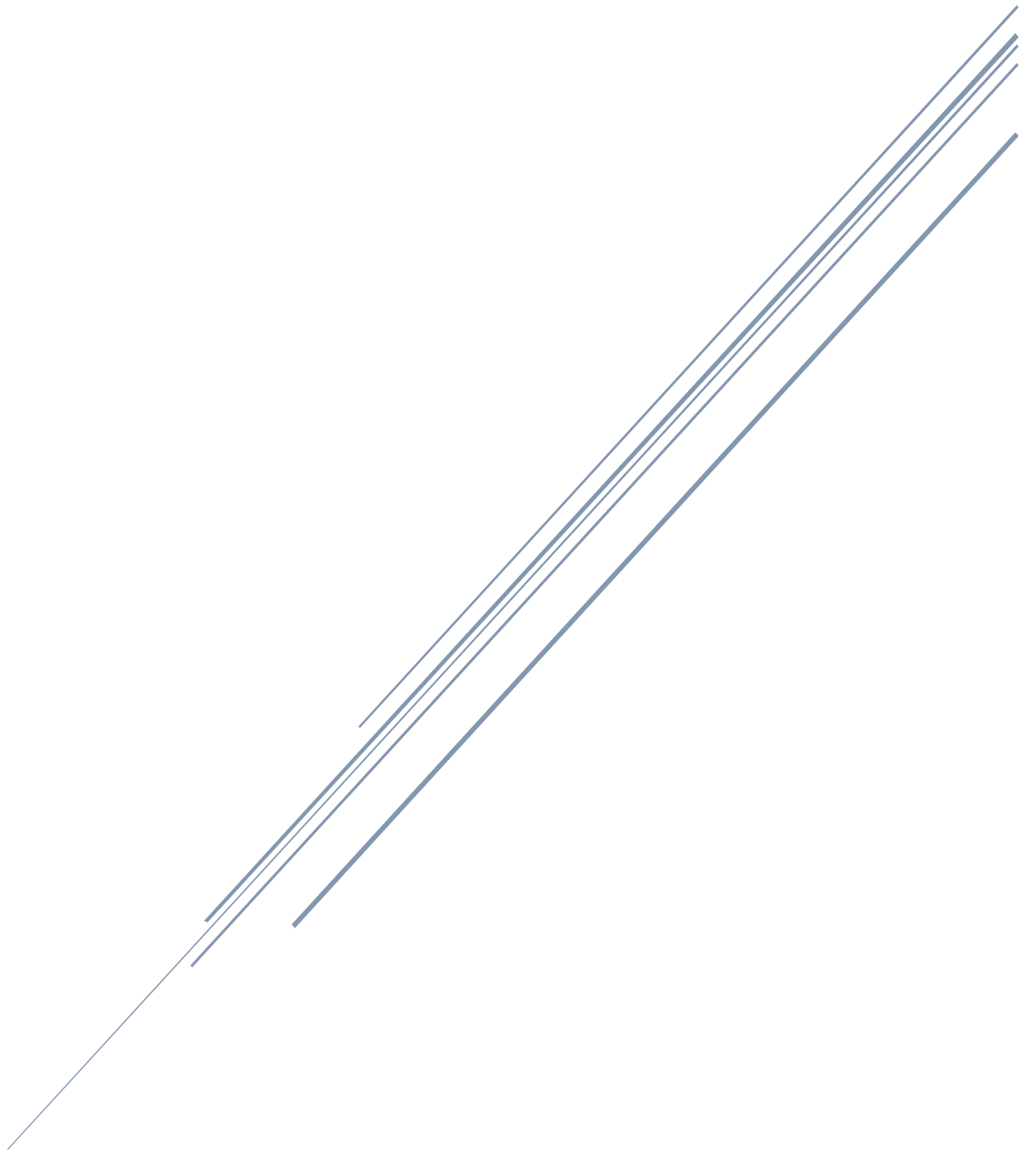


CAE & STRESS ANALYSIS

M5X02064



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1 ABSTRACT

In this report the internals of a gearbox were assembled, and a gearbox housing was designed. Research was carried out on features used and calculations done to determine the correct distance of the gear to get the gears to mesh correctly and the uses of equations in Solidworks to allow for future design revisions. The assembly was simulated in a motion study to determine if there were any mating relationships that were over constraining the assembly. Forces such as motor force and friction were added to gain a better understand of the behaviour of the gearbox. The motion study calculated that there were redundant mates which needed to be eliminated. This was an indication that the gearbox could be over constrained, and revision needed to be made so the simulation could be carried out correctly and the data collect was as accurate as possible. After the revisions were made the final redundancy amount was one. Data analysed showed that there was an increase in angular velocity of the output shaft from 1st to 2nd gear, which is exactly as a gearbox behaves. With the minimal redundant mates and data showing the same behavioural characteristic of a gearbox it is concluded that there are no mates over constraining the assembly and stopping it moving as it should.

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3 INTRODUCTION

The purpose of this report is to give a level of understanding of the use of Computer Aided Design (CAD) and features such as 3D modelling, motion simulation and Finite Element Analysis (FEA). CAD features and calculations will be used to build and simulate motion of a motorbike gearbox with an emphasis of reducing redundant mates, so the gearbox can be as little constrained as possible. Data of velocity and acceleration will be plotted on graphs to see if the behaviour of the gearbox is as expected.

3.1 TABLE OF ACRONYMS

CAD – Computer Aided Design

FEA – Finite Element Analysis

FEM – Finite Element Method

HCI – Human-computer interaction

3D – 3 dimensional

2D – 2 dimensional

PDE – Partial differential equation

Deg/s – Degrees of angular velocity per second

4 HISTORY

4.1 COMPUTER AIDED DESIGN MODELLING

