Modelling and Analysis of an Integral-Compressor GMV Engine using Creo Parametric

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Abstract. This report illustrates 3D modelling and analysis of an engine-compressor crank-slider (piston) mechanism. In this paper we are going to discuss about a specific compressor engine known as GMV. We will discuss how a virtual prototype is made using Creo Parametric and different analyses are performed to observe and validate the motion of engine.

1 Objectives

In this project we are designing a Cooper-Bessemer GMV engine, the objectives of this project include virtual prototype of a GMV engine with an equal bore to stroke ratio (1:1 Ratio),the engine design comprises of two power pistons and one compressor piston. The pistons are connected via a balanced crankshaft. Once the assembly is generated we are required to perform kinematic and static analysis to obtain desired results. Following is the design of a simple GMV integral compressor engine with equal bore to stroke ratio whose virtual prototype we wish to design:

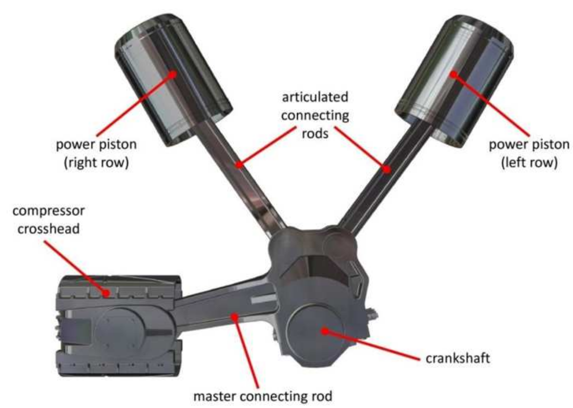

Fig. 1. GMV Engine Model

2 Introduction

Since the start of 21st century, technological progress has grown on an exponential scale. Due to advancement in the field of software engineering, today we have computer software's that can provide us with accurate computational results. Thus we no longer have to rely on physical experimentation but can use simulations to provide us with reasonably accurate results. Advanced software suites include updated necessary data and mathematical models for different processes and have the ability to generate required simulations. In the case of designing an engine there are several parameters that would be needed to be changed to observe and study the effect of those changes such as changing of bore and stroke lengths and thus the bore-stroke ratio, retrofitting multiple pistons on a single crankshaft, dimensions of pistons etc. All of these changes can be easily performed while designing a virtual prototype but if the model was physical then these changes would mean creating the model from scratch again to observe the effects. Engine virtual prototypes are made by using real world engine data combined with geometrical and mathematical computation to generate desired results. Once a virtual prototype is designed, it forms the basis for final product because upon that model we fine tune our parameters to ensure that the final output matches our desired output. [1]

3 Literature Review

GMV integral compressor engines are considered to one of the world's earliest compressor engines that had the ability to generate reciprocating motion with pistons and their own connecting rods. They were steam powered engines connected to a belt drive system. These engines later became the industrial standard engines and brought economic prosperity which eventually paved the way for technological improvement [2]. Following is a cross section image of an industrial GMV integral compressor engine with equal bore to stroke ratio:

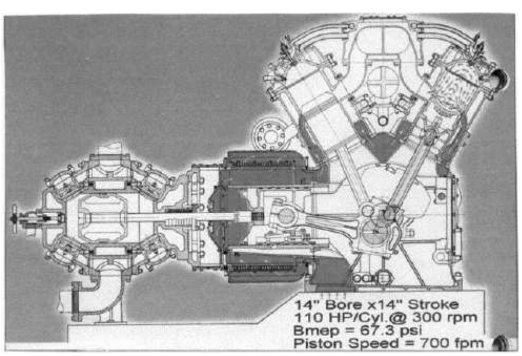

Fig. 2. GMV Engine Cross Section

Since the scope of this paper is based on functioning mechanism of an engine, if we were to perform the same experiment using physical equipment not only would it be expensive but it would also lack the sufficient skill set to integrate the hardware with sensors to collect data for analysis. This is the point where computer simulation assist us. We have developed a virtual prototype of an integral compressor GMV engine with an equal bore to stroke ratio using Creo Parametric 6.0. Then performed different types of analysis such as static analysis to observe the equilibrium position and kinematic analysis to observe the motion of the pistons. These analyses will be further discussed below in different sections. The results from these analyses will be used to observe and compare the computer model with an actual model of engine.

As mentioned above the engine whose design and analysis is studied in this paper is an Integral-Compressor Engine. The specific series we are designing is the GMV Engine that has an equal bore to stroke ratio. An integral-compressor engine is used in fuel supply systems specially natural gas supply systems to compress the molecules of gas for transmission over long distances. The V in GMV stands for the 'Vee-Angle' configuration between the engine's power pistons, the angle is termed as bank angle. The engine model contains two power pistons followed by a compressor piston with a crank shaft slider mechanism. The unique feature of crank shaft sliding mechanism is that it has the ability to convert linear motion to rotary motion, the details of this will be discussed below.

4 Background and working of the mechanism

An integral-compressor engine has a crank slider mechanism, in this system the mechanical parts are designed and arranged in a specific manner to convert straight line motion to rotary motion. This gives birth to the reciprocating motion observed in an engine where the power pistons are moving in an up down motion which rotates the crank shaft. The power pistons and crank shaft then with their combined motion moves the compressor piston in a back forth constant motion. The crank is crank shaft which is rotating about a fixed center point while the sliders are the pistons. The pistons are connected to the crank shaft using piston shafts also known as a connecting rod. Below is a picture of a simple crank slider mechanism:

The beauty of this mechanism that it has the

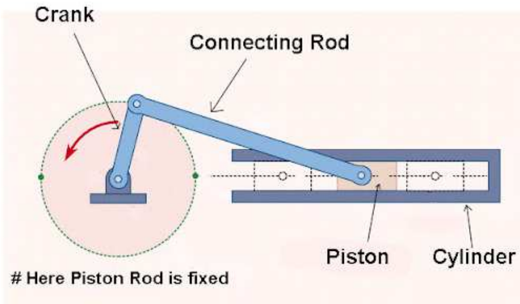

Fig. 3. Crankshaft Sliding Mechanism

ability to exhibit linear and rotary motion simultaneously and convert one form of motion into another. The linear motion of the power pistons which is due to the combustion of fuel is converted into rotary motion of the crankshaft which is in turn converted into the linear motion of the compressor piston. The significance of generating a virtual prototype of an engine to replicate the simulation of this mechanism is that we are able to generate accurate analytic quantities through kinematic, dynamic and static analysis. These quantities include the position, velocity, acceleration of the crankshaft using kinematic analysis while dynamic analysis provides us with torque and other inertial forces. These quantities play a crucial role while designing engines since one of the objectives of the project is to design and assemble a balanced crankshaft. The term balanced implies that when counter weight is applied to the crank shaft it automatically compensates for the weights of the moving components such as the pistons and other connected components to the crankshaft. The articulated motion of the engine remains unaffected and any unwanted vibrations in the system due to addition of counter weight is adjusted. Below is the picture of our balanced crankshaft model:

5 Benefits and limitations of a Crankshaft Sliding Mechanism

As no design is perfect each model has its fair share of benefits and limitations, thus it is important while designing a part that its potential limitations are considered and ensured to be a minimum while the benefits are a maximum. Following are the list of benefits and limitations of a crankshaft sliding mechanism:

Benefits

1. Cost effective
2. Reduced number of parts
3. Reduced weight
4. Compact design

Limitations

1. Delicate positioning of the connecting rods
2. No torque generated

6 Application of DFM in Part's Designing

Since we have created a virtual prototype of the crank slider mechanism, all the parts were designed separately and the most important thing that must be kept in mind when designing virtual prototypes is to ensure that DFM, techniques are followed because the object we are designing is an engine which is a manufactured product, thus our design is DFM based. DFM stands for Design For Manufacture. According to DFM, it aims to optimize the product‘s design in this case it GMV Engine for its manufacture and assembly. Since we created separate part files and them assembled them together it was crucial that the parts were designed accurately using the correct dimensions because this way we are minimizing the assembly time. If DFM is not followed then we would end up spending more time on assembly of the engine and there is a very high chance that we might not be able to assemble the engine at all. If the engine is not correctly assembled then it is impossible to generate the articulated motion and perform any sort of analysis. Thus all the this time would have gotten wasted. DFM prevents this from happening because it ensures the designing process in done in a manner to meet the required objectives. Following is the list of parts we have designed for our GMV Engine model:

1. Piston
2. Piston Cylinder
3. Piston Shaft
4. Crankshaft
5. Master Rod
6. Compressor Piston Pin
7. Power Piston Pin

7 Assembling Designed Parts

Once all the above mentioned parts are designed, the phase of the virtual prototyping process is creating an assembly using these parts. The parts were all designed using Creo Parametric 6.0 and so is the assembly made using the same software. The assembly phase was a multi step process, in this first phase we assembled a power piston using the piston cap, piston, piston shaft and power piston pin the parts were assembled to complete assembly of a single power piston. During assembly of the entire engine we used different joints to assemble the parts and hold them in place since some of the parts are moving during the motion of the engine we had to ensure that while assembling the parts the desired motion of the parts will not get hindered once we finalize the assembly. We employed the following connections in our engine assembly:

1. Sliding Connections: These connections are used between pistons and piston caps.
2. Pin Connections: These connections are used to connect pistons (pistons here refer to both power pistons and compressor pistons) with connecting rods or piston shafts.
3. Cylinder Connections: These connections are used to connect other end of connecting rods or piston shafts to the crankshaft.

Following is the assembled picture of our GMV engine along with its exploded view image that shows all the parts assembled together to design our engine:

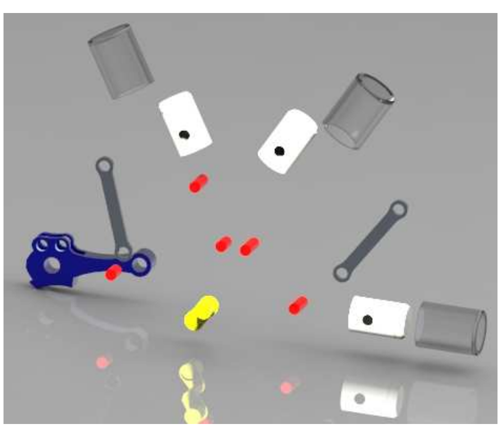

Fig. 4. Exploded View Of Our Model

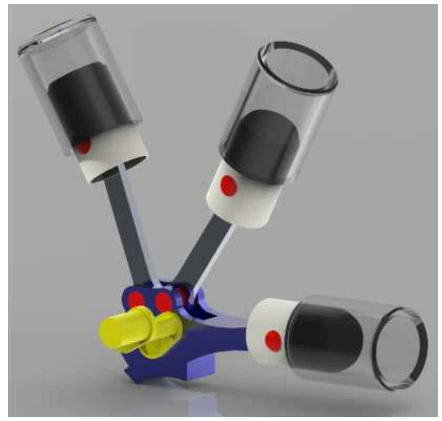

Fig. 5. Assembled Model

7.1 Challenges faced in Engine Assembly

Assembling the components of engine proved to be a challenging task since we are designing a GMV engine and as mentioned above the significance of ”V” is the ”Vee-Angle Configuration” which means that all three pistons, two power pistons and one compressor piston are 60° apart this was the first challenge that we had to address. The second challenge was that the radius of circular motion the crankshaft should be consistent with our bore stroke ratio, in our case we had to maintain a 1 to 1 bore stroke ratio. Starting with the second challenge, we addressed this challenge by creating a reference part which comprised of a simple center circular sketch. The circumference of this circular path represents the path of motion by our crankshaft. We then constructed a center datum axis inside the circular sketch to align our crankshaft center with it. We also created three reference lines within the circle 60° apart as a reference for our pistons. This was constrained using the default constraint option, there was no extrusion or sweeping member on the reference part, it was just a simple sketch that assisted us in setting up the basis for our engine assembly. Thus we took extra caution in this part, this task was smartly performed using the connections functionality mentioned above along with constraining of parts, another functionality present in Creo.

