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Rack And Pinion Mechanism for Continuous Variable Valve Timing of IC Engines

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Abstract
The valve timing is a very closely studied event and effects the performance of an IC Engine greatly with respect to the Brake Power Produced, Volumetric Efficiency and Emissions etc. The valve event if varied and experimented with, can result in higher efficiencies and overall improved performance of the Engine. Hence, various researchers have attempted to temper with the valve timing and thus many Variable Valve Timing systems have been proposed till date with many of them being implemented by various manufacturers. However, on reviewing the presently employed systems, the lack of existence of a single system capable of independently altering both the timing and the lift of the valves was recognized. Thus, a single system capable of achieving the above was thought of and designed. A rack and pinion mechanism powered by a programmed servo motor mounted vertically seemed most practical in achieving this within the size and space constraints. A single cylinder diesel Engine was simulated with 'Lotus Engine Simulation' software to derive the optimum valve angles and lifts for a range of the Engine operating speed and the system was accordingly programmed and designed to achieve them. The system was designed in 'Creo' software and analysed correspondingly in 'Ansys' software and then finally assembled on a Diesel Engine in the lab.
Keywords: Variable Valve Timing, Rack and Pinion Gear system, Servo Motor, Crankshaft position sensor, volumetric efficiency

I. Introduction

In internal combustion engines, Valve timing is the event of the opening and closing of the inlet and exhaust valves respectively. It is denoted in terms of the crank angle at which the event occurs with respect to the TDC and BDC positions. It is one of the most important parameters in the Suction process and influences the Engine performance up to a great extent. It is found that the Optimum Valve Timing, Lift and duration settings at low engine speeds are quite different from those at high engine speeds. Any optimal setting accordingly would cause lesser amount of Air and fuel at high speeds resulting in loss of power output. Similarly, any setting for high speeds would result in difficult idling and very rough engine performance at low speeds. Thus most cars use a setting which is in the mid-Engine speed range thus compromising on the low and high speed ends vehicle performance. Thus a need for a Variable type of valve timing setting was recognized which would thus not compromise on the Engine performance over the spectrum. Variable Valve timing (VVT) is the process of altering the timing and/or Lift of a valve lift event and is often used to improve performance, fuel economy and emissions. There are many ways in which this can be achieved, ranging from mechanical devices to electro-hydraulic and cam-less systems. Increasingly strict emissions regulations are causing many automotive manufacturers to use VVT systems although; their use is still limited to high-end cars due to cost considerations.

II. Literature Review

First, a basic understanding of the impact of the change in opening and closing timings of both the inlet and the exhaust valves was felt to be acquired. Upon researching it was realized that in general at low engine rpms, it is desirable to have lesser valve opening angles i.e. lesser IVO (bTDC), lesser IVC (aBDC), lesser EVO (bBDC) and lesser EVC (aBDC). The reverse is the case at higher engine rpms where higher amounts of all the above angles are desirable [1].

There are many ways in which VVT can be implemented. Many of these methods have thus been developed and put in use by Car manufacturers. The first among them is **Cam switching** where an actuator is used to swap between two or more Cam profiles. The actuation is done by mainly pneumatic or hydraulic means. This system is mainly adopted by manufacturers like Honda and Fiat (i-VTEC which stands for intelligent Variable Valve Timing and lift Electronic Control). However, the major problems with these systems are viscosity change of the oil in hydraulic systems with temperature needing expensive insulation techniques and large power needed for an air compressor in case of the pneumatic ones and the major problem is the discrete nature of these type of systems with the use of at most 2-3 Cam lobes possible due to space constraints and hence optimization only for 2-3 rpms, i.e. generally one for low speed and one for high speed.