The history of CAD can be dated back to the 1960 where Ivan Sutherland as part of his PhD thesis created Sketchpad (Massachusetts Institute of Technology, 2018). The program which he created pioneered human-computer interaction (HCI), it was done by using the TX-2 computer, lightpen and keyboard (Reilly, 2003). Sutherland used the lightpen to draw lines of objects which would be displayed on the TX-2, the objects drawn were limited to 2D models. Before this point objects were modelled using command-based programs which limited the user (Reilly, 2003).

From this point on as computers processing power advanced so did the CAD programs and the ability to model 3D objects and assemblies. However, it was not until 1989 when seven students from STANKIN Technological University, Moscow created CAD software TopCAD which allowed parameters to be set when designing models (Top Systems, 2019).

The 90's is where CAD really become part of mechanical engineering. Companies such as Solidworks, Autodesk and Siemens all released 3D modelling software packages with a focus on the end user (Caudill, 2019). These packages allowed for complex assemblies to be created and engineering drawings to be made.

4.2 FINITE ELEMENT ANALYSIS & MOTION ANALYSIS

FEA can be traced back to the 1970's where engineers craved a way of calculating mechanical properties of designs quickly. FEA was originally calculated by using partial differential equations (PDE) (Suli, 2019) and would be a long and hard task to complete. In the mid 1970's there was a need for safety testing in the automotive industry. This forced the engineers of the time to have more extensive test-

ing on products to satisfy the customers safety needs. With the growing demand in such testing companies devoted large amounts of resources into the research and development of products (Bjarnemo, et al., 1993). FEA become a vital part of product design form this time onwards and with the growing 3D modelling become an integrated part of the design phase. Now FEA can be defined as a *“computerised method for predicting how a product reacts to real-world forces, vibration, heat, fluid flow and other physical effects.”* (Autodesk, 2019). FEA calculates if the product will fail if so where and why. It is done by putting the part or assembly into a real-world situation such as a motion analysis or adding forces to a part. Each part is broken down into a vast number of finite elements or small shapes. Then a mathematical equation will calculate the performance of each shape, then calculates them all together. This will then show the overall performance of the part (Chang, 2009).

