Parametric Study of Cam-less Engine Systems

Girish Subhash Yemul[1], Tanay Atish Deo[1], Sehaj Singh[1], Mohammed Rayyan Khan[1], Vezhavendhan R[1,*]

Abstract

This research paper focuses on designing a 2-Stroke engine that employs a cam-less mechanism for operation and performing its analysis considering various parameters like an analysis of stress (For finding the stress distribution), strain, and displacement, Steady State Thermal Analysis to determine the heat loss. The engine operation is computerized and controlled by an electronic control unit (ECU) which regulates the opening and closing of the valve/port. Its mechanism is operated by electromechanical actuators, which control the flow of the inlet air-fuel mixture, and this operation is operated by the control unit, which increases the energy efficiency, and we do not require a separate throttle valve which will increase the efficiency of our system. These types of engines are also referred to as "Free Valve Engines." In this paper, the simulations were conducted, showing that the Forced convection Air cooling method will be a better option for maintaining temperature stability. Gray Cast Iron Material was used in carrying out analysis on Dassault Systems Solidworks Software. Structural analysis also depicted that materials are safe and working under applied conditions. FMEA Form helped us detect system failures and solutions to make the system reliable and defect-free.

Keywords: Microcontroller, Electromechanical Actuator, Solenoid valve, Valve, Piston, Connecting Rod.

1. Introduction

Camshafts have been traditionally used to operate the valve mechanisms on the cylinder head to bring in air and fuel and to evacuate/release exhaust gas since the invention of internal combustion engines. The single-lobed cam is designed to operate the valves only during specific stages of the Otto cycle, preventing the engine from reaching maximum torque at higher rpm. [14] The geometry of the cam profile constrains the valves' opening and closing. The concept of cam-less engines provides for higher overall engine performance optimization during various periods of operation. Cam-less engine technology [2] is rapidly approaching commercial vehicle adoption. It has various pros, like reduction in engine noise and weight with almost infinite ratios for Variable Valve timings. [13] By removing Cams and their associated devices, we are reducing complexity and mitigating its losses. The construction has become simpler as compared to the cam-operated engines.We can use different actuators, such as hydraulic, pneumatic, and Electromechanical. Studies have shown that the Electromechanical Actuator is more reliable and durable and supports the company's requirements for commercializing this technology.An Electromechanical actuator consists of both electrical as well as mechanical components. The electric components consist of electromagnets which are nothing but ferromagnetic material (such as soft iron, steel, cobalt) wrapped tightly by copper coils, armature coils, motors (if any), solenoids, etc., whereas the mechanical components consist of springs, Pushrods, valve head, piston, connecting rods. Industrial Applications of these systems- They are very useful in automobiles, especially racing cars because of their accurate throttle response and efficiency at high rpm. The cam-less engine can emit less harmful emissions, and more precise combustion control that is complete combustion is encouraged; our cam-less engine can further reduce NOx emission with the enlightenment of fuel staging. As this

[1]School of Mechanical Engineering, Vellore Institute of Technology, Vellore, Tamilnadu, India
*Corresponding: vendhan.rp@gmail.com

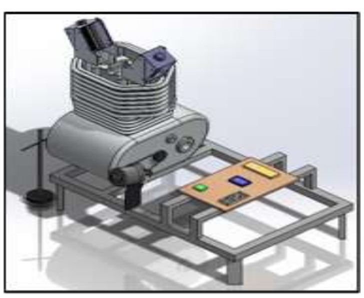
technology overcomes most of the shortcomings experienced during the operation of cam engines, it can be considered for certain potential applications in the aerospace industry. Also, this cam-less technology requires less crew maintenance, therefore being effective in marine and power stations wherein ECU and solenoid valves play significant roles during the control valve activation process.