Another method implemented is the **Cam Phasing**. This is done by giving a slight rotation to the Cam shaft with respect to the Crank shaft by a device known as a variator to create a phase change between them thus varying the opening and closing angles of the valve but maintaining the total duration of the valve lift event constant. This allows continuous adjustment of the cam timing however the duration and lift cannot be adjusted which is a disadvantage. A typical type of this system was proposed by Osama H.M Ghazal and Mohammed S.H Dado in their paper “Gear drive mechanism for continuous variable valve timing. [2]

Another system employed is the **Oscillating Cam** mechanism which uses an oscillating or rocking motion in a part cam lobe, which acts on a follower.This follower then opens and closes the valve. The BMW (valvetronic), Nissan (VVEL), and Toyota (valvematic) oscillating cam systems act on the intake valves only.The advantage of this design is that adjustment of lift and duration is continuous. However in these systems, lift is proportional to duration, so lift and duration cannot be separately adjusted.

The most new and novel method in VVT are the **Camless systems.** These do not rely on a camshaft to operate the valves and have greater flexibility in achieving variable valve timing and variable valve lift [3].Camless systems use electromagnetic, hydraulic, or pneumatic actuators to open the poppet valves instead. Common problems include high power consumption, accuracy at high speed, temperature sensitivity, weight and packaging issues, high noise, high cost, and unsafe operation in case of electrical problems as reported by Chihaya Sugimoto et al.in their paper “Study of Variable Valve timing using Electromagnetic Mechanism”[4].

Thus on reviewing each of the above systems and examining their advantages and disadvantages we hereby propose a system attempting to do away or minimize the disadvantages while ameliorating the advantages.

III. The Need to Develop a new VVT system

On reviewing the systems in the Literature review we concluded that all the presently proposed systems vary either only the timing of the valve opening and closing event by either Cam phasing (Prof. Dado), Cam Switching (i-VTEC) or eccentric Cam (Toyota) or only the valve lift (BMW’s Double Vanos and Ferrari’s 3D Cam lobe) but until now there is no one single system which has the capability of changing the valve timing as well as the valve lift independently of each other. Also, most of the above systems achieve discrete VVT i.e. optimized for 2 or 3 rpms, generally one for low speed and one for high speed like the Honda’si-VTEC technology, but this leads to a considerable loss of efficiency at other engine rpms which is thus overcome by the new Continuously Variable Valve Timing systems (CVVT) which vary the valve timing continuously over the Engine rpm range rather than at discrete levels. Therefore, the need to develop and synthesize a system which could vary the Valve Lift and Timing both, independently of each other and also do so Continuously rather than in 2 or 3 discrete steps was felt and hence attempted for.

IV. Working of The proposed System

As shown in the Cad model below (Fig.1), it consists of a Servo motor connected to a Rack and Pinion arrangement which is in turn connected to the lever arm of the Valve Arrangement.

The crankshaft position sensor gives input data of the current engine rpm and the crankshaft position (degrees) as input to the Arduino microcontroller of the servo motor. The data regarding the valve timing and lift at different engine rpms is already pre-fed to the microcontroller based on the simulation of the Engine by the LOTUS Engine Simulation Software. Thus depending on the Engine speed the microcontroller chooses the correct valve actuation timing and lift and with the crank position input (degrees) from the crankshaft position sensor, rotates the servo motor at the required time for the desired amount of angle. This rotation of the servo motor then translates into the rotation of the pinion gear of the rack and pinion arrangement, which is keyed to its shaft, which thus causes an equivalent translatory movement of the rack. As the rack is connected to the lever arm it thus causes a differential actuation of the valve depending upon the amount moved by the Rack. Thus a differential amount of rotation of the servo motor will amount to a different valve lift at each rpm. As the servo motor is made to rotate precisely at the desired angle by input from the crankshaft position sensor and the microcontroller, Valve Timing is possible to be varied for many rpms. Thus in the above way, this system can provide a variable valve Timing along with a variable valve lift with a high accuracy due to the use of a microcontroller powered servo motor. How this system was synthesized as shown in the methodology below and the corresponding results obtained are discussed later.