Adjustments can then be made at the design phase if there any imperfection or design flaws before a physical part has been made. FEA helps determine the behaviour of physical elements such as mechanical, stress, vibration, fatigue, motion, heat transfer and fluid flow (Autodesk, 2019). The advantage of this is shorter lead times, efficiencies in product development process, improved product performance as well as an overall higher quality product (Bjarnemo, et al., 1993). The outcome of all these improvements is a reduction in overall costs of the design phase by reducing the number of prototypes needed and giving the customer a quality product. While FEA and motion are a critical part of the design phase. Physical testing of prototypes will always be carried out to ensure that the part behaves as intended and if design flaws have not been accounted for in the simulation.

With the growing demand for additive manufacturing there is now a change coming in 3D modelling software (Gibson, et al., 2015). Parts can be made by adding material instead of subtracting therefore the part must designed with that in mind. Topology optimisation is now becoming a very important part of 3D modelling and simulation (Chang, 2015). It allows bodies to be designed then put into a simulation environment where forces and other variables will be added. Once the simulation has been calculated the topology algorithm will subtract the unnecessary material. It allows for maximum

strength with minimum material, this is extensively used in Formula one and the aerospace industry where the smallest weight saving gives a massive advantage (Zhu, et al., 2015).

Car manufactures such as Ford are using FEA, motion analysis complied with topology optimisation to try and make vehicles as lightweight as possible without comprising on safety (Hopf, 2019). Having a vehicle which has been optimised by FEA and topology will have greater fuel efficiency and have a far more favourable power to weight ratio that a car made from traditional design. Commonly topology, FEA and simulation is used throughout the chassis design but now it is becoming seen far more in interiors of vehicles to further save weight and possibly make the vehicle safer (Yang & Chahande, 1995).

5 DESIGN & ASSEMBLY

In this section features that were used to mate the components into an assembly and features used to create the gearbox housing will be listed with an explanation and justified.