2. Literature Review

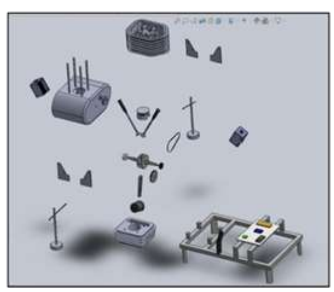
Two Stroke engines consist of only Compression and Power strokes where the air-fuel mixture is compressed inside the chamber and is finally burned to raise the temperature and pressure level, which will push the piston down and rotate the crankshaft. In the Electromagnetic / Electromechanical actuator, it was observed that the accurate control of these actuators for valves is significant for regulating airflow in the IC engine. It was eventually concluded that the actuator exhibited good dynamic performance, and its further integration with electronics will improve the overall engine efficiency and satisfy the emission standards. The microchip in the CAD model is given to represent it.The PWM (Pulse Width Modulation) collects the digital signals from Engine Control Module and converts them into analog signals, energizes/de-energizes the solenoid, which in turn opens and closes valves. The Crankshaft position sensor will determine the position or angle of the crankshaft, which will help us to manipulate the engine speed (rpm) by regulating the valve action. These regulate the movement of the valves and get the input from the control unit, which in turn decides the action of valves for controlling the engine’s breathing at different loads and rpm. We get a linear motion as an output (which is the up and down movement of valves) from rotational motion (motor input) . There are springs in the system that will store the energy and utilize it. Here we pass an electric current through an inductor that interacts with the magnetic field to produce the motion per the Electromagnetic Induction Principle. The valve movements are faster because this mechanism speeds up the processes to produce power. In this way, we can control the movements of valves and their action.

3. CAD Modeling

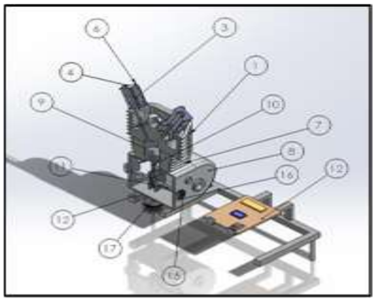
From Figure 1 (A, B, C), we can see the rendered view of the full assembly of our engine. This gives us a detailed view of the engine, its components, and how they are assembled. This section view gives us the inner view of the engine through which we can view the components, such as valves, pistons, and connecting rods, representing the mechanical system undergoing motion. The given CAD Model of the Engine is drafted on an A3 Size Sheet, and the scale is kept around 1:4. The Following views and the dimensions are projected along with the section view [Fig 1 (D)].



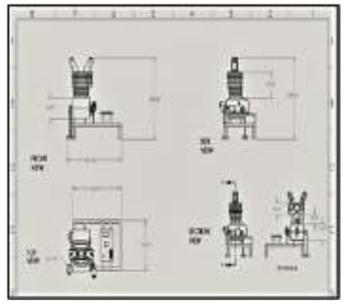
(A)



(B)



(C)



(D)

Figure 1. (A) Design of the Engine, (B) Exploded view of the design, (C) Section view of the CAD Model (Ref: Table 1), (D) Cam-less Engine Two-Stroke Drawing

The following Table 1 gives the part list of all the engine components for Figure 1b.

Table 1. Part List for Figure 1 (C)

S No.	Part Name		S No.	Part Name
1.	Engine main body		9.	Piston head
2.	Valves(2)		10.	Connecting Rod
3.	Actuator(2)		11.	Crankshaft
4.	Actuator rod(2)		12.	Chipset
5.	Clamp(4)		13.	Belt
6.	Actuator Clamp		14.	Frame
7.	Engine Body: Combustion chamber		15.	Pulley
8.	Engine Body: crank housing		16.	Stand