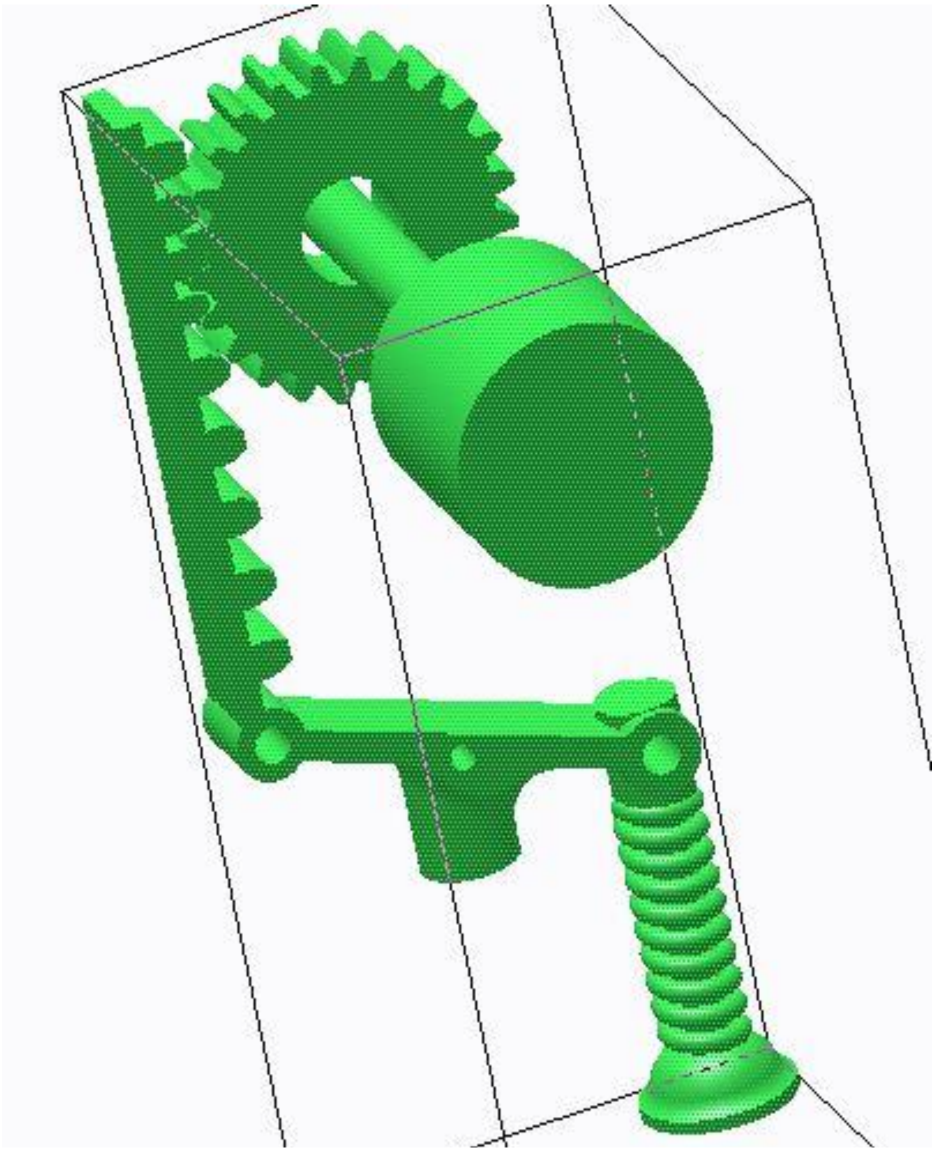


Fig 1. – CAD Model of System

V. Methodology Adopted

5.1) First, A Cad Model of the system was made for better understanding and conceptualization using CREO 1.0 PTC Software (Pro-E).

5.2) Next, An appropriate Engine was selected for the experiment which is the Ganga Diesel Engine adopted due to its single cylinder nature and simple cylinder head making the mounting of the system simple and feasible. All the dimensions and parameters needed for designing of the system like the current Valve timing diagram, valve throat dimensions, cylinder dimensions etc. were measured or obtained from the Engine manual and thus here we show the method we adopted for fabrication. Any other fabrication can be done similarly for any other desired Engine.

5.3) Lotus Engine Simulation for the above mentioned Engine was performed and all the required performance characteristics of the Engine found out. A sample screenshot of the simulation is as shown below.