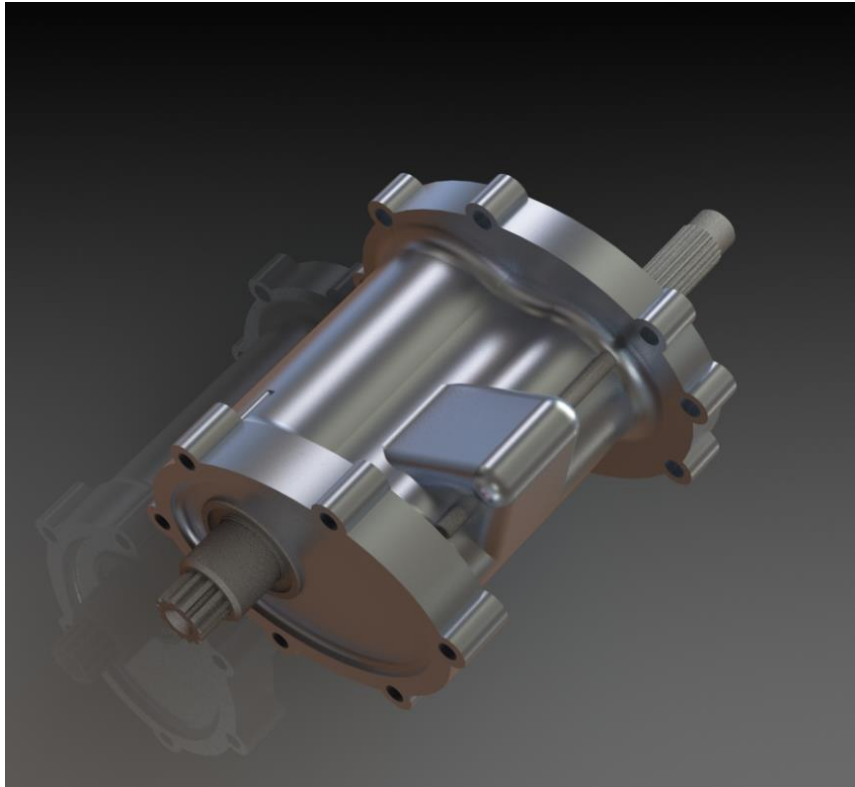


Figure 1 Gearbox Rendering

5.1 MODELLING

To make the modelling of the gearbox quicker, it was drawn within the assembly of the gears so critical features would be to the required dimensions. Features were hidden using the visibility features which suppresses unnecessary parts. Once the gearbox was built the transparency was changed to ensure that all parts fitted correctly.

5.1.1 Design Features

Fillet – Allows for radius to be put on edges which can be internal or external. Fillet have been used on some external edges for aesthetics.

Extrude – Transforms 2D sketches into 3D models, this was used throughout the design. The body of the gearbox was sketched around the gears and extruded the length of the shafts. Once a hollow body was created faces were created on each end. The shell feature could have been used but due to each face being different dimensions it would have taken more time to use the feature.

Extrude cut – Is the opposite to extrude, it allows material of the part to be taken away. This was used on all the holes and end faces so it can be offset from the original face.

Split – The split feature was used to cut a part into as many single parts as possible, this saves times designing two separate parts which will be mated together. Split was used on the end face to expose the internals of the gearbox and would be fixed but bolts going through the holes.

Thread – The thread tool allows to put either extruded or extrude cut threads on holes or shafts. This was used on the holes of the bell face so that it can be fastened when fitted.

5.2 ASSEMBLY MATES

Concentric mate – Is a mate that uses the concentric centre points of two parts to form a relationship. This mate was used to mate the gears and bearing to the corresponding shafts. This feature was used throughout the assembly at the start due to firstly all parts being concentric and the mating parameters being very simple.

Coincidental mate – This is a mate that mates two parallel planes of a part and make the parts coincide with each other. It can be physical surfaces or planes of the part that can be mated. This was used multiple times throughout the assembly to set distances of the gears from fixed surfaces on the shaft. It was also used to mate the bearings to the gearbox housing.

Hinge mate – A hinge mate is a mechanical mate, which uses two mates to make a single mate. A hinge needs a concentric and coincidental mate. This will reduce the number of mates by combining the two. A hinge mate was used when parts need both a concentric and coincidental this allowed to reduce the number of redundant mates in the simulation phase.

Limit and fixed distance – A limit distance mate is the amount of movement of a part has with reference to another part.; it can be set from faces or planes. A minimum and maximum limit must be defined to allow the movement. In the gearbox the primary combined gear has limits, so it will not go past the gears. A fixed distance is a set distance of apart from another part, commonly from either surface of planes. Fixed distances are usually associated with coincidental and concentric mates this was used to set the distance between the shafts before the gearbox was designed.

Rigid group – This feature allows the grouping of multiple objects and fixes them as a single piece. This allows the reduction of redundant mates within a motion study.

Global Variables - Global variables are a numerical value that is set, so dimensions can be set based upon that value (SolidWorks, 2019). For instance, the radius of outside dimension of the primary bearing was set as a global variable. When designing the gearbox housing the dimension of the bore to fit the bearing was set to the value of the global variable. If in the future the dimension was changed on the bearing, then the gearbox housing will change accordingly. The equation for the bearing was diameter = $2r$, this can be seen in Figure 2.

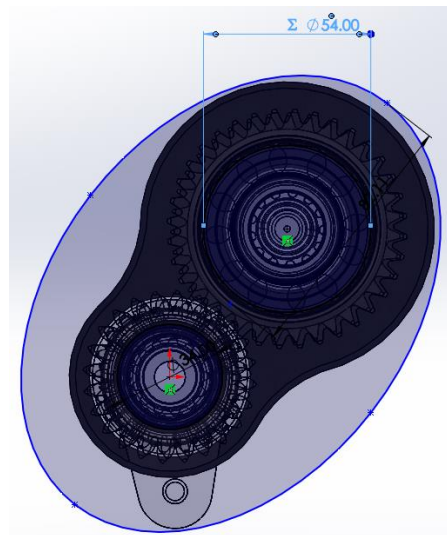


Figure 2 Global Variable Equation

The exported equation sheet can be seen in Appendix 1.