8 Design Specifications

Since we are following the DFM or Design For Manufacture techniques for designing our parts. We chose custom dimensions for our parts, the key thing that was noted here was that the bore to stroke ratio was equal that is i.e. both the lengths were 14 inches as instructed in the project rubric. Initially the parts were designed separately but later on during the assembly phase we had to modify the part dimensions to ensure that the assembly of our engine is generated without any issue and we are able to generate the desired articulated motion of the engine. This phase required trial and error approach to achieve the perfect dimensions for our engine parts. The engineering drawing attached shows the important dimensions we have used in designing the parts for our engine model.

1. Power Piston Pin
2. Piston Cylinder
3. Power Piston
4. Piston Shaft
5. Compressor Piston
6. Master Rod
7. Crank Shaft

Following is the engineering drawing of our GMV engine assembly, as mentioned above that GMV engine has a special ”Vee-Angle Configuration” of pistons that are 60° apart from each other. The configuration of pistons along other with other relevant dimensions is displayed below:

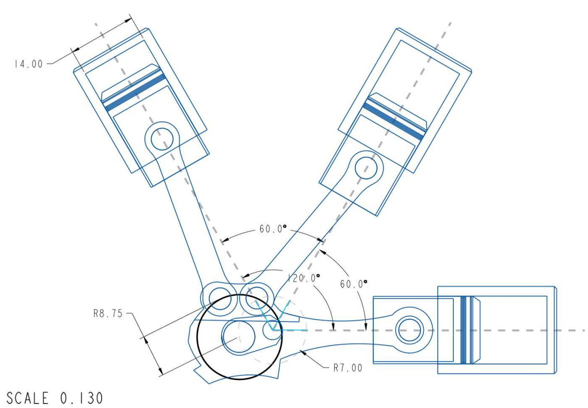

Fig. 6. Engineering Drawing of our GMV Engine

9 Analysis

This section marks the start of second part of our project, which the analysis of our engine model and calculation of various dynamic and kinematic quantities which were mentioned above. This section is divided into further three sections each of which will discuss different aspects of the analysis, starting from static analysis to kinematic analysis and then dynamic analysis in the end. In each section we will examine the results of analysis which are in a graphical format, these graphs have been generated using Creo Parametric 6.0. Data set is also extracted which is then modified using Microsoft Excel to generate desired graphical results. Then we will discuss the trends and analyze how accurately does the analytical data obtained matches the actual data set. If there are discrepancies that what are the possible reasons behind those discrepancies and them compute the percentage difference between the simulated and actual values. We will run each type of analysis for different sets of values as per the provided instructions.

9.1 Static Analysis

In this section we will discuss the results of static analysis of our GMV engine. Static analysis provides used with equilibrium position of our assembled object and provides us the direction of gravity. We performed static analysis twice first time without effect of friction on the engine and second time with the effect of friction on the engine and then compared and analyzed the results. Following pictures show the initial position of pistons in our and then the position of pistons at equilibrium position after static analysis has been performed.

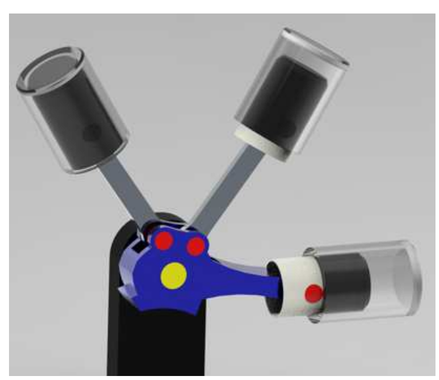

Fig. 7. Static Analysis - Initial Position

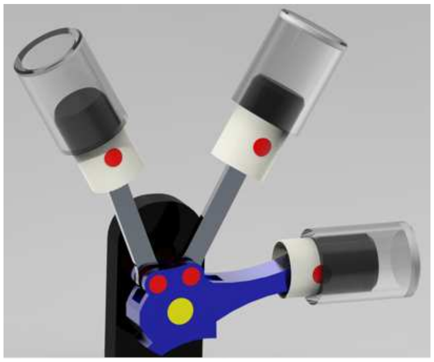

Fig. 8. Static Analysis - Equilibrium Position

Following graphs generated from analysis in Creo Parametric, they display the result of static analysis with and without friction:

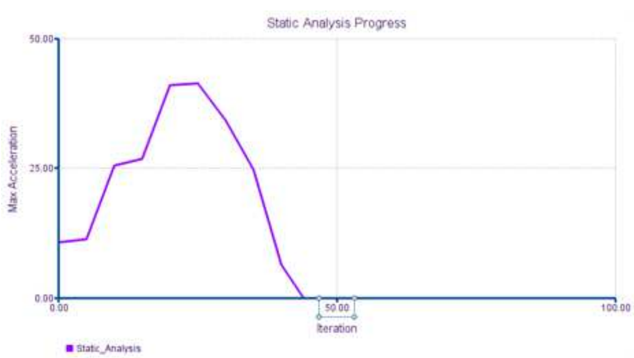

Fig. 9. Static Analysis Without Friction

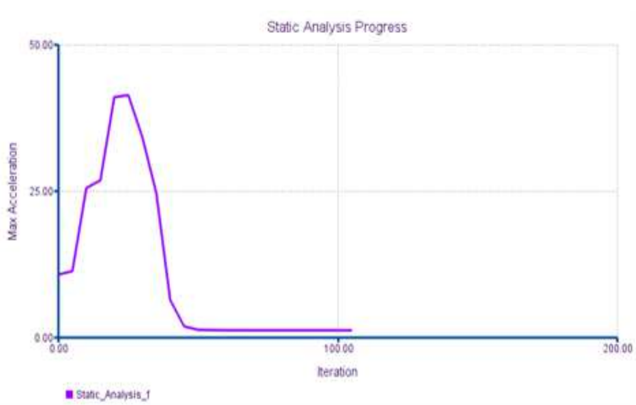

Fig. 10. Static Analysis With Friction

From the above plots we can conclude that in both cases of no friction and with friction, static analysis tells us that the engine initially accelerates at a constant rate for a few iterations (seconds) for few iterations until reaches a maximum point then onward it starts to decelerate and again reaches zero acceleration. However in the case of static analysis with friction it reaches the maximum point quickly and then experiences a sharp decline and stays equal to zero.