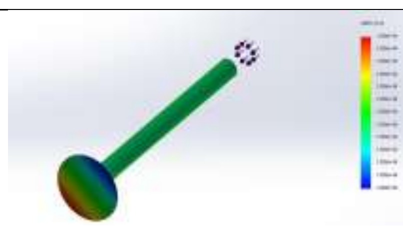
4. Parametric analysis

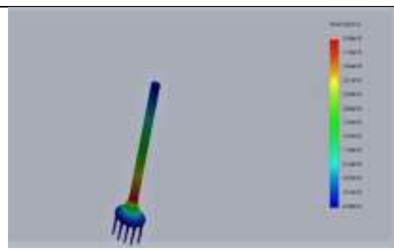
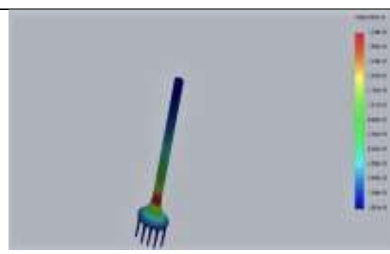
Our parametric study will involve the Static Structural analysis [1] & Thermal Analysis of parts that undergo stress and deformation during the engine's work. These are Engine Valves, Piston heads, and connecting rods. Since we are using a cam-less mechanism, we will determine its effects on these components during its operation, which will help us design these components once we compute its failure. Meshing has been done for medium size.This will help us to discretize the object into elements which will help the solver to find the accurate solution by numerical analysis. Hence, meshing is important. Finer the mesh makes the solution more accurate, but it would also take a lot of computation time, and we are getting the required results with the help of medium size mesh.Once meshing is done, we can give the applied boundary conditions to solve the problem and determine the stresses and strains at different locations across the geometry based on the mathematical equations. This will give us the values in the form of colour bands, i.e., contours that give us the region which may fail.

Valve

The valve controls the inlet mixture of air and fuel and the flow of exhaust gases from the cylinder. The springs on the upper face of the valves, which store the energy, help to put pressure on the valves to move up and down. These valves can be made of different materials such as steel, stainless steel, ductile iron, brass, cast iron, etc. These valves undergo different stresses, such as thermal and mechanical stresses. These stresses are generated due to cyclic loading, which can generate cyclic stresses. These can, in turn, reduce the valves' strength and result in failure. The tensile forces acting on them can result in stresses, too, which can wear out the component [9].While carrying out the design & simulation for the valve [8], we have defined a load of 200N on the top face. The shear stress applied due to spring was given as 175 N (for experimental purposes). Since the top surface is smaller than the opposite end, the pressure acting on it will be larger and can cause a region of Stress concentration. This is also seen in the underhead region because of abrupt change in cross sectional area. Hence it is made smooth or in round shape to reduce the stress concentration. The top region is provided with fillet and chamfers to reduce the stress concentration there. Now the applied normal and shear load is simulated to get the following results.

Table 2. Valve Simulations

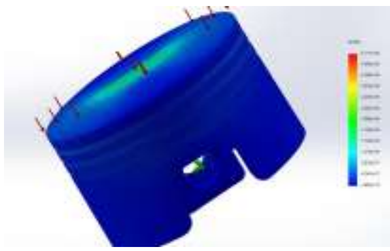
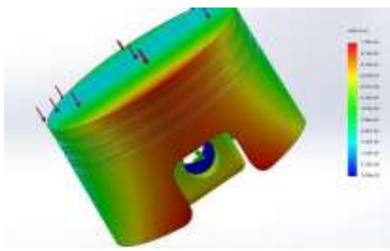
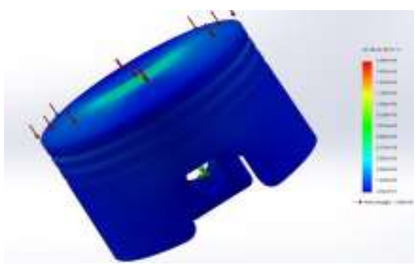
Case	Simulation	Explanation
a)Equivalent Strain		This shows us the Equivalent strain acting on the valves. The maximum strain obtained was 0.000035, and the minimum strain observed was 0.000001015, which is under permissible limits
b)Displacement		This gives us the static displacement plot as URES Scale. Through the contours, we can see that there is a uniform displacement occurring over the valve

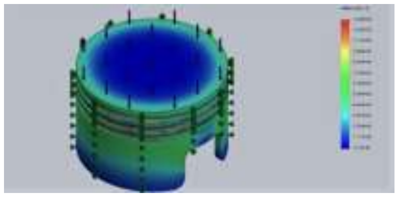
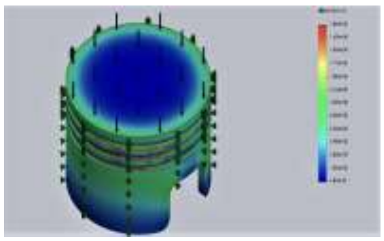
c)Stress		Finally, we determine the stress acting on the valves. Since the material used is ductile, we determine these parameters with the help of Von Mises Yielding Criteria, which helps us determine whether the material will fail. The maximum stress obtained is 15.7 Mpa, whereas the yielding strength of the material valve is 282.7 Mpa. This shows that the stress acting is under limits. Hence the component will not fail or break, and it remains safe
d)Total Heat Flux (Free Convection)		We can see a maximum heat flux of 3.459 X 10^5 W/m^2 generated through the valve head portion with the maximum temperature kept at 350 ^{0}C
e)Total Heat Flux (Forced Convection)		We can see a maximum heat flux of 1.726 X 10^6 W/m^2 generated through the valve head portion with the maximum temperature kept at 350 ^{0}C