5.2.1 Gear Meshing Equation

To calculate the correct distance that the centres of the shaft needed to be for the gears to meshed correctly dimensions of the gears needed to be found. This was carried out in the evaluate function in Solidworks which allows the measurements of parts. (KHK, 2019)

$$\text{Pitch } \emptyset = \frac{\text{Number of teeth} \times \text{Outside } \emptyset}{\text{Number of teeth} + 2}$$

$$\text{Primary 1st} = \frac{23 \times 52.5}{23 + 2} = 48.30$$

$$\text{Primary 2nd} = \frac{24 \times 56}{24 + 2} = 51.69$$

$$\text{Output 1st} = \frac{36 \times 77.4}{36 + 2} = 73.33$$

$$\text{Output 2nd} = \frac{35 \times 75}{35 + 2} = 70.95$$

Mean of distances

$$\text{Distance} = \frac{48.30 + 73.33}{2} = 60.82$$

$$\text{Distance} = \frac{51.69 + 70.95}{2} = 61.32$$

The distance used for the centre of the shafts, so the gears will mesh correctly:

$$\text{Distance of gears} = \frac{60.82 + 61.32}{2} = 61.07\text{mm}$$

6 MOTION STUDY IN SOLIDWORKS

A motion study is a mechanical simulation of what would happen to the assembly if put under certain criteria such as forces. It allows contacts of components to calculate what would be the outcome of motion. Data can be extracted from the analysis and used to make the assembly more efficient.

A motion study also indicates if there are redundant mates which could be restricting or over-constraining the motion of the assembly (SolidWorks, 2019). When the motion study is calculated it will display all the redundant mates that can be eliminated from the study. If mates are removed from the motion study, they will not be removed from the assembly.

To remove the redundant mates the degrees of freedom are defined and then can be replaced with more efficient mates (Chang, 2009). Degrees of freedom is the amount of freedom an unconstrained rigid body has in space (Solidworks, 2016). A body can move on six axes, three translational and three rotational. A body can move along the x, y and z and equally rotate around those axes. By adding mates within the assembly, you restrict the degrees of freedom that the body can move (Solidworks, 2016).

6.1 MOTION STUDY OF GEARBOX

To simulate a gearbox running and changing gear forces and contacts needed to be added so the gearbox would behave as expected. Firstly, solid body contacts were applied to 1st and 2nd gear on both shafts so that they will mesh together as physical bodies. Secondly, the combined gear was made a solid body contact with 1st and 2nd gear on the primary shaft give the gears drive. The contact bodies material was set as greasy steel so that the gears and selector would slip into position far easier and would simulate more of a real-life situation.

A rotary motor force was added to the primary shaft to simulate drive from an engine, an opposing torque was added to the output shaft to simulate friction. Then two opposite forces were added to the gear selector but were offset so the combined gear would select 1st gear then after 2.8 seconds would select 2nd.

Once the gearbox was assembled the first motion study was carried out. As seen in **Error! Reference s**

ource not found. it calculated a total of ten redundant mates. This

is a reasonably low number considering all the possible degrees

of freedom that each body has in the assembly. This is mainly due

to the use of hinge mates within the assembly and fixing some

components as a rigid body as seen **Error! Reference source not found.** before the motion study was

calculated. Many of the redundant mates of the gearbox were the

mates that was used in fixing the initial shafts in place so that the

gearbox could be designed around the gears. Once the position

mates were removed the second simulation calculated that there

were eight redundant mates seen in Figure 3**Error! Reference source not found.**.