9.2 Kinematic Analysis

In this section we will discuss the results of kinematic analysis of our GMV engine. As mentioned earlier that kinematic analysis provides us with data and calculations regarding position, speed and acceleration. However as the project instructions we need to perform the analysis at three different speeds and then plot a graph at each speed to show the axial distance of the three piston's (two power pistons and one compressor piston) top surface which is known as the crown from the crank axis. Before this we need to specify the materials we are using for our parts and the coefficient of friction that is used at different joints. Following is the materials assigned to different parts:

Aluminum Alloy A6061

1. Piston Head
2. Piston Pin
3. Piston Cylinder
4. Hinge Pin
5. Master Rod

Cast Iron

1. Crankshaft
2. Piston Shaft

The coefficients of frictions assigned to the materials are based on the type of materials coming in contact. The materials in contact are aluminium to aluminium thus the coefficient of both static and kinetic friction are based on aluminium material. However it is important to state that we had to reduce the value of coefficients of friction because using the exact values would result in technical issues in our static analysis thus through trial and error approach we obtained the values of coefficients of friction that yields the optimum result. These values are as follows:

1. Coefficient of Static Friction:

$$\mu_s = 0.03$$

2. Coefficient of Kinetic Friction:

$$\mu_k = 0.02$$

9.3 Kinematic Analysis With Friction

Following are the results obtained from kinematic analysis with friction:

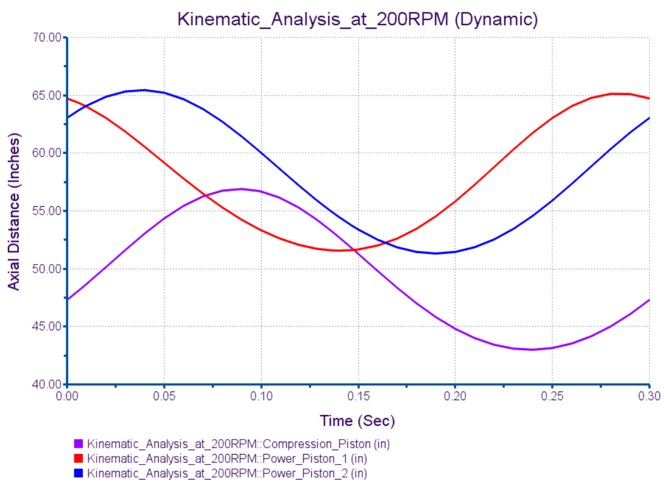

Fig. 11. Kinematic Analysis at 200 RPM

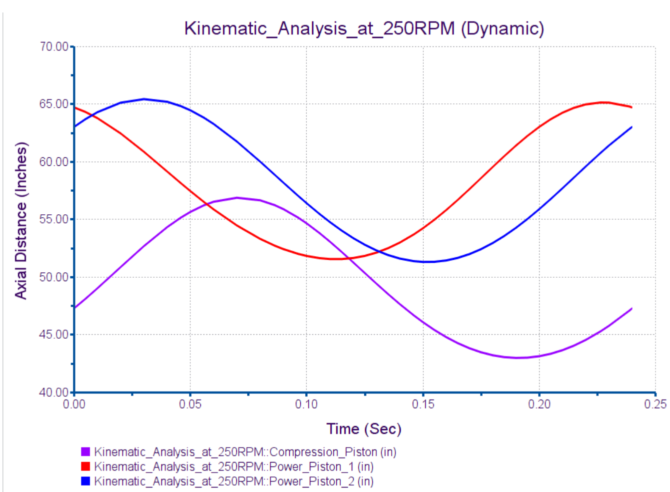

Fig. 12. Kinematic Analysis at 250 RPM

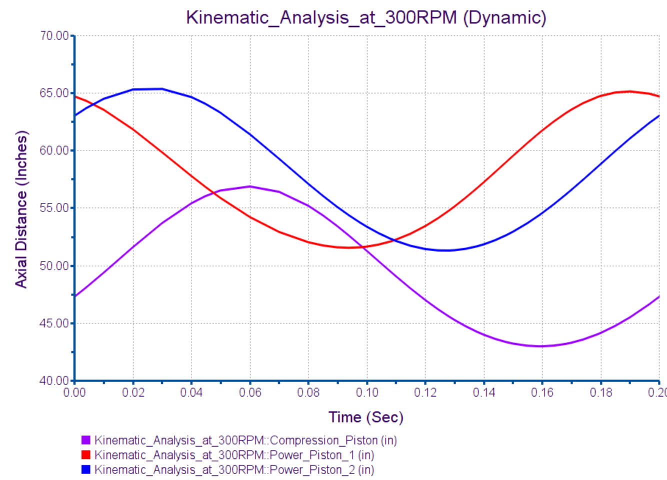

Fig. 13. Kinematic Analysis at 300 RPM

9.3.1 Kinematic Analysis Without Friction

Following are the results obtained from kinematic analysis without friction:

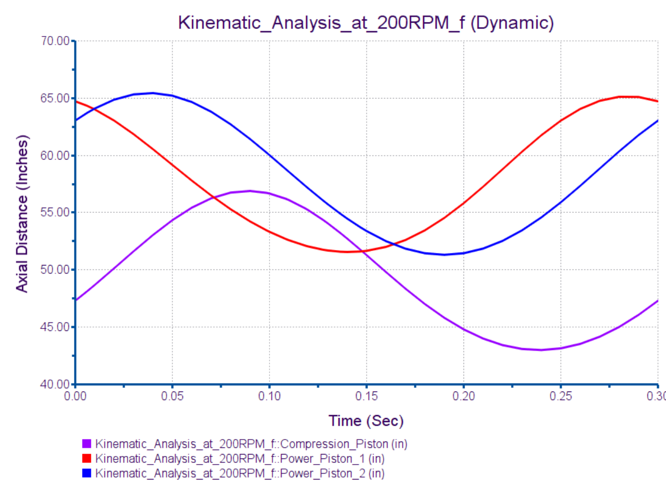

Fig. 14. Kinematic Analysis at 200 RPM Without Friction

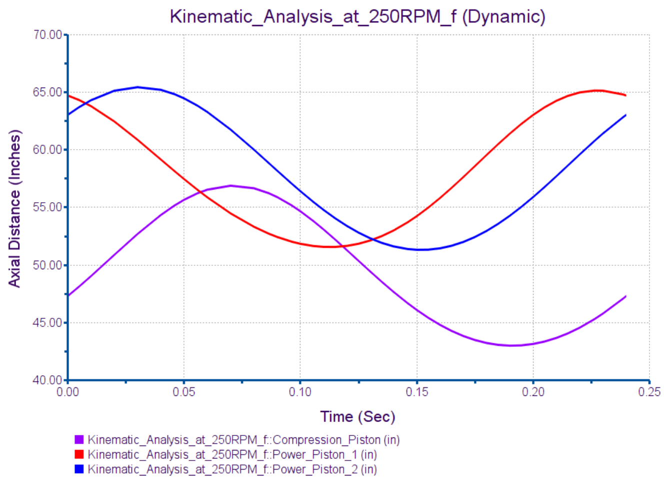

Fig. 15. Kinematic Analysis at 250 RPM Without Friction

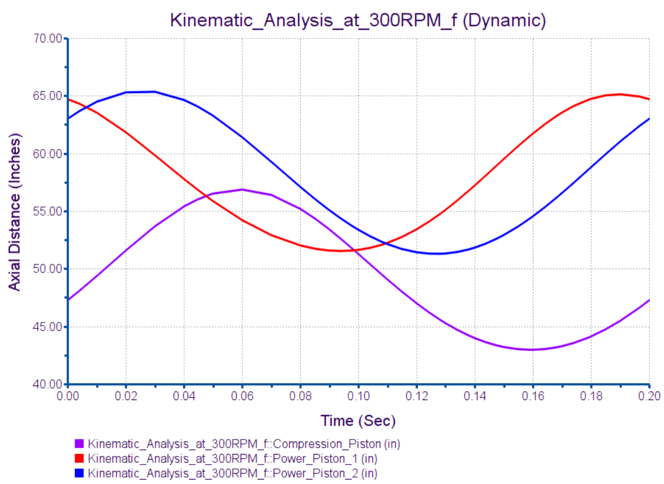

Fig. 16. Kinematic Analysis at 300 RPM Without Friction

9.3.2 Comparison Of Results

As we can observe from the results above that with or without friction makes no difference in speeds because in performing kinematic analysis our objective is to observe position, velocity and acceleration properties of our assembly. Friction is a force and it would come under analysis of forces which comes under dynamic analysis, it will be discussed in the next section. Furthermore, friction doesn't impact the speed rather it impacts the mechanical torque produced by the engine thus another reason that the plots of speed with and without friction are same for both power pistons and compressor piston at different speeds.

9.3.3 Location of Power Piston Pin

Since we modelling a GMV engine with an equal bore to stroke ratio of 14 inches, our virtual prototype should yield the same result. We will compare our experimental results with the analytical results by using the power piston pin location equation and plug in the values of our measured parameters and then plot the graph to observe the results. The following picture highlights the region whose displacement we are calculating:

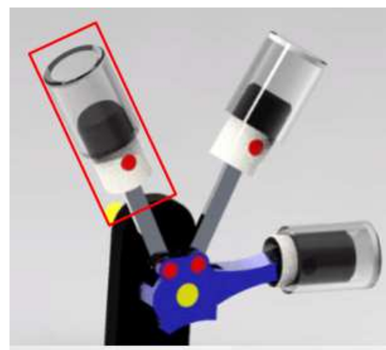

Fig. 17. Power Piston Pin Displacement

The equation for deriving power piston pin location is:

$$\mathrm{PP} = R\cos\theta + e\sin\left(\alpha - \arcsin\left(\frac{R\sin(\beta-\theta)}{L}\right)\right) + \sqrt{l^2 + \left(R\sin\theta + e\cos\left(\alpha - \arcsin\left(\frac{R\sin(\beta-\theta)}{L}\right)\right)\right)^2} \quad (1)$$

Following is the table of the dimensions used in the equation above along with labeled image to identify the parts whose dimensions are used:

Parameters		
Master Rod length	L	35.14″
Piston Shaft length	I	35.00″
Crank Radius	R	07.00″
Hinge Pin offset	e	08.75″
Hinge Pin angle	α	60,120
Piston Angle	β	63.13, 114.34

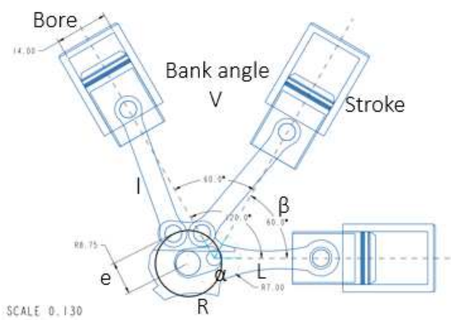

Fig. 18. Labeled Engineering Drawing

The resulting equation is plotted on an online graphing tool known as Desmos, from where we get the following result:

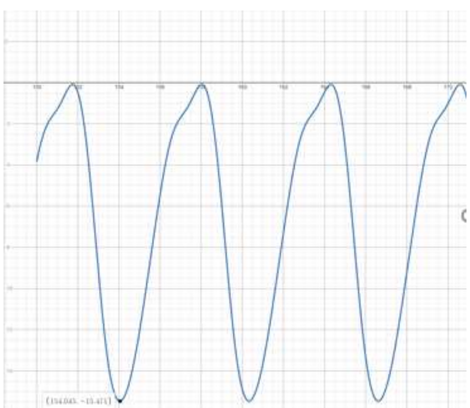

Fig. 19. Result Of Analytical Equation

Generating the same result experimentally produced the following graph:

Fig. 20. Experimental Result

Thus, following values of stroke or power pin displacement are calculated:

1. Experimental Value: 14
2. Analytical Value: 15.5

Our experimental value perfectly fits our bore stroke ratio however the analytical value is slightly larger, this is due to the difference in units of parameters we used to calculate the result.