Piston Head

Pistons are sliding members that help transmit the motion to the crankshaft via connecting rods. The linear motion is converted to rotary motion. It moves down because of the thrust provided by the combustion of the air-fuel mixture, and this energy is transmitted into the piston. Generally, we use Cast iron and cast steel as the material. We can also go with forged steel as an option for high speeds. The skirt opening has a major role in improving thermal performance. The rings are important for lubrication. These also help slide smoothly because of less contact with the side walls and affect the side thrust acting on them.The piston head is where the maximum amount of load is felt. Hence for design and simulation [6, 7, 12], we have applied a pressure of 5000 N/m^2 on the piston head, with a fixed contact at the middle for the connecting rod to determine the maximum stress which can act on the piston head [12], we have applied a pressure of 5000 N/m^2 on the piston head, with a fixed contact at the middle for the connecting rod to determine the maximum stress which can act on the piston head [12]. It is attached to the connecting rod via a gudgeon pin. Hence the simulation results are obtained as following sub-sections.

Table 3 . Piston Head Simulations

Case	**Simulations**	**Explanation**
a)Equivalent Strain		This shows the equivalent strain results for the piston head. The maximum strain obtained is 0.00000511, which is under control.
b)Displacement		This gives us the static displacement plot as an URES Scale. The maximum displacement obtained is 0.0007352 mm, which is acceptable
c)Stress		The stress on the head is determined because of the pressure acting on it, which displaces it. The maximum stress generated is 1.584 MPa, and the critical or yielding limit is 170 Mpa. Hence the design is safe and reliable. Once again, we will use the Von Mises yielding criteria for computing the yielding or failure of the material.

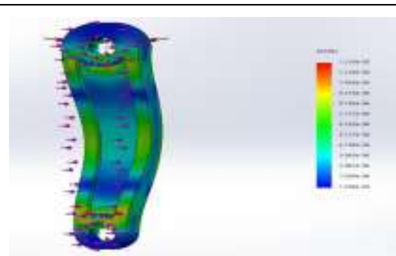
d)Total Heat Flux (Free Convection)		We can see a maximum heat flux of 1.34 X 10^5 W/m^2 generated in the piston with the maximum temperature kept at 350 ^{0}C.
e)Total Heat Flux (Force Convection)		We can see a maximum heat flux of 1.564 X 10^6 W/m^2 generated in the piston with the maximum temperature kept at 350°C.

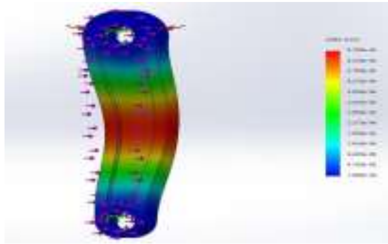
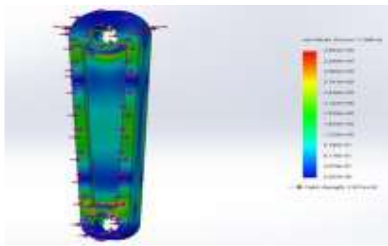
In this way, we can design the piston by considering the loads acting on it and using the Von- mises criteria as it undergoes distortion during the mechanism. We can also see that the forced convection method will give us more heat transfer rate, which will help us cool the piston and valve systems faster and ensure they are under temperature limits.