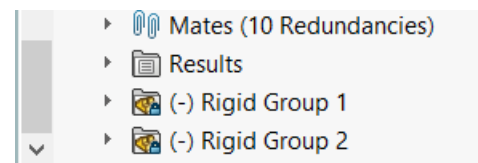


Figure 4 First Simulation

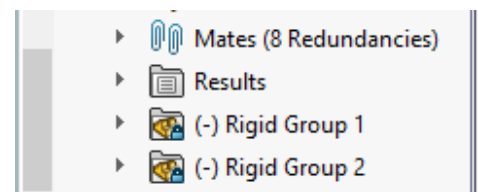


Figure 3 Second Simulation

Redundant Mates Removed:

- Distance limit between shafts
- Distance and concentric mate of primary shaft to housing replaced with hinge
- Distance limit of primary combined gear
- Coincidental mate of housing by grounding body

Degrees of Freedom	
Gruebler Count (approximate DOF):	
10 moving parts	60 DOF
9 revolute joint(s)	-45 DOF
1 cylindrical joint(s)	-4 DOF
1 planar joint(s)	-3 DOF
1 rotational motion(s)	-1 DOF

Total (estimated) DOF = 7	
Total (actual) DOF = 8	
Total number of redundant constraints = 1	
The following redundant joint constraints will be removed:	
Concentric11, Rotation about X	

Figure 5 Final Simulation

After revisions of mates and removal of more redundant mates. The outcome was one redundant mate shown in Figure 5, which indicates that there is a redundant rotational mate around the x axis of the selector shaft. This was removed to gain a better understanding of the mate, the results was the combined gear not behaving correctly. This shows

that while this mate is redundant to the selector shaft it has a relationship to the combined gear, to eliminate the mates of the combined would have to be investigated. Due to the combined gear working as intended one redundant mates is acceptable amount to show that there is very little redundant mates restricting or over constraining the motion study.

6.2 RESULTS

To prove that the redundant mate has very little effect on the workings of the gearbox, the angular velocity against time of the output shaft can be analysed Figure 6. The initial < 0.25 s of the graph is where the force added to act as friction on the output shaft has been applied before the combined gear as engaged with first gear. Once first gears are engaged the angular velocity is at an approximately 400 deg/s. Then at 2.75s, second gear is engaged and there is a slight increase in angular velocity to approximately 420 deg/s. This indicates that the

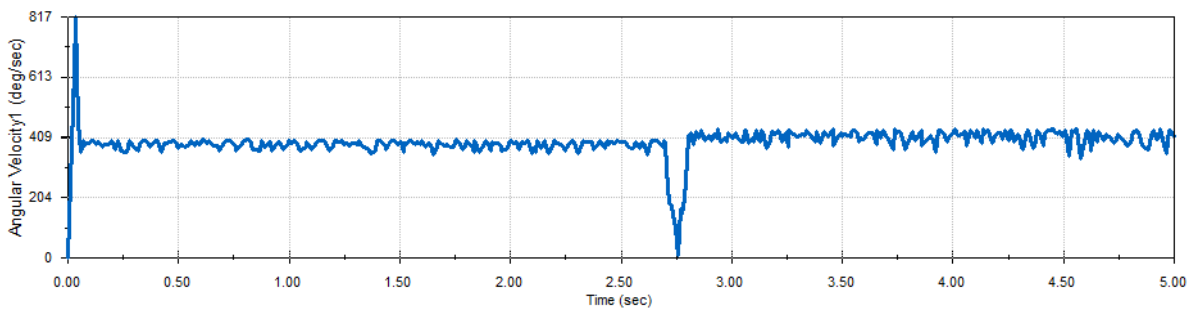


Figure 6 Output Shaft Angular Velocity

gearbox is working as expected.

Other data collected from the motion study is the angular acceleration against time of the output shaft. In Figure 7, there is an anomaly at the start which also could be caused by the opposing force of the output increasing the velocity. By having this figure, it shows the rest of the graph to be almost flat this is due to the units of the y axis being so large.