9.4 Acceleration of Piston

In this section we will observe the acceleration of power piston as a function of crank angle degrees. Since acceleration is nothing except double derivative of the displacement function, thus our graph should follow a similar trend. Following is the graphical result of acceleration versus crank angle:

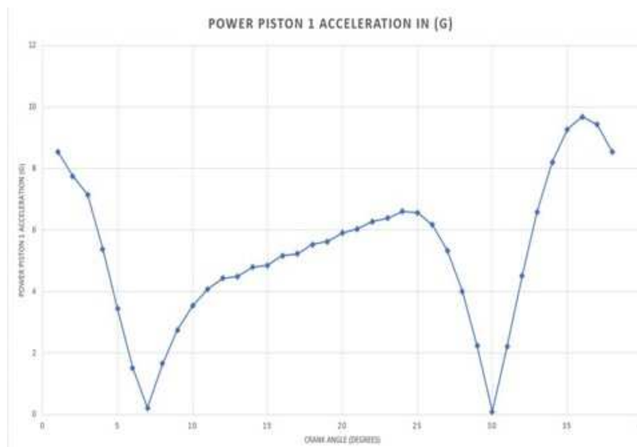

Fig. 21. Experimental Result

9.4.1 Hinge Pin Motion

In this section we will observe the motion of hinge pin which connects the crankshaft to the master rod, when articulated motion is generated, we will generate a trace curve of motion of hinge pin at different speeds and observe if speed affects the trajectory of motion of hinge pin or not. Following picture shows the hinge pin in our model:

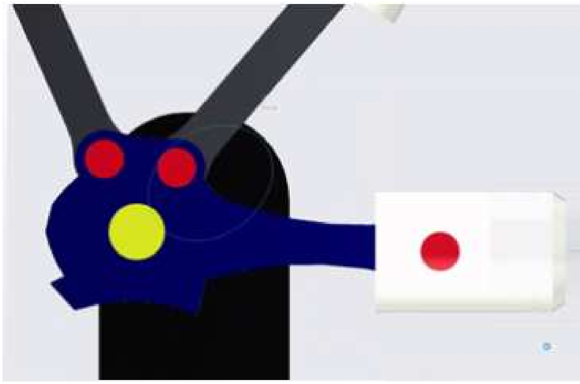

Fig. 22. Hinge Pin

Following are the trace curve that map the trajectory of motion of hinge pin at different speeds:

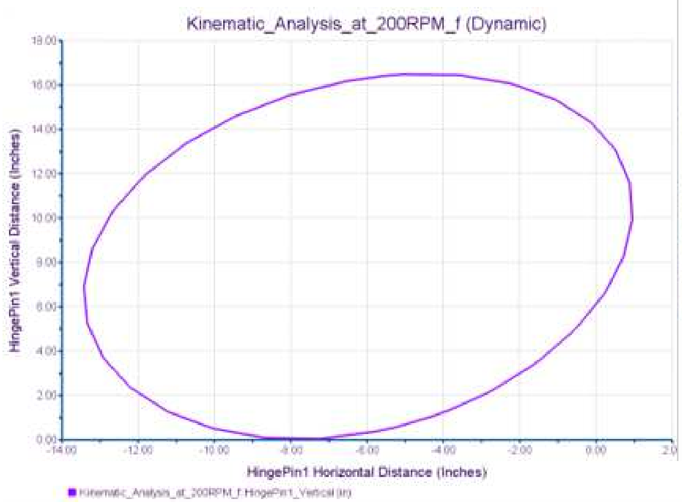

Fig. 23. Trace Curve at 200 RPM

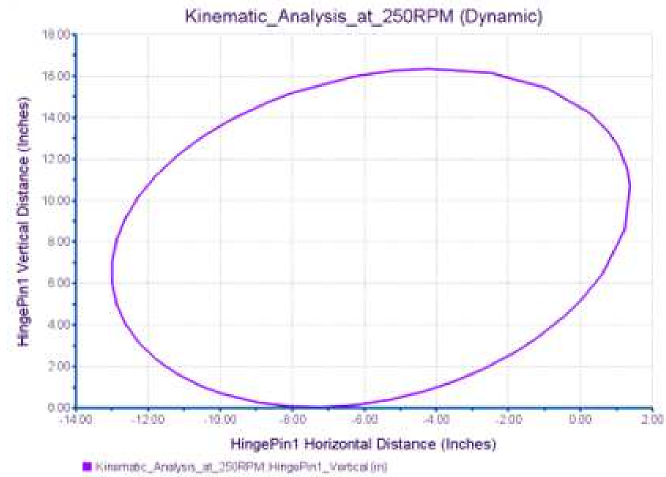

Fig. 24. Trace Curve at 250 RPM

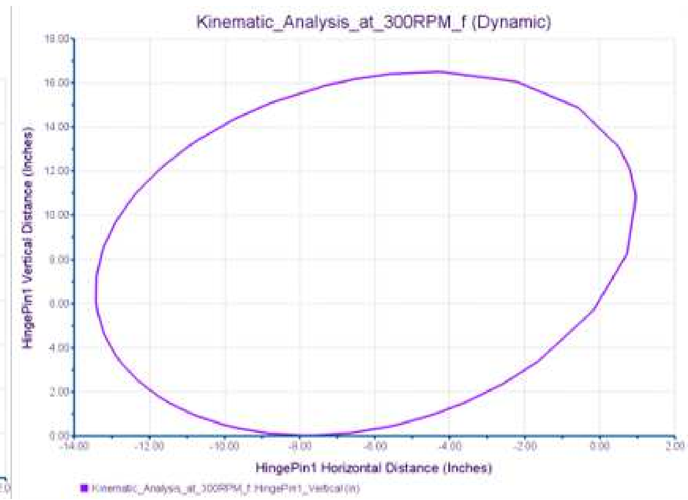

Fig. 25. Trace Curve at 300 RPM

From the results above we can conclude that the speed of movement of crankshaft does not have an impact over the hinge pin motion orbital trace curves because it follows the same path just at a faster speed now.