Connecting Rod

This is the intermediate link between the piston and the crankshaft. This transmits the up and down motion of the piston into the rotary motion to the crankshaft through the crankpin.These various forces act on the connecting rod, i.e., forces due to the piston, piston pin, and crankpin. Due to the loads acting on it, the connecting rods often buckle due to the compressive stresses generated. The load is acting on it axially. This is where the member (connecting rod) can bend laterally and fail at one point. The magnitude of it will be different based on the end conditions.Optimization is carried out to remove the unwanted material to reduce weight and increase strength [11]. The areas that provide low stiffness are cut out; hence, we get the shape of a connecting rod like this. Now for designing and simulating [10], we have applied a force of 25 N at the crank pinpoint and a pressure of 125 N/mm^2 on top. The results are obtained for various analyses, as shown in Table 4.

Table 4. Connecting Rod Simulations

Case	**Simulations**	**Explanation**
a)Equivalent Strain		The strain equivalent is calculated, and the maximum value obtained is 0.00001228. within the limits and acceptable.

b)Displacement		This gives us the displacement plot curve on the URES Scale, and we obtain a maximum value of 0.00057 mm.
c)Stress		The maximum stress produced is 3.65 MPa, and the yield limit for Von Mises criteria is 282.7 Mpa. Hence it is safe and reliable.

5. Results

Hence, using Von Mises criteria, we could determine the safe limits for our design. This plasticity theory is applicable to the ductile materials we use so that we can know about the failure that does not occur suddenly. It can be used under different types of loading conditions. This is also termed the “Maximum Distortion Energy Theorem.” In this way we carried out parametric analysis of structural components of our engine for designing and making them safe and reliable to use.By using Heat Transfer equations we determined the heat losses acting on the piston and valve systems and found out that forced convection method of cooling is better to maintain thermal stability at high temperatures. We have also carried out FMEA Analysis of the engine components associated with the Cam-less setup. FMEA (Failure Mode and Effects Analysis) [3] is an organized way to analyze all the components by listing down their failure states, what harm they can cause and how they can be detected and avoided. We will be able to predict which component is more susceptible to failure by the RPN (Risk Priority Number) which give us which components failure is dangerous and should be taken into consideration earlier.

RPN = Severity (S) x Occurrence (O) x Detection (D)

FMEA Ratings are scaled from 1 to 10 where 10 should be considered as first priority and 1 should be considered as the last priority. The **FMEA Form** is given in Table 5.

Table 5: FMEA Table

FMEA NO.	Component/Item	Function	Failure Mode	Failure Cause	Failure Effect	S	O	D	RPN	Failure Detection

1	Valves	Control the inlet & exhaust supply of air- fuel & exhaust gases	Leakage of air-fuel mixture. Improper timing of opening & closing	Piston striking can cause bending of it, error in programming for timing	Fuel is wasted and efficiency has been affected	7	6	7	294	Valve position sensors will detect the position of valve and send signals to ECU
2.	Piston	Transfer the thermal energy during combustion into mechanical motion	The member will wear out and leakage of fuel can occur through piston rings	Because of friction forces generate during continuous up and down motion	Power loss during every stroke	6	5	7	210	Leak-Down test
3.	Connecting Rod	Transfers linear motion of piston into rotary motion	Buckling	Excessive Compressive loading, fatigue loading	Bending of rod, collapsing, and breaking	7	7	2	98	Visible Inspection of rods, Oil pressure gauge as oil pressure reduces because of leaking
4.	Electromechanical Actuator	Actuates valves up and down motion	Incorrect timing of opening and closing of valves	Error in programming	Valve failure, improper combustion, decrease in fuel efficiency	9	4	6	216	Control Unit and feedback controller
5.	ECU (Electronic Control Unit)	Controls the operation of engine systems	Incorrect processing of signals	Electromagnetic Interference affects functioning of circuit	Risk of accident, failure in operation	10	4	6	240	Circuit Testing of ECU

Hence, we can see that the RPN of Valves is the highest [Table 5] as it is the main component in the engine system responsible for the fuel's control flow rate. If it fails, the whole engine setup will fail as there will not be proper combustion, and engine performance will be severely affected. Fuel leakage will occur thereby reducing efficiency of the engine.Followed by ECU which once gets affected will result in severe mismanagement of all the operations and affect the process.