If the first 0.5 seconds of the motion study are removed and then plotted as Figure 8. It is clear to see there is variation in the acceleration of the shaft, where the highest peak occurs is when the change in gear occurs and the frictional force accelerates the output shaft.

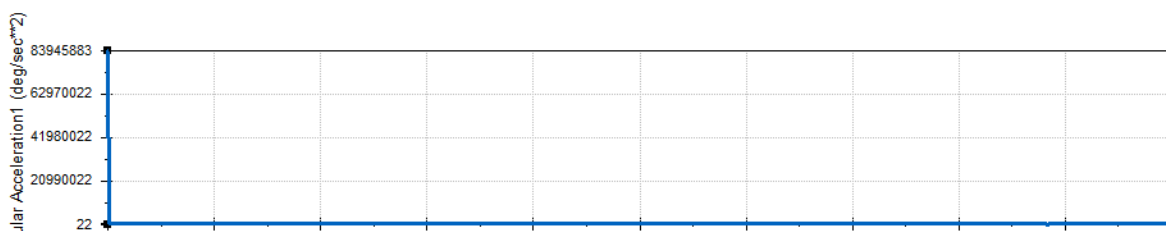


Figure 7 Output Shaft Acceleration

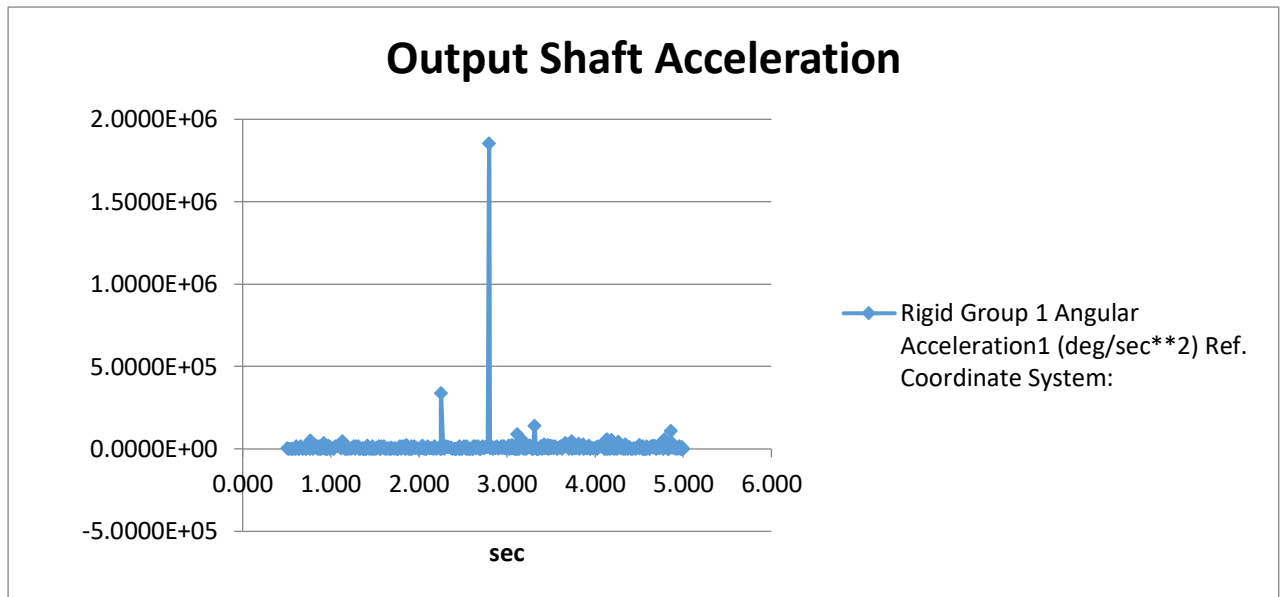


Figure 8 Recalculated Output Acceleration

7 CONCLUSION

After analysing the graphs of acceleration and velocity the gearbox behaves just as expected. There is a slight increase of velocity in the output shaft from 1st to 2nd gear. However, there were some anomalies in the acceleration graph of the output shaft at approximately 2.3 seconds. To gain further understanding of this anomaly this could be cross referenced against the displacement direction to understand which direction it was turning and determine what the cause was.

