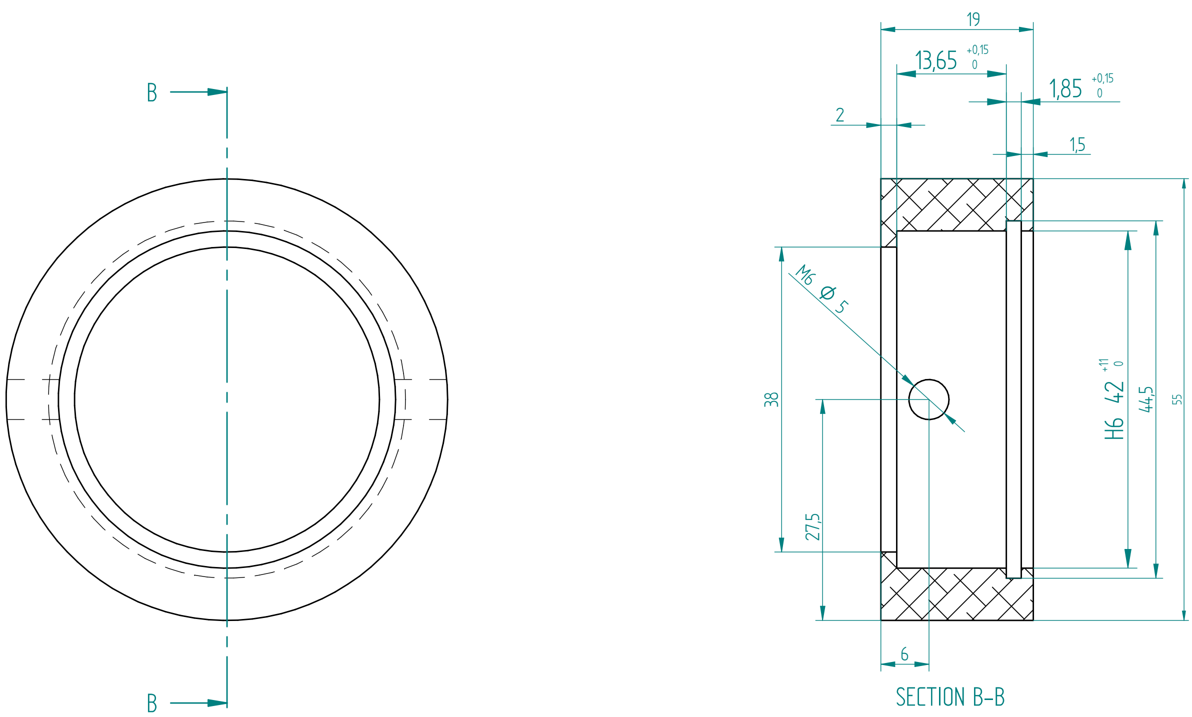

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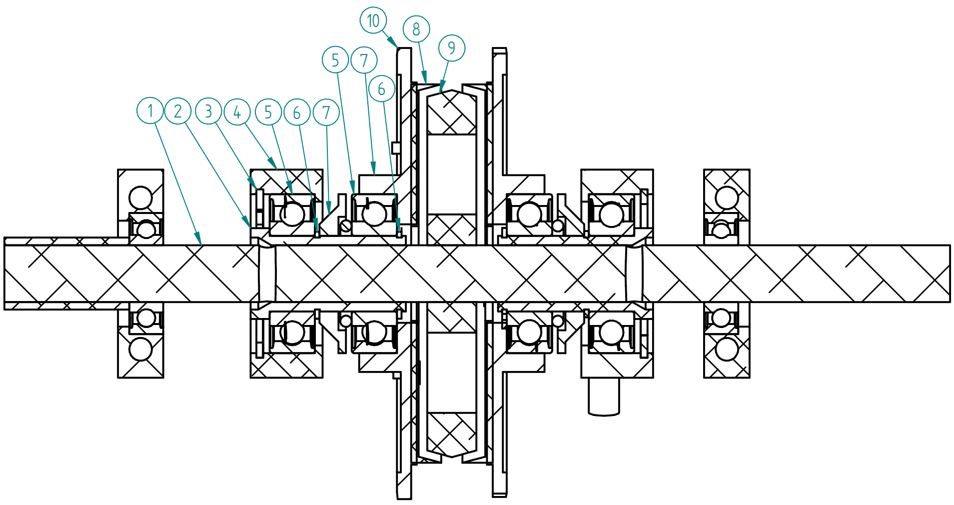

SECTION A-A

BOM	
Nr	Part
1	Shaft(Axel)
2	Socket (Hylsa)
3	Lock ring
4	Bearing seating (lagersaete)
5	Deep grove roller bearing
6	Lock ring
7	Spacer (distans)
8	Clutch outer part
9	Central disc conical
10	Sprocket

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