6. Conclusions

We can see that the safety limit is reached for each parameter, as seen in the chart. Compared to conventional engine stresses and displacement we see that the stresses and displacement would be more due to frictional stresses from cam and follower movements. Also, for the connecting rod we can see that for the given force the displacement is very large and would be almost the same for the conventional engines. Hence, we can say that as these factors can play key roles in defining load on an engine which in turn will affect fuel consumption, cam-less engines can be very effective in this regard and can also be permanently employed in engine manufacturing. Since we used Gray cast iron for piston and valve systems as they have better thermal conductivity which allows us to ensure that heat is transferred quickly and our free valve system remains under control and thermally stable and we can use a forced convection cooling setup to achieve these results. We also carried out FMEA Analysis to develop our product [4] which will help us to manufacture it and optimize it. We carried out the following parametric analysis of the components which falls into this cam-less Engine setup to develop and design a cam-less Engine over Traditional Camshaft based Engines. Furthermore, we look forward to improving our study by embedding advanced electronics to estimate accurate and fast response from the engine.The advantages of Current Design is that it gives a reduced overall size of the system, making it more compact to install thereby decreasing the constraints. Along with the size the simulation results determine the failure points and optimize it. Having electromagnetic actuators installed replacing conventional camshaft systems help us in achieving better control of the system and making our design more efficient as the whole free valve system is structurally and thermally stable as concluded.

References

[1] Gill, K. J. S., Cho, H. M., Lim, H. C., Chauhan, B. S., & Park, D. H. (2014). Static structural analysis of crankshaft for single cylinder cam-less engine. Journal of Energy Engineering, 23(3),231–234. https://doi.org/10.5855/energy.2014.23.3.231

[2] REVIEW ON CAM-LESS ENGINE. (2017). 5(3), 1–6.

[3] Danny, F., & Shariman, M. (2013). Failure Mode and Effect Analysis of Diesel Engine for Ship Navigation System Improvement.

[4] Stamatis, D. H. (2003). *Failure mode and effect analysis: FMEA from theory to execution*. Quality Press.

[5] Pal, A., Sahani, A., Shukla, K., Shinde, S., & Mate, A. (2018). Design And Modification Of cam-less Engine: A Review. International Journal of Scientific & Engineering Research, 9(5), 263–272. http://www.ijser.orghttp//www.ijser.org

[6] Srinadh, M., & Rajasekhara, K. B. (2015). Static and thermal analysis of piston and piston rings. *International Journal of Engineering Technology, Management and Applied Sciences*, *3*(8), 51-58.

[7] Bhattacharya, S., Basu, A., Chowdhury, S., & Upadhyaya, Y. S. (2014). 'Analysis of Piston of Two Stroke Engine. *International Journal of Research in Engineering and Technology*, *3*(06), 642-648.

[8] Kumar, G. U., & Mamilla, V. R. (2014). Failure analysis of internal combustion engine valves by using ANSYS. *AIJRSTEM*, *14*(183), 169-173.

[9] Raghuwanshi, N. K., Pandey, A., & Mandloi, R. K. (2012). Failure analysis of internal combustion engine valves: a review. *International Journal of Innovative Research in Science,Engineering and Technology*, *1*(2), 173-181.

[10] Haider, A. A., Kumar, A., Chowdhury, A., Khan, M., & Suresh, P. (2018). Design and structural analysis of connecting rod. *International Research Journal of Engineering and Technology*, *5*(5), 282-285.

[11] Muhammad, A., Shanono, I. H., & Shanono, I. H. (2019). Static analysis and optimization of a connecting rod. *Int. J. Eng. Technol. Sci.(IJETS)*, *6*(1), 24-40.

[12] Zhao, S. G., Li, K., & Gao, Z. X. (2013). Design the Piston of Internal Combustion Engine by Solidworks. In *Advanced Materials Research* (Vol. 749, pp. 546-549). Trans Tech Publications Ltd.

[13] Regner, G., Johnson, D., Koszewnik, J., Dion, E., Redon, F., & Fromm, L. (2013). Modernizing the opposed piston, two stroke engine for clean, efficient transportation. *SAE technical paper*, *26*(2), 0114.

[14] Herold, R. E., Wahl, M. H., Regner, G., Lemke, J. U., & Foster, D. E. (2011). *Thermodynamic benefits of opposed-piston two-stroke engines* (No. 2011-01-2216). SAE Technical Paper