The mating of the gears is where the most efficiencies were made in this assembly. This was due to the use of hinge mates, and grounding components. When the assembly was first simulated in the motion study it had very few redundant mates, which some of were from initially setting distances of the shafts and planes when first assembling. This allowed for a further reduction in mates which finally led to one redundant mate.

With regards to the design of the gearbox housing, after completing this design there are many revisions to design method which could have been used. For instance, instead of individually drawing each mounting hole on the faces a pattern could have been used which would have reduced time. With more time and a now better understanding of redundancies the possibility of no redundant mates is easily feasible if a gearbox housing was designed with this in mind.

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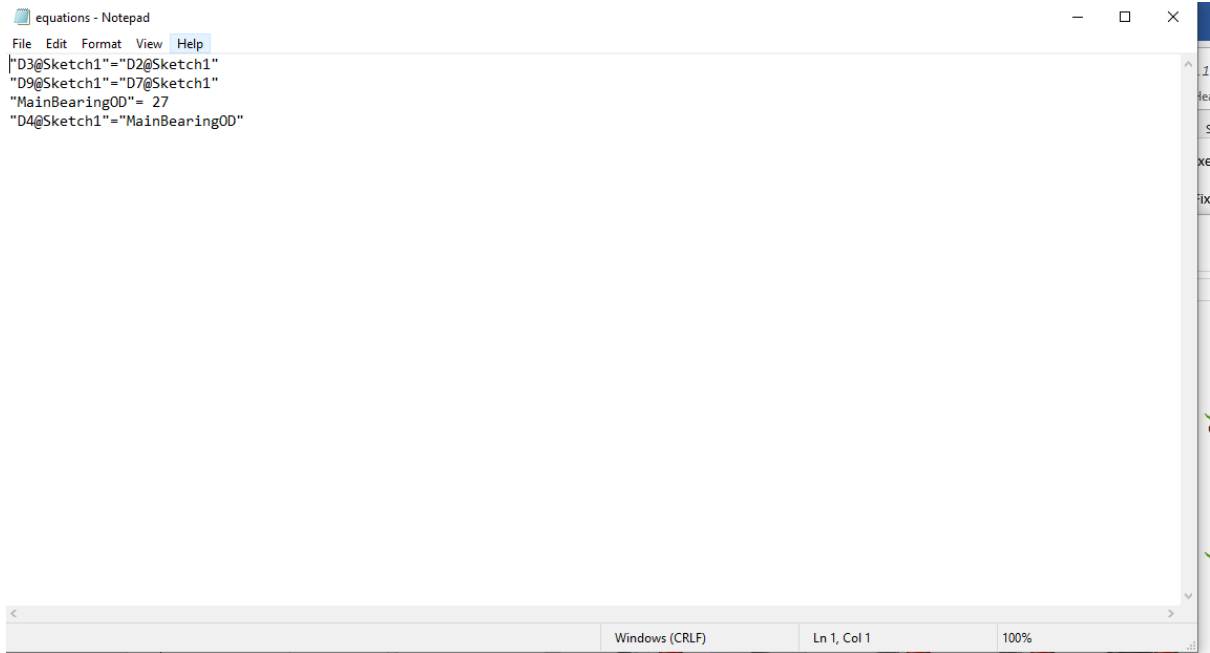
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10 APPENDIX



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equations - Notepad
File Edit Format View Help
"D3@Sketch1"="D2@Sketch1"
"D9@Sketch1"="D7@Sketch1"
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Appendix 1 Equation for Global Variables

CAD files can be found at:

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