9.4.2 Changing Hinge Pin Offset

In this section we will observe the effect of varying the hinge pin position from its equilibrium position to apply a certain angular offset to it. Following engineering drawing shows the position where will we applying an offset:

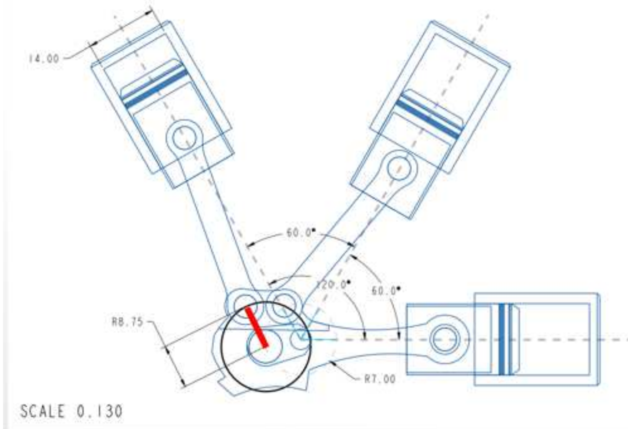

Fig. 26. Engineering Drawing with an Offset

Following are the effect on speed of varying hinge pin off set:

At e = 8.75"

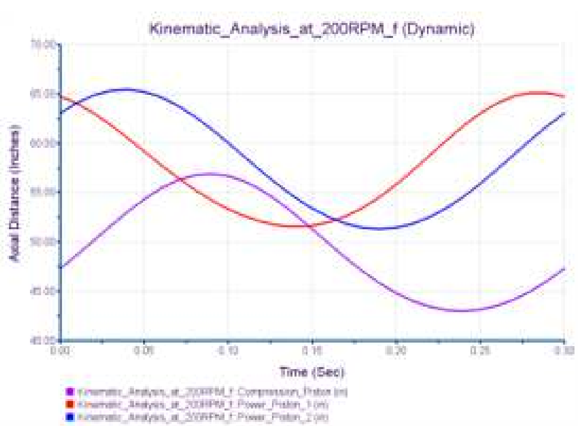

Fig. 27. Kinematic Analysis at 200 RPM with an Offset

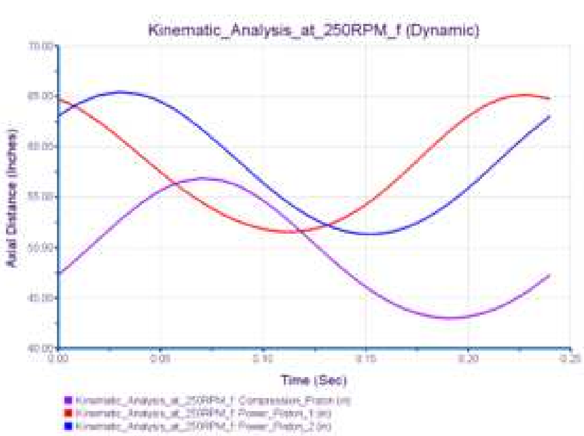

Fig. 28. Kinematic Analysis at 250 RPM with an Offset

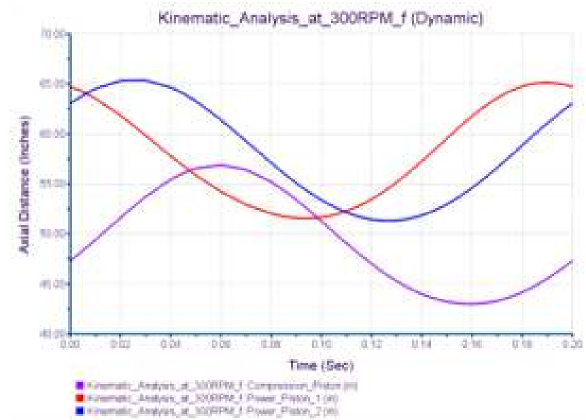

Fig. 29. Kinematic Analysis at 300 RPM with an Offset

At e = 9.00"

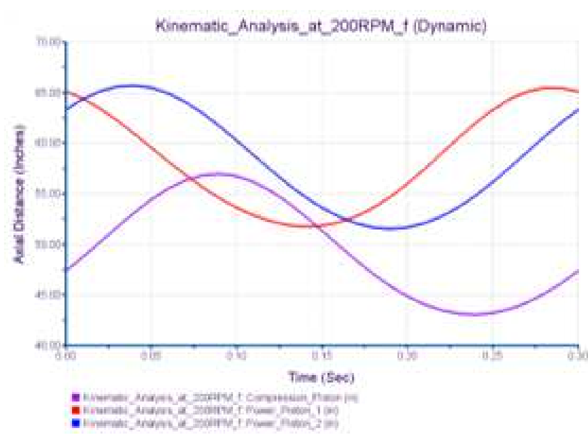

Fig. 30. Kinematic Analysis at 200 RPM with an Offset

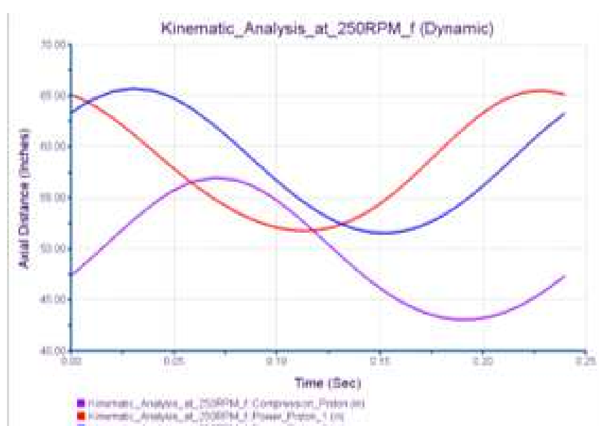

Fig. 31. Kinematic Analysis at 250 RPM with an Offset

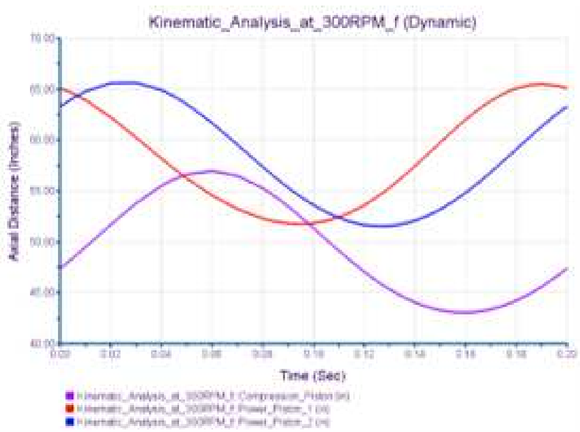

Fig. 32. Kinematic Analysis at 300 RPM with an Offset

Following are the effect on trace curves of varying hinge pin off set:

At e = 8.75”

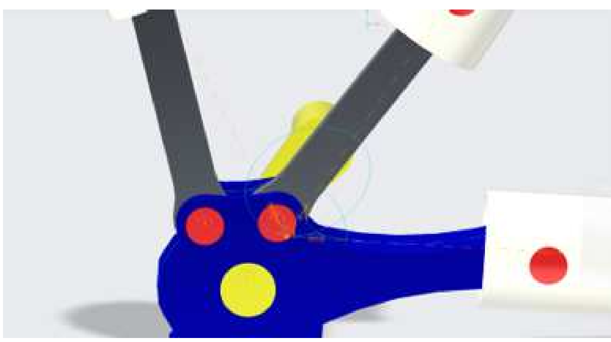

Fig. 33. Position of Hinge Pin at an an Offset

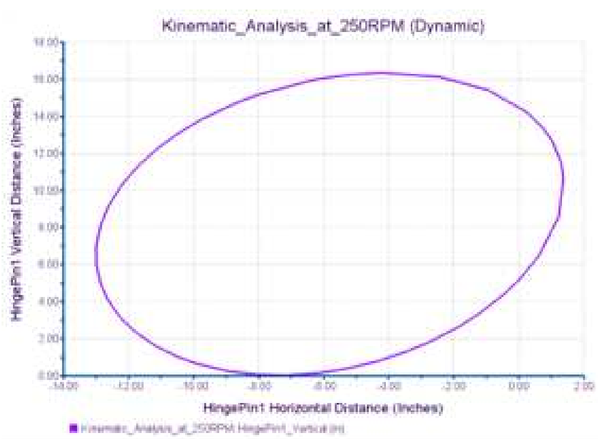

Fig. 34. Trace Curve with an Offset

At e = 9.00”

Fig. 35. Position of Hinge Pin at an an Offset

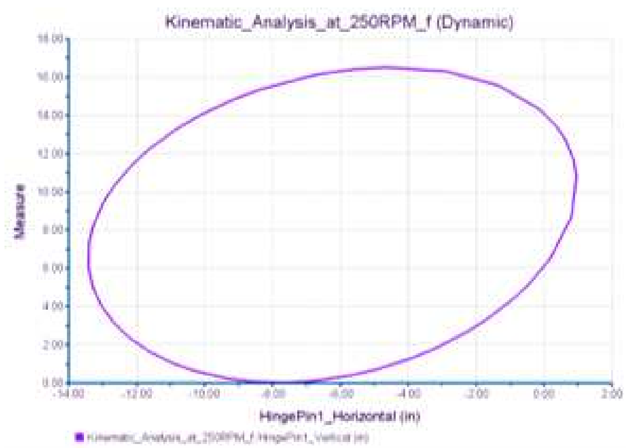

Fig. 36. Trace Curve with an Offset

Thus from the above plots we can conclude that there is no impact of an offset to the hinge over the results of kinematic analysis and trace curves of the hinge pin orbitals.

9.5 Dynamic Analysis

In this section we observed the effect of forces in our assembled GMV engine model, as per the rubrics we performed the tasks.

9.5.1 Torque Requirements

In this section we will discuss the torque requirement that are required in the project rubrics.

We calculated the torque requirement with the following torque equation

$$\text{Equation Torque (lb.in)}=63{,}025 \times \text{Power (HP)}/\text{ Speed (RPM)} - - - (1)$$

The GMV engine that we have considered has a rating of 110HP/Cyl at 300RPM [1]. We used this information to find out the rated torque output of a single piston cylinder of the engine using equation (1) to provide the rated output power for different speeds. It is observable from the table that the output torque of the piston decreases as the speed of the engine is increased. Table of our results is as follows:

Speed RPM	Power required per cylinder HP/Cyl
200	110
250	110
300	110

Output Torque lb.in	Total Power HP	Total Torque HP
34663.63	220	69327.26
27730.91	220	55461.82
23109.09	220	46218.18

9.5.2 Balancing of Crankshaft

The crankshaft was designed to be balanced by making it inverted about the axis of rotation for the consequent cylinder bank similar to the pedals of a bicycle. It can be observed from the mass property window in Creo 6.0 that the crankshaft is balanced about the X and Y axis meaning it is balanced around the axis of rotation. The rod is unbalanced in the Z-axis as the consequent crankshaft segments are not yet added. In the complete design with all the cylinder banks present the ends of the crankshafts would be made such to balance the rod in the Z-axis as well.

10 Conclusion

In conclusion, we can say that we were able to successfully design a GMV integral compressor engine with equal bore to stroke ratio and balanced shaft motion. We applied different types of analysis to obtain different physical characteristics of our virtual engine model and observed its articulated motion. We also implemented functional crank shaft sliding mechanism our model is converting the linear motion to rotary motion. We observed the speed and its changes on the motion of the engine through kinematic analysis and torque and friction is observed through dynamic analysis. Following is the results from Creo:

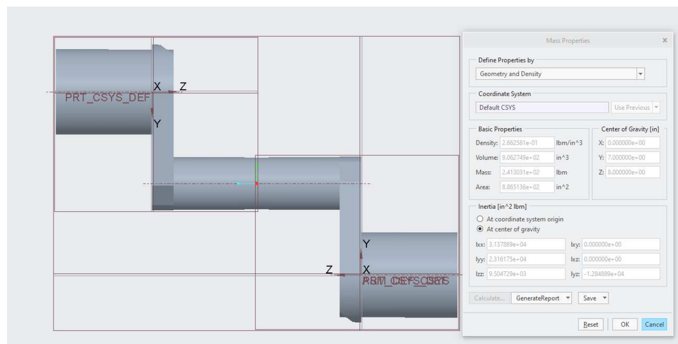

Fig. 37. Results from Creo

References

[1] M. J. Helmich, "Cooper-Bessemer Type GMV Integral-Angle Gas Engine-Compressor," ASME and Knox County Historical Museum, Mount Vernon, Ohio, 2006.

[2] Kelsey, "Kinematics of an Articulated Connecting Rod and Its Effect on Simulated Compression Pressures and Port Timings," Journal of Engineering for Gas Turbines and Power, 2018.