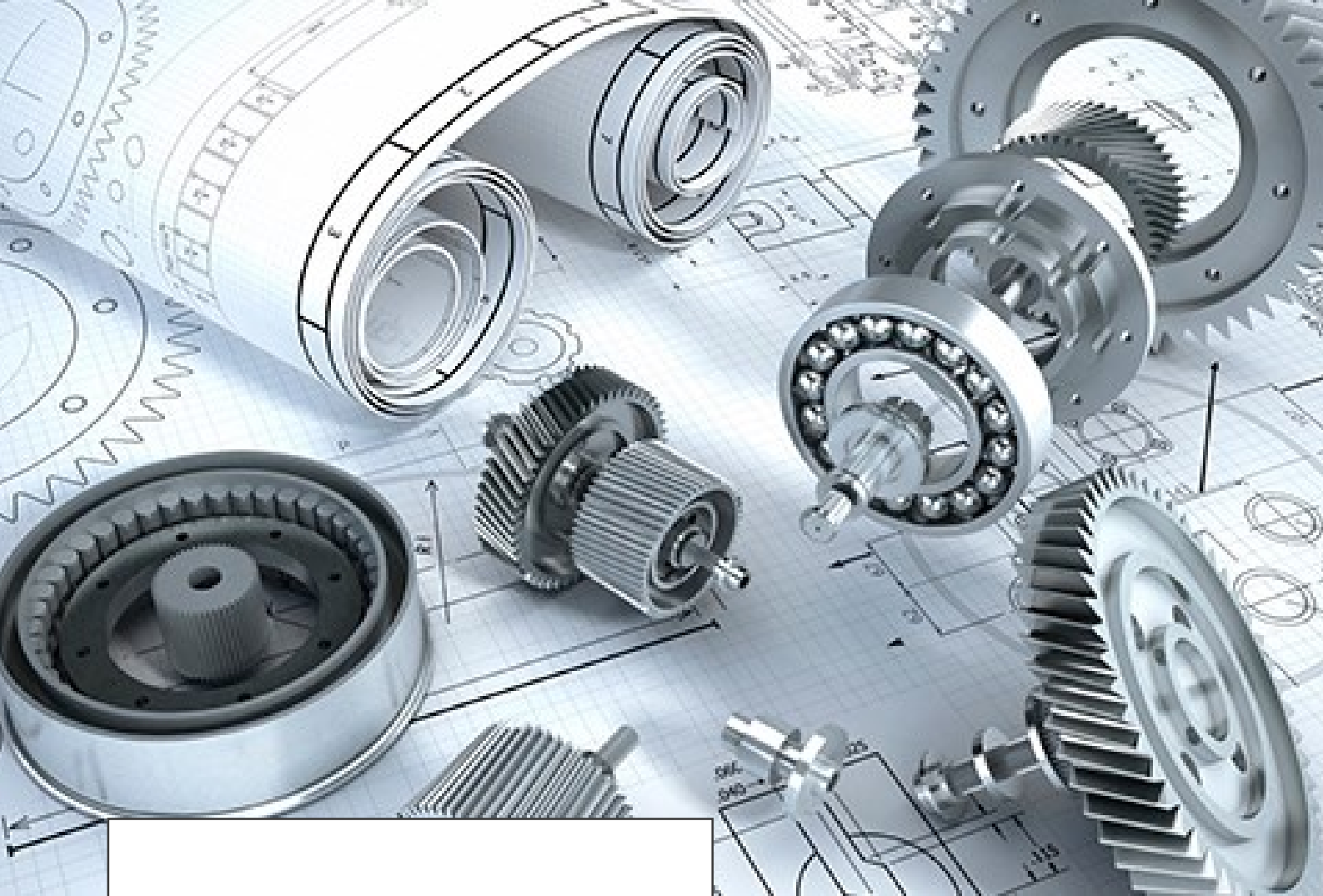




Motion Simulation of a Gearbox

CAE & Stress Analysis
(M5X02064)

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2. Abstract

This is a report on a simple gearbox, working with the already modelled gears the designer has assembled them and designed a gearbox housing in which to contain them. Consideration has been made with regards to the manufacturability of the components, with attention to how the models have been created and the data managed. Upon completion of the design of the gearbox housing, a series of simulations were created and the results thereof analysed. Comparison has been made between the original standard design for manufacturing process, and how tools such as motion simulation and FEA have been used to improve the entire process for the better.

An introduction to FEA has been investigated, in an attempt to understand what this process is and why it is so important to stress analysis for many engineering based industries, from aerospace to automotive and civil engineering.

3. Introduction

This is a study on FEA (Finite Element Analysis), and the use of SolidWorks for design and motion simulation of a gearbox housing. There is much information regarding FEA and how it has evolved from the 1940's to what it is today (Logan, 2012), and how it is used in industry. FEA and motion simulation has greatly impacted the way we design and produce products today, Chang (Chang, 2008) and Kurowski (Kurowski, 2018) discuss how it has impacted industry, although Kurowski looks at the computer simulation side whereas Chang reviews the larger picture of design through to manufacture.

General design standards may vary between organisations, although all have a common goal which is to standardise throughout the organisation, in order to maintain a working common standard. Mario et al (Mario, et al., 2013) has a broad range of information on computer aided design and how it can be standardised to manage the files and data.

4. FEA (Finite Element Analysis)

FEA is widely used in a wide range of engineering industries, it is an integral part of being able to create products that meet safety requirements and structural integrity (Ragab & Fayed, 2018) (Koutromanos, et al., 2018). FEA is a method of calculating the stresses and strains on any given product, using several techniques that can include the use of matrices (Ragab & Fayed, 2018) (Logan, 2012) (Barbero, 2014).

In the 1940s, structural engineers Hrennikoff (Hrennikoff, 1941) and McHenry (McHenry, 1943) are said to be the originators of modern FEA, with their work on stresses within solids consisting of one dimensional beams and bars (Logan, 2012). This was then built upon by other engineers throughout modern history, (Logan, 2012) speaks of others who developed more complex methods such as Levy who contributed greatly to modern FEA through his work on interpolation and later his method of displacement and stiffness. These methods were time consuming to calculate and therefore Levy's work did not gain much traction until the popularity of computers (Logan, 2012). In 1976, Belytchko (Belytschko, 1976) improved the techniques of calculation for FEA through his methods of advanced numerical methodologies (Logan, 2012).

FEA begins through a process of creating a finite element mesh that will be unique to any given product (Logan, 2012). This mesh can consist of a series of simple two-node line elements, two dimensional triangulars and quadrilaterals, but most often by a series of three dimensional segments such as tetrahedrals and hexahedrals or cubes (Logan, 2012) (Koutromanos, et al., 2018). Given the cubes, each one will be applicable to certain stresses, by calculating the stresses on each individual cube, it is possible to build a picture of what areas are under greater stresses than others. It is possible to pinpoint the highly stressed areas and modify the design accordingly, by increasing material thickness or through the addition of features such as ribs or larger radii.

The greater the mesh segments, the more accurate the overall analysis, as there will be more data points to analyse. It is important to understand however that the greater the number of

mesh segments, the larger the number of calculations required (Comsol, 2017), ultimately increasing calculation time. Factors must be considered in order to determine the optimum accuracy of the mesh (Comsol, 2017), as in industry there are deadlines to meet, and therefore it is not possible to spend a long and sometimes unnecessary period of time analysing something that does not require as long a calculation period. There is no definitive calculation for this however the process is known as 'The Mesh Refinement Process' (Comsol, 2017), it is down to the skill and experience of the people involved in the analysis.

When the mesh has been defined with regards to size and shape, the criteria can then be set for the calculations, this is in the form of defining the strain/stress & strain/displacement (Logan, 2012). These are significant relationships as to derive a formula for each given finite element, e.g. given direction (x), strain (ϵ) and related to displacement (u) can be expressed as

$$\epsilon_x = \frac{du}{dx}$$

Furthermore, all stresses have a relationship to the strain according to the stress/strain law known as constitutive law. It is important to define the behaviour of the material, this can be done using Hooks law as is common for stress analysis. Given stress in the direction of x (σ_x) and Young's modulus of elasticity (E), this is expressed as

$$\sigma_x = E\epsilon_x$$

The next step is to derive the element stiffness matrix & equation (Logan, 2012) (Ragab & Fayed, 2018).

FEA is carried out on many different materials, one of the most complicated being that of composite consisting of ply skins and honeycomb core for example (Barbero, 2014) (Barbero, 2013). Composite structures are used widely within the aerospace industry, and analysis of a considerable sized structure can take up to days to calculate. As discussed by Barbero (Barbero, 2014), the general methodology for using FAE for composite materials is very similar to that of traditional solids such as steel, although there are additional factors to consider due to the fact

that the core is often of a different material, thickness and grain direction. FEA is not used only for static objects, it is also used for dynamic structures such as to analyse how car bodies crumple during impact (Zienkiewicz, 2014) and is used in fluid dynamics (Reddy, 2015).

5. Motion Simulation

Motion simulation is a CAE tool (SolidWorks, 2008) that is used to solve a motion study by using geometric interpolation, this means that the software is looking at different points in a simulation and interpolating them linearly in order to calculate an outcome (Solidsolutions, 2019). A benefit of using motion simulation is that a product may be simulated to prove it works without the need to build a physical product (Chang, 2008). CAE has been available since 1980 in the form of FEA that was used to aid with the development of products (Solidsolutions, 2019). Motion simulation is very widely used today (SolidWorks, 2008), this could arguably be because of the ever increasing complexity of products.

Motion simulation has provided a new production process, the motion simulation driven process is to create the models in CAD, motion simulate, modify in CAD and repeat, then go through prototyping and testing to production with a good product. Whereas the traditional process is to design in CAD, prototype and test, then production, of course the negative of the traditional process is that the product may not operate as expected and then the whole process is repeated (Kurowski, 2018).

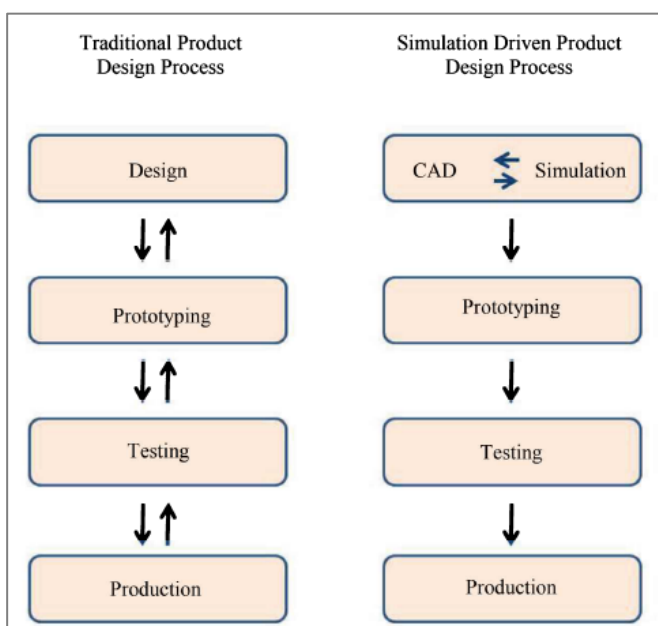


Figure 1 Traditional and CAE design to manufacture processes

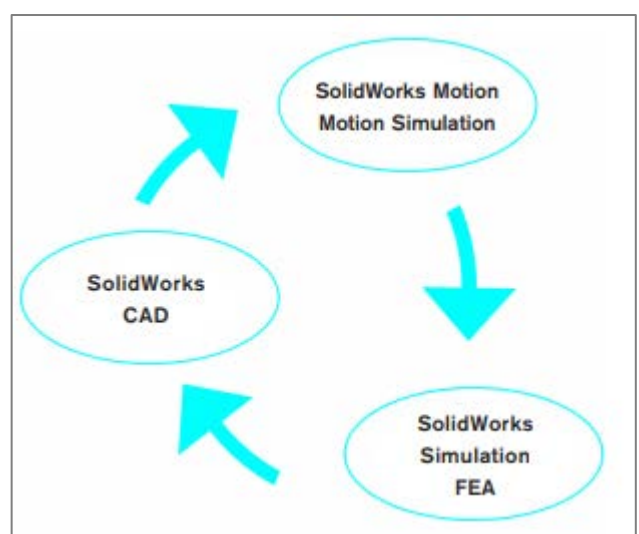


Figure 2 CAE design process

The SolidWorks guide (SolidWorks, 2008) looks closer of the design part of the process, showing in the image how there is a continuous cycle between the CAD design, motion simulation and then FEA simulation. This shows how both tools can be used to create a good product that could potentially be produced right first time.

6. Gearbox Housing Design

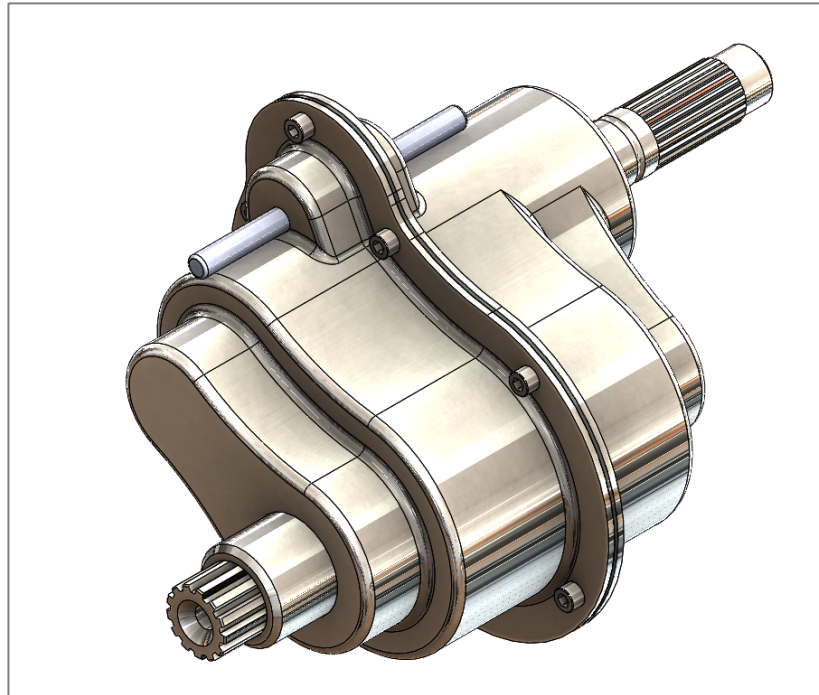


Figure 3 Complete gearbox (Kilbane, 2019)

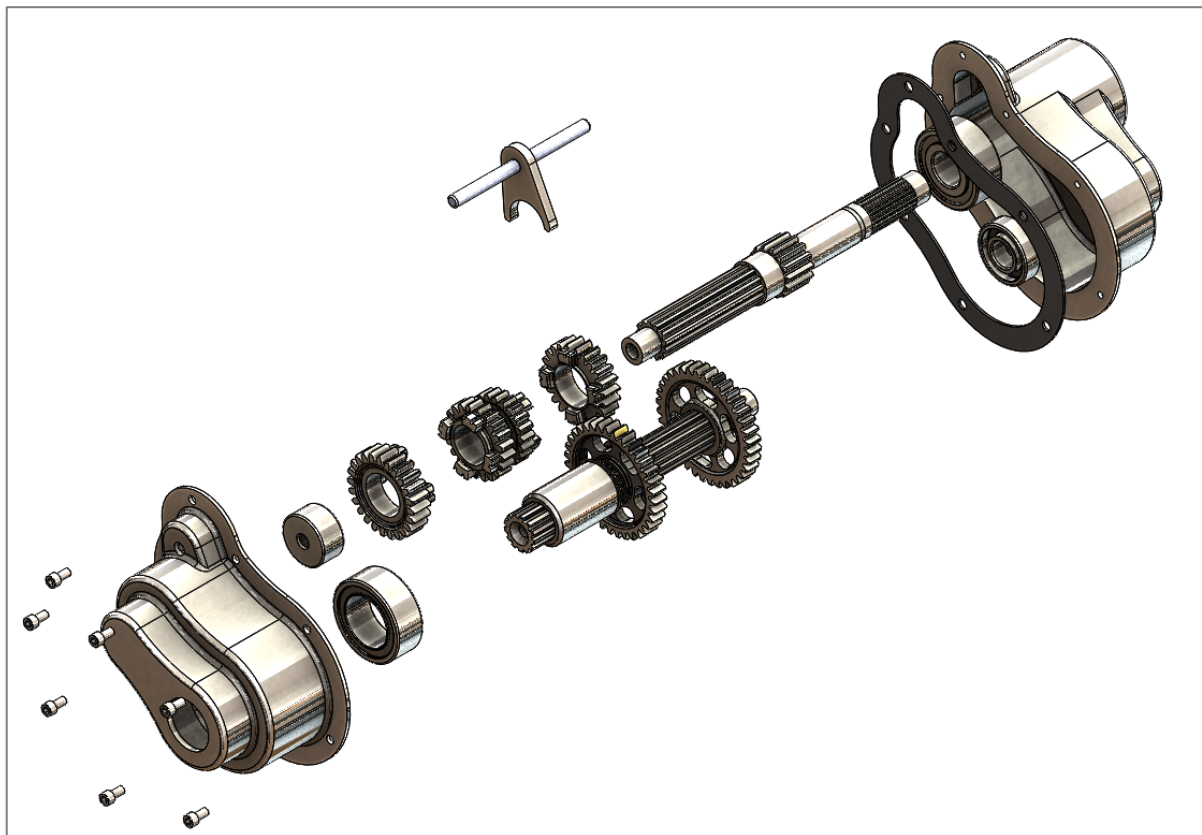


Figure 4 Gear box exploded view (Kilbane, 2019)

6.1. Gear assembly

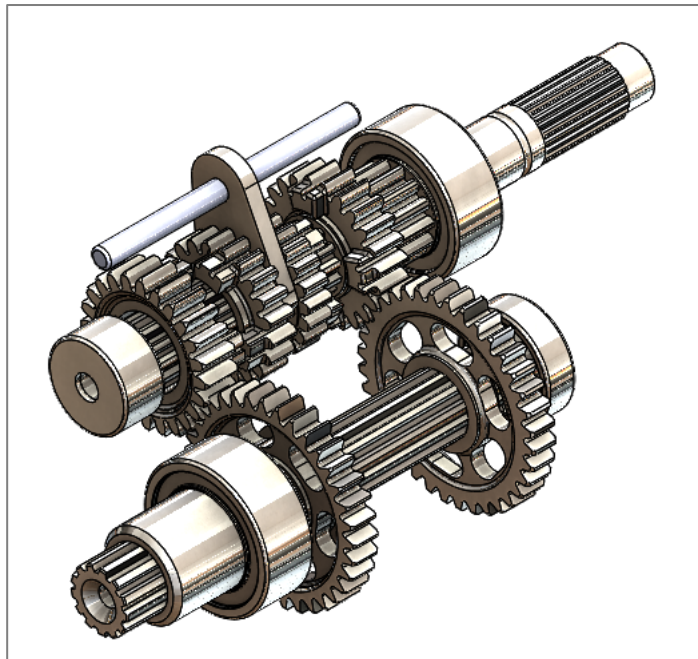


Figure 5 Gear assembly (Kilbane, 2019)

The distance between the centres of the gears is important, this allows the gears to rotate smoothly without putting undue stresses on the teeth. The pitch in this instance is calculated thus: -

$$Pitch \ \varnothing = \frac{\text{Number of Teeth} \times \text{Circular Pitch}}{\pi}$$

Or

$$Pitch \ \varnothing = \frac{\text{Number of Teeth} \times \text{Outside } \varnothing}{\text{Number of Teeth} + 2}$$

The benefit of using formula 1 over formula 2 is that formula 1 is more accurate, where formula 2 provides a more approximate value. The pitch $\emptyset$ is then used to determine the overall distance of the centres, as shown: -

$$\text{Centres Distance} = \frac{\text{Pitch } \emptyset \text{ Gear 1} + \text{Pitch } \emptyset \text{ Gear 2}}{2}$$

(MiSUMi, 2015)

As the circular pitch is not available, it would need to be worked out as an approximate, thereby giving no advantage over using formula 2, for this reason formula 2 has been used.

$$\text{Pitch } \emptyset \text{ In}_1 = \frac{23 \times 52.5}{23 + 2} = 48.3\text{mm}$$

$$\text{Pitch } \emptyset \text{ In}_2 = \frac{24 \times 56}{24 + 2} = 51.69\text{mm}$$

$$\text{Pitch } \emptyset \text{ Out}_1 = \frac{36 \times 77.4}{36 + 2} = 73.33\text{mm}$$

$$\text{Pitch } \emptyset \text{ Out}_2 = \frac{35 \times 75}{35 + 2} = 70.95\text{mm}$$

$$\text{Centres Distance 1st Gears} = \frac{\text{Pitch } \emptyset \text{ in}_1 + \text{Pitch } \emptyset \text{ out}_1}{2}$$

$$\text{Centres Distance} = \frac{48.3 + 73.33}{2} = 60.82\text{mm}$$

$$\text{Centres Distance 2nd Gears} = \frac{\text{Pitch } \emptyset \text{ in}_2 + \text{Pitch } \emptyset \text{ out}_2}{2}$$

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

The calculations show that there are two ideal centres, this is not practical as the gears are to be assembled to two fixed shafts. Therefore it is reasonable in this instance to calculate an average distance.

$$\text{Average distance} = \frac{\text{Centres 1st Gears} + \text{Centres 2nd Gears}}{2}$$

$$\text{Average distance} = \frac{61.32 + 60.82}{2} = 61.07\text{mm}$$

Therefore to simplify, the distance has been set at 61.00mm.

6.2. Housing Design

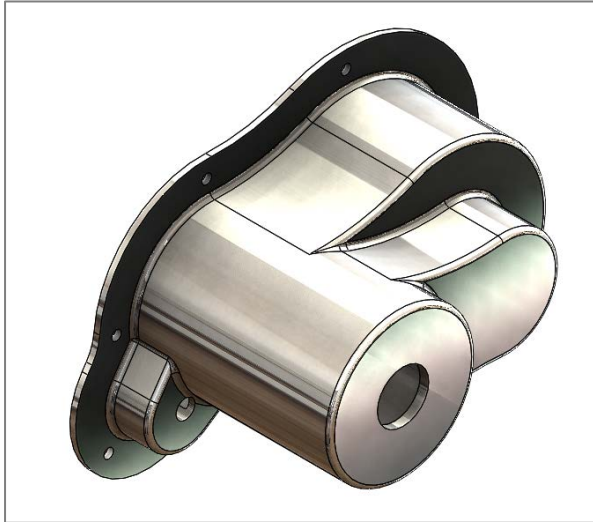


Figure 7 Gear box housing half isometric view (Kilbane, 2019)

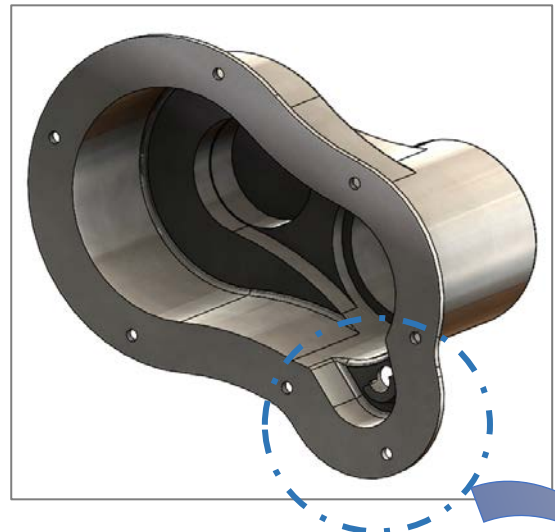


Figure 6 Gear box housing half reverse isometric view (Kilbane, 2019)

The housing is designed in two halves, so that it may easily be assembled about the gears. The bearings are to be housed within the two recessed areas at the end of the housing, using a standard H7 limit and fit tolerance.

There is a feature within the shifter fork part of the housing, it provides a stop on the gears, preventing them bottoming out and fouling on the radii. This feature does not hinder the gears from engaging sufficiently, it is simply to aid with the workings of the mechanism in order to achieve better results.

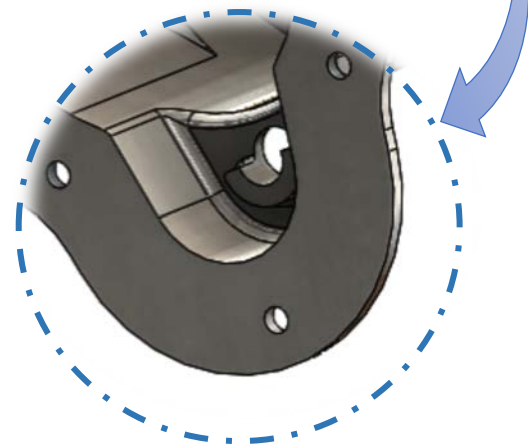


Figure 8 Gearbox housing stop feature (Kilbane, 2019)

There is an approximate gear to housing wall distance of $\sim 3\text{mm}$ disregarding the primary combined gears, this is so that oil can reach all the moving parts thereby lubricating the teeth of the gears.

Equations are used to create a relationship between two features in separate models, these equations can be useful because when a part is to be edited in future, and simply by updating one model the update will drive a change to the linked other.

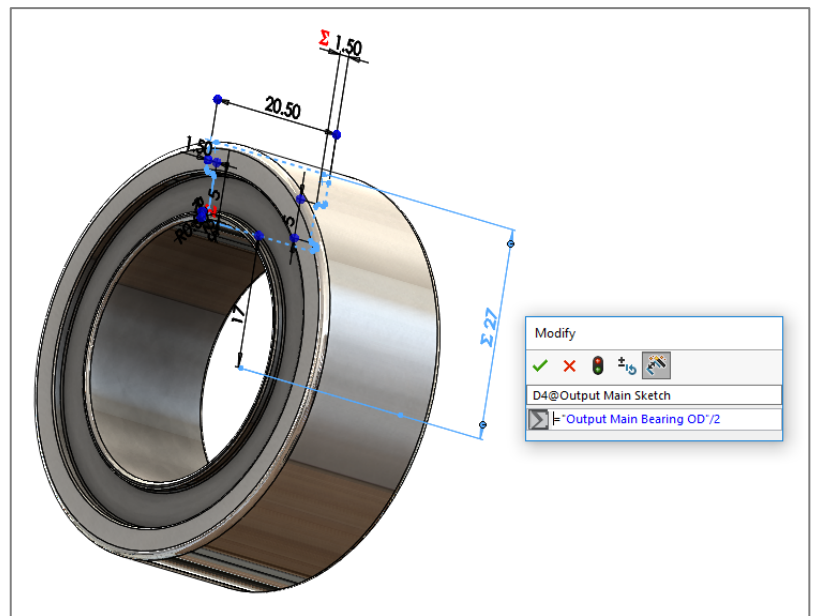


Figure 9 Bearing equation (Kilbane, 2019)

A link has been created to the 'Output Main Bearing' model, the equation has been given this name for reference. It is good practice to name the equations rationally to aid with clarity for future work on the models for oneself and others.

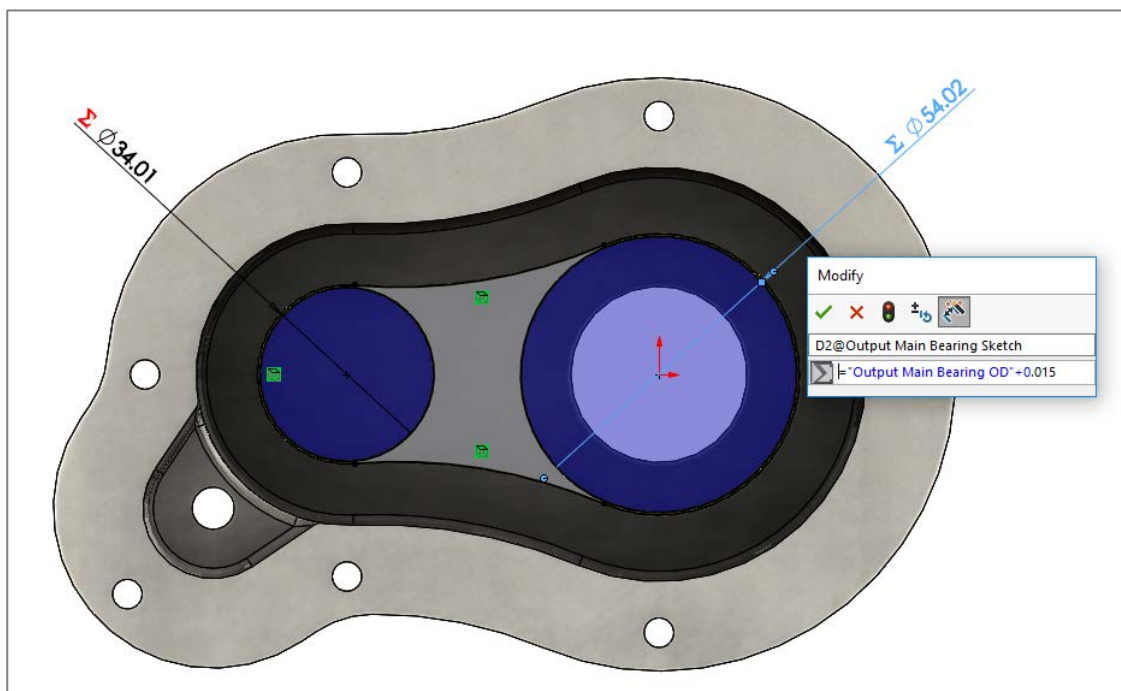


Figure 10 Gear box housing equation (Kilbane, 2019)

The housing is to have a bearing recess that must be driven by the outside diameter of the bearing. But there is a requirement for a H7 limit and fit (Zeus Precision Charts Ltd, 1976), so this can be added into the equation in the form of ["Output Main Bearing OD" + 0.015]. The standard H7 tolerance for a $\varnothing 54\text{mm}$ hole is +0.030/-0.000 (Zeus Precision Charts Ltd, 1976), therefore to aid with production, it is good practice to model to the mean of the required hole size, this is how a value of '+0.015' has been determined.

To hold the housing together, M5 socket screws have been selected, there is a clearance hole of 5.5mm as is standard for an M5 screw (Zeus Precision Charts Ltd, 1976). The mating half of the housing has an M5 tapped holes in order to receive the screw, meaning there is no need for a receptacle such as a separate nut, also making assembly easier. Rather than modelling each individual hole, a feature was used to copy the holes about a sketch that consisted of a series of holes.

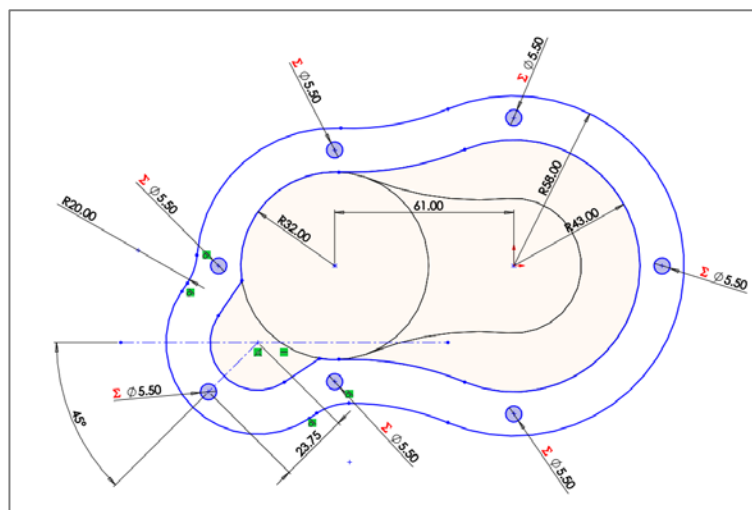


Figure 11 Gear box housing hole equations (Kilbane, 2019)

Considering that the hole size will vary depending on the screw used, it is a good idea to use an equation so that all screw clearance holes will update globally if a different screw is to be used in future.

The gasket will be of a Thermiculite® 715 material, this is known for its properties such as its ability to maintain structural integrity through extremes of temperature, and to be highly resistant to chemical and oil. Thermiculite® 715 fits the application of a gearbox gasket due to the increase in temperature during operation, and the fact that oil will be used within the gearbox. Thermiculite® 715 has a compressibility of 10% (Flexitallic, 2019), this has been calculated and positioned as such in the final assembly, creating a small clash between the two housing halves.

The gasket has been created by using the convert entities command in 'Sketch', the entities converted is the relatively complex profile of the housing flange, this makes it a lot faster than to create a new sketch using a series of lines and fillets. Then, by simply offsetting the inner face means that the inner most edge of the gasket will not protrude into the assembly thereby limiting the risk of interference with the moving parts within. Equations were also used to create the holes within the gasket, completing the whole item using one single sketch.

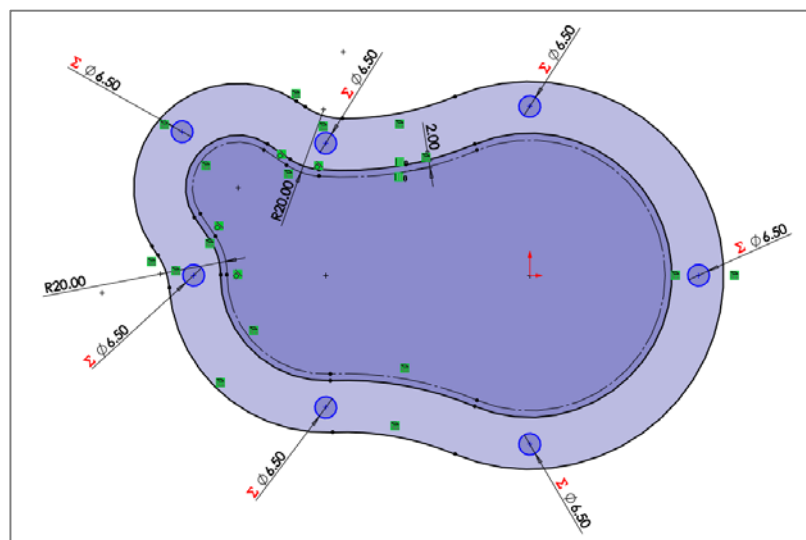


Figure 12 Gasket sketch with equations, convert entities and offset feature (Kilbane, 2019)

6.3. Final Assembly

It is important to consider the 6 degrees of freedom, these consist of X Y Z and a rotation about each of these. The mates should be as such that the minimum necessary mates are used. The motion analysis displays the redundant mates, it is good to reduce these as much as possible. The bearings first get inserted into the housing by locating into their respective places.

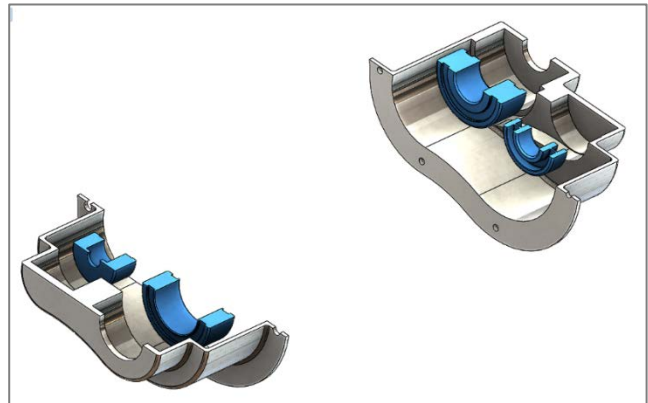


Figure 13 Cross section of gear box & bearings (Kilbane, 2019)

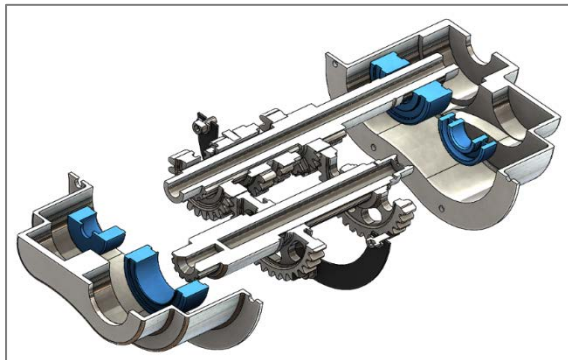


Figure 15 Cross section of gearbox with gears and shaft added (Kilbane, 2019)

The housing is then closed, with the gasket sitting in between the two halves. The entire assembly is fastened together using the M5 socket head screws and washers.

The input and output shafts along with the gears get inserted into the bearings at one end, this allows an open end so that the assembly may be closed without clashing into any of the parts.

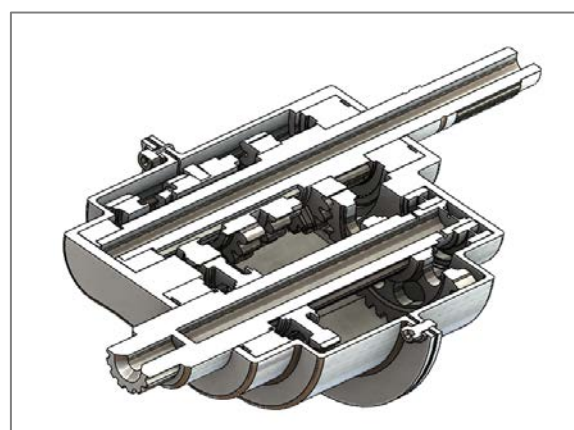


Figure 14 Cross section of assembled gear box (Kilbane, 2019)

6.4. File and Model Management

It is good practice to manage the CAD files in a way that they are revision controlled, as in industry it is unlikely that one person will own the work from start to finish, therefore it is important to be neat and tidy. Here is an example of how older files can be archived but not deleted, the reason for keeping original files is so that they can be referred to or even reverted back to in future.

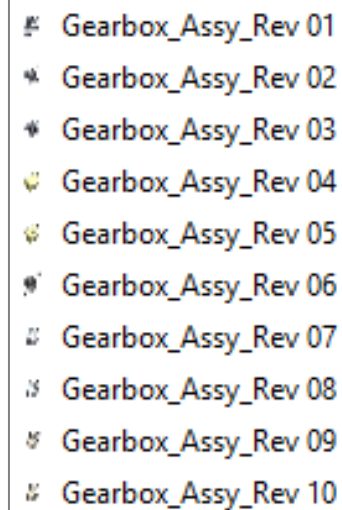


Figure 16 Revision control filing system (Kilbane, 2019)

It is also good practice to manage the assembly tree in a way that is rational, most industries like to keep similar parts of the product grouped together i.e. main bodies at the top of the tree and fasteners at the bottom. One could take this a step further and name features within the product tree, such as “Bearing Cut Out” or “M5 Clearance Hole” etc. This will also aid with editing in future as it will be clearer to interpret the model or faster to find a particular feature. To aid with reviewing the simulation data, again it is good practice to label

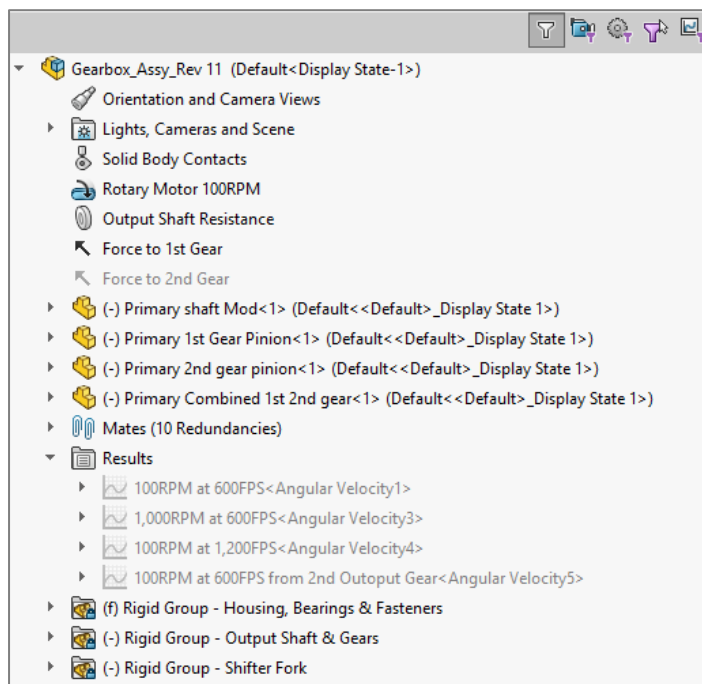


Figure 17 Motion simulation housekeeping (Kilbane, 2019)

and name all the data so that

whoever working on the file can clearly see what has been done.

This image displays the RPM that the motor is currently set to. The rigid body groups are named in according to content groups. Results are important as one must know what graph means, therefore each graph has been names according to RPM rate and FPS rate.

7. Simulation, Analysis & Results

The angular velocity graph was taken from the output shaft, this determines the velocity at which the output shaft varies with regards to input. There was a 100RPM motor applied to the input shaft, the shifter fork first moved to 1st gear to engage the gears, then to 2nd gear, and a rotation was viewed from the output shaft.

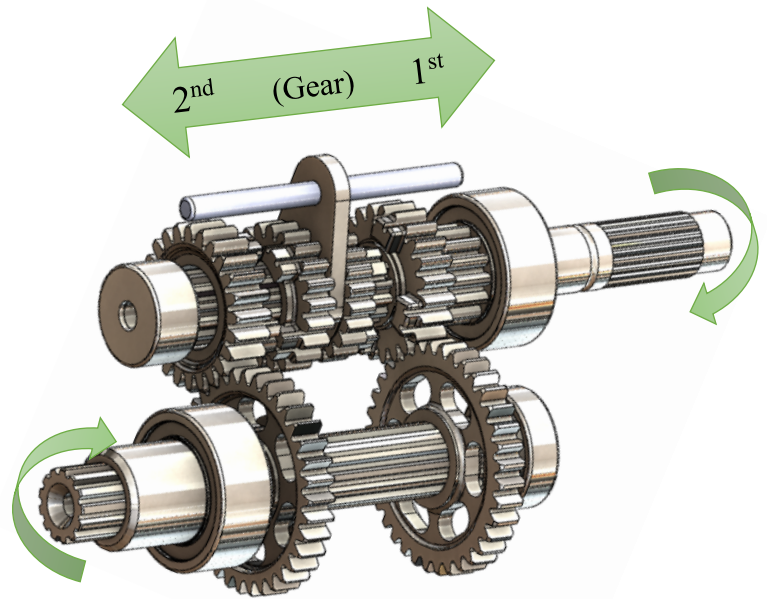


Figure 18 Gearbox motion overview (Kilbane, 2019)

The graph exhibits a change in velocity as the gears transition between 1st and 2nd, this is visible in the form of a step at ~2.5 seconds. This is what would be expected as the change in gears means that the input RPM can remain the same as the output RPM increases.

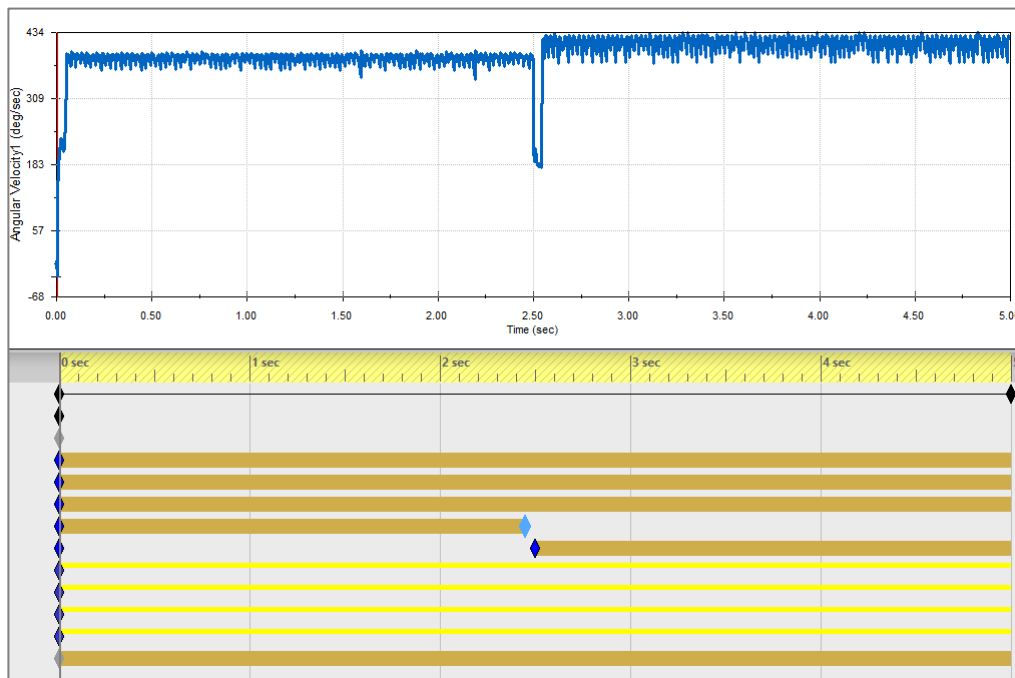


Figure 19 First motion analysis graph (Kilbane, 2019)

At 2.45 seconds, the force is removed from the shifter fork, although the gears remain engaged at this point.

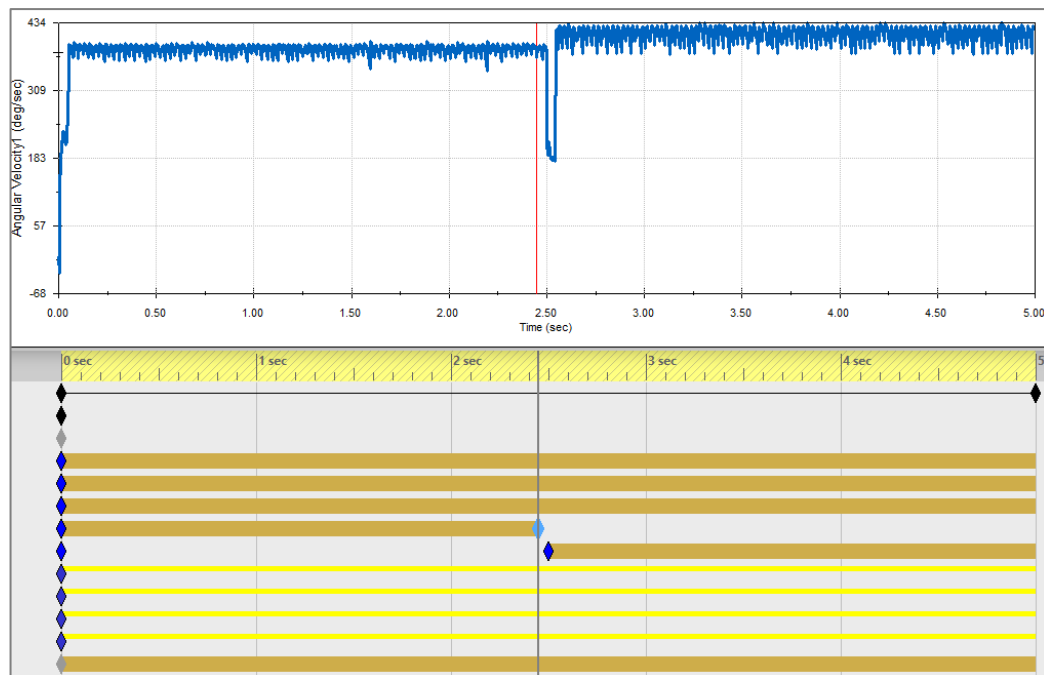


Figure 21 Motion analysis graph at 2.45 sec (Kilbane, 2019)

2.5 seconds is the point in time when the force to the shifter fork is applied in the opposite direction, thereby moving into 2nd gear.

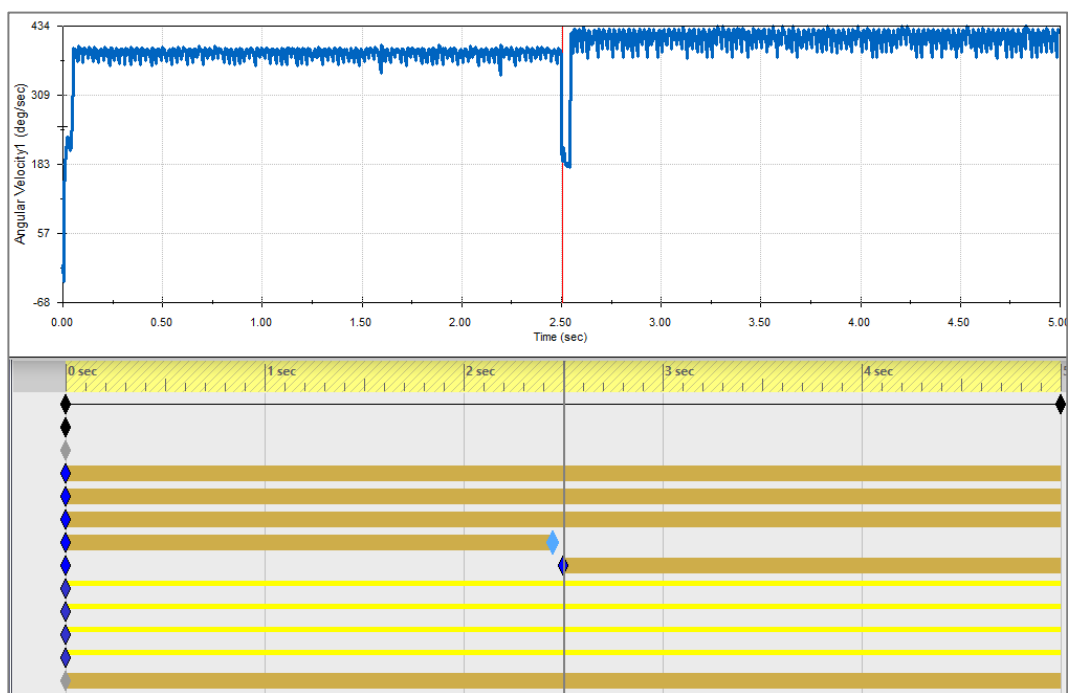


Figure 20 Motion analysis graph at 2.5 sec (Kilbane, 1983)

There is a visible negative spike in the graph at this point in time, representing a decreased angular velocity, this is due to the small amount of time that the gears are transitioning from 1st to 2nd. The relatively clean rise at ~2.55 seconds suggests that the gears engage at a good time, meaning there is no 'crunching' of the gear teeth. It is worth noting that when the simulation was created for the first time, the start of the graph was relatively uneven, exhibiting sharp spikes, this was also displayed at the mid-point of the graph. This is an indication that the teeth of the gears did not align properly. To prove this theory, the gears were strategically repositioned in a rotation about the shaft so that they would align, the results were different and therefore it is reasonable to conclude that sharp spikes in the graph are due to gears falling into place brought about by misalignment of the teeth.

By exporting the graph to Excel, it is possible to examine the actual data points further. Given seconds 1 – 2, by taking a sum of the value of the points, then dividing them by the number of points we can calculate the average velocity.

$$\text{Average Velocity} = \frac{\text{Sum of Data Points}}{\text{Number of Data Points}}$$

$$\text{Average Velocity 1st Gear} = \frac{299,944}{780} = 384.5 \text{deg/sec}$$

The result shows that the average angular velocity for 1st gear is 384.5deg/sec. This simple process is followed for the 2nd gear.

$$\text{Average Velocity 2nd Gear} = \frac{321,836}{780} = 412.6 \text{deg/sec}$$

The average angular velocity for 2nd gear is 412.6deg/sec, meaning it has a higher velocity than 1st gear, this is to be expected. It is important to note that in reality the basic RPM applied to the input shaft would most likely be approximately 1,000RPM, this is based on an idling speed of a car or motorbike. As the analysis was based on 1/10th of what the expected RPM would be, it is possible to determine therefore that at 1,000RPM, 1st gear would have an output velocity of 3,845deg/sec, where 2nd gear would have an output velocity of 4,126deg/sec. Increasing this further to 5,000RPM, 1st gear output velocity would be 19,225RPM, and 2nd gear output velocity would be 20,630RPM.

Further analysis of the graph can be done using Excel, by removing all the smaller data points and keeping only every 0.1 of a second intervals, a pattern is visible in the graph. The graph is not as accurate a representation as the actual analysis, but it is sometimes good to view the data from a distance. TAs there is an obvious pattern, the new graph could mean that the gears are not engaging as expected, this could be because they are sitting perfectly perpendicular to each other, and this theory could be tested by rebuilding the entire gear assembly, creating a new motion analysis and comparing the results.

The frame rate is important to this analysis, the higher the frame rate (FPS), the greater the accuracy of the results. The frame rate is calculate by taking the RPM, dividing it by 60 to calculate the revolutions per second, then finally multiplying by 360 which represents the degrees in a full revolution.

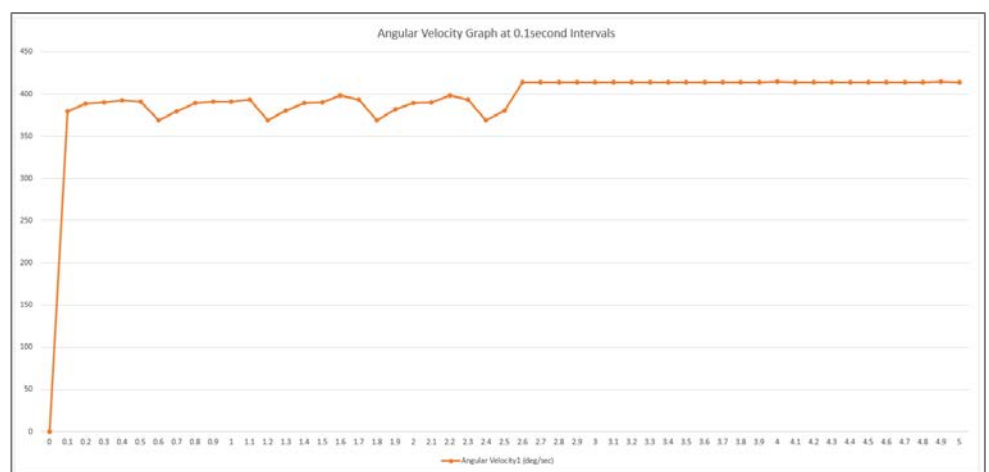


Figure 22 Excel graph of motion simulation with 0.1 sec intervals (Kilbane, 1983)

$$\text{Fram Rate} = \frac{\text{RPM}}{\text{Seconds per Minute}} \times \text{Degrees in a Revolution}$$

$$\text{Fram Rate} = \frac{100}{60} \times 360 = 600$$

Here are two graphs, the 1st at 100RPM and the 2nd at 1,000RPM, both with a frame rate of 600FPS.

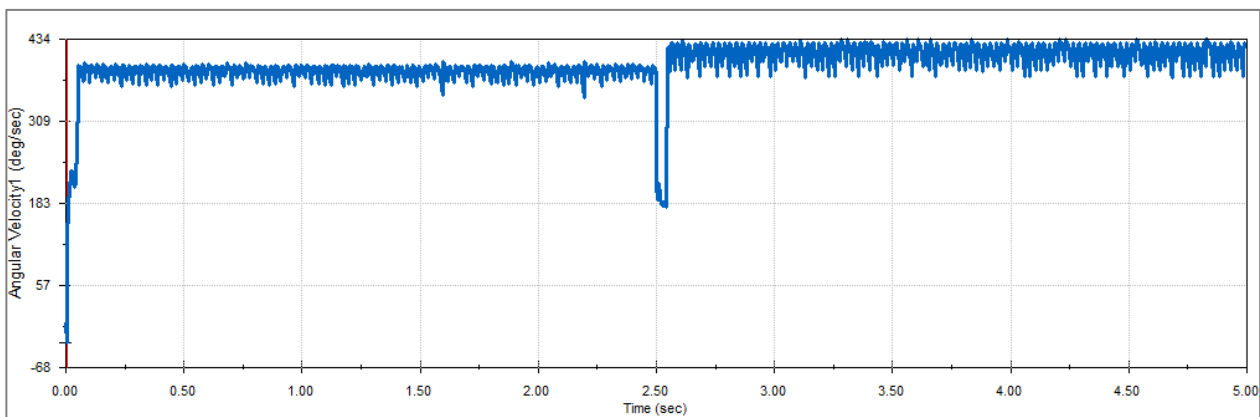


Figure 23 Motion simulation graph 100RPM at 600FPS (Kilbane, 2019)

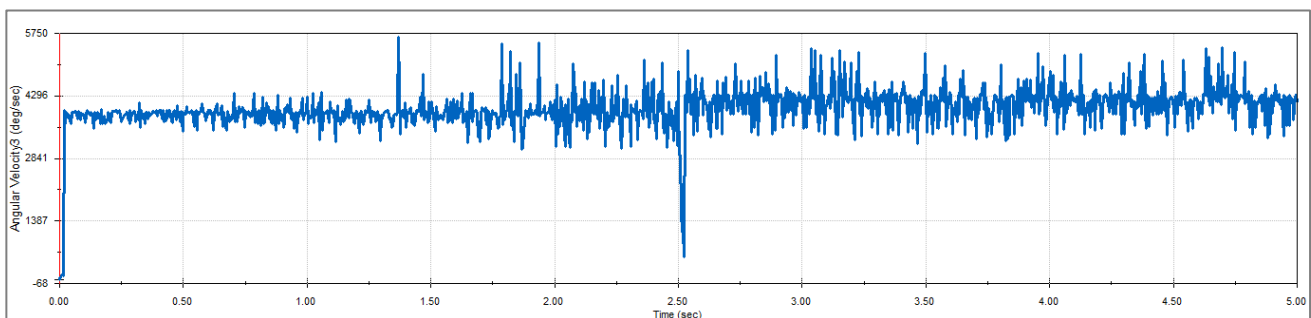


Figure 24 Motion simulation graph 1,000RPM at 600FPS

The 2nd graph at 1,000RPM with a frame rate of 600FPS is significantly messier than the first. In an attempt to improve on graph quality, the following graph was done at double the frame rate by using a frame rate of 1,200FPS with 100RPM.

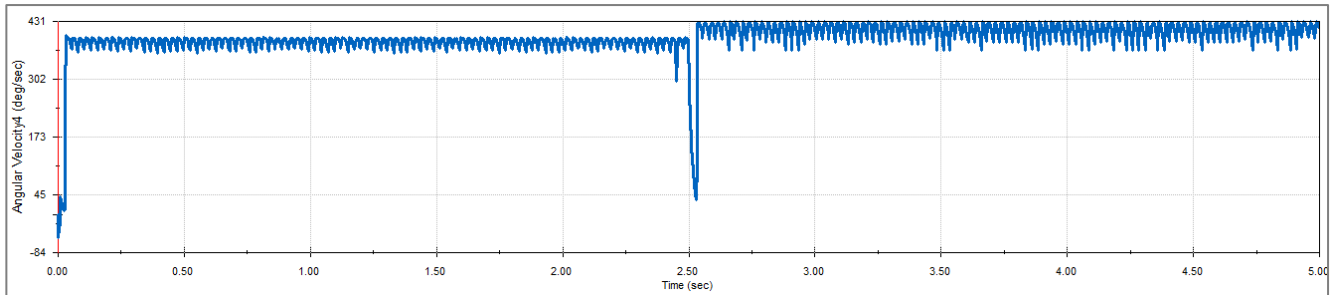


Figure 25 Motion simulation graph 100RPM at 1,200FPS (Kilbane, 2019)

There is no significant difference between 600FPS and 1,200FPS, although all the graphs would be expected to be smoother than what is viewed, there may be an error within the assembly or the analysis. To check against another point of measure, the face of the 2nd output gear was analysed with identical results, therefore no other investigation will be done at this point as the gathered data confirms the difference in velocity between two gears.

8. Conclusion

The gearbox housing can be used as a working product, although it is worth noting that for industry products must be subject to developing and testing, therefore it is reasonable to claim that the product is not currently to a production standard, it is purely conceptual. The analysis carried out thus far on motion analysis provides evidence that the assembly does work as expected, with no clashes or interference to the mating parts therefore it fulfils its intended purpose. The design is as such that the models can be modified relatively easily, the relationships between significant characteristics such as hole to shaft diameter and hole to screw diameter have been linked using equations, a very powerful tool. Such tools as loft, sweep cut and others could be used in this assembly, although they would not use any significant benefit to the assembly and would be used simply for the sake of using them, therefore have been omitted on the ground of simply not being required here.

The modelling filing system has been done rationally, for each time the assembly has been worked on, a new revision file was created and the old assembly archived. Each organisation has their own filing or PLM system for the storage and revision controlling of products and assemblies, as there is no such system in this instance, a simple method has been used.

So to conclude, the design of the gearbox housing and the motion simulation has proven to be a powerful tool in the early development of this product, and will greatly help when applied in industry.

All CAD data can be found at this location: -

https://uwotds-my.sharepoint.com/:f:/g/personal/1705015_student_uwotds_ac_uk/EuxfvWolIchEnPs794USVYoBzHs-NoURDp82o7H-GxXEiw?e=msxgbA

9. References

Works Cited

Barbero, E. J., 2013. *Finite element analysis of composite materials using Abaqus*. 1st ed. Boca Raton: CRC Press.

Barbero, E. J., 2014. *Finite Element Analysis of Composite Material Using Ansys*. 2nd ed. Boca Raton: CRC Press.

Belytschko, T., 1976. A Survey of Numerical Methods and Computer Programs for Dynamic. *International Journal of Numerical Methods in Engineering*, 10(3), pp. 579-596.

Chang, K. H., 2008. *Motion Simulation and Mechanism Design with COSMOSMotion 2007*. 1 ed. Oklahoma: KHC.

Comsol, 2017. *Comsol Multiphysics Cyclopedia*. [Online]
Available at: <https://www.comsol.com/multiphysics/mesh-refinement>
[Accessed 02 June 2019].

Flexitallic, 2019. *Flexitallic Brochures*. [Online]
Available at: <http://www.flexitallic.eu/resources/brochures/>
[Accessed 19 May 2019].

Hrennikoff, A., 1941. Solution of Problems in Elasticity by the Frame Work Method. *Journal of Applied Mechanics*, 8(4), pp. 169-175.

Koutromanos, I., McClure, J. & Roy, C., 2018. *Fundamentals of Finite Element*. 1st ed. Blacksburg: John Wiley & Sons Ltd.

Kurowski, P. M., 2018. *Engineering Analysis with SolidWorks Simulation 2018*. 1st ed. Mission: SDC Publications.

Logan, D. L., 2012. *Finite Element Method*. 5th ed. Stamford: Cengage Learning.
Mario, H., Dietrich, W., Gferrer, A. & Lang, L., 2013. *Integrated Computer-Aided Design in Automotive Development: Development Processes, Geometric Fundamentals, Methods of CAD, Knowledge-Based Engineering Data Management*. 1 ed. London: Springer.

McHenry, D., 1943. A Lattice Analogy for the Solution of Plane Stress Problems. *Journal of Civil Engineers*, 21(1), pp. 59-82.

MiSUMi, 2015. *MiSUMi MECH LAB*. [Online]
Available at: <https://blog.misumiusa.com/qa-center-to-center-spacing-for-shafts-with-spur-gears/>

[Accessed 3 June 2019].

Ragab, S. A. & Fayed, H. E., 2018. *Introduction to Finite Element Analysis for engineers*. 1st ed. Blacksburg: Taylor & Francis Group.

Reddy, J. N., 2015. *An Introduction to Nonlinear Finite Element Analysis*. 2nd ed. Texas: Oxford University Press.

Solidsolutions, 2019. *SiolidWorks*. [Online]

Available at: <https://www.solidsolutions.co.uk/solidworks/tutorial-videos/tips-tricks-motion-simulation.aspx>

[Accessed 6 June 2019].

SolidWorks, 2008. *Understanding Motion Simulation*. [Online]

Available at:

https://www.solidworks.com/sw/images/content/Training/SIM_Motion_UnderstandingMotion_WP_ENG.pdf

[Accessed 5 June 2019].

Zeus Precision Charts Ltd, 1976. *Zeus*. 1 ed. Jersey: Seal House Press Liverpool.

Zienkiewicz, O. C., 2014. *The Finite Element Method for Solid and Structural Mechanics*. 7th ed. Barcelona: Elsevier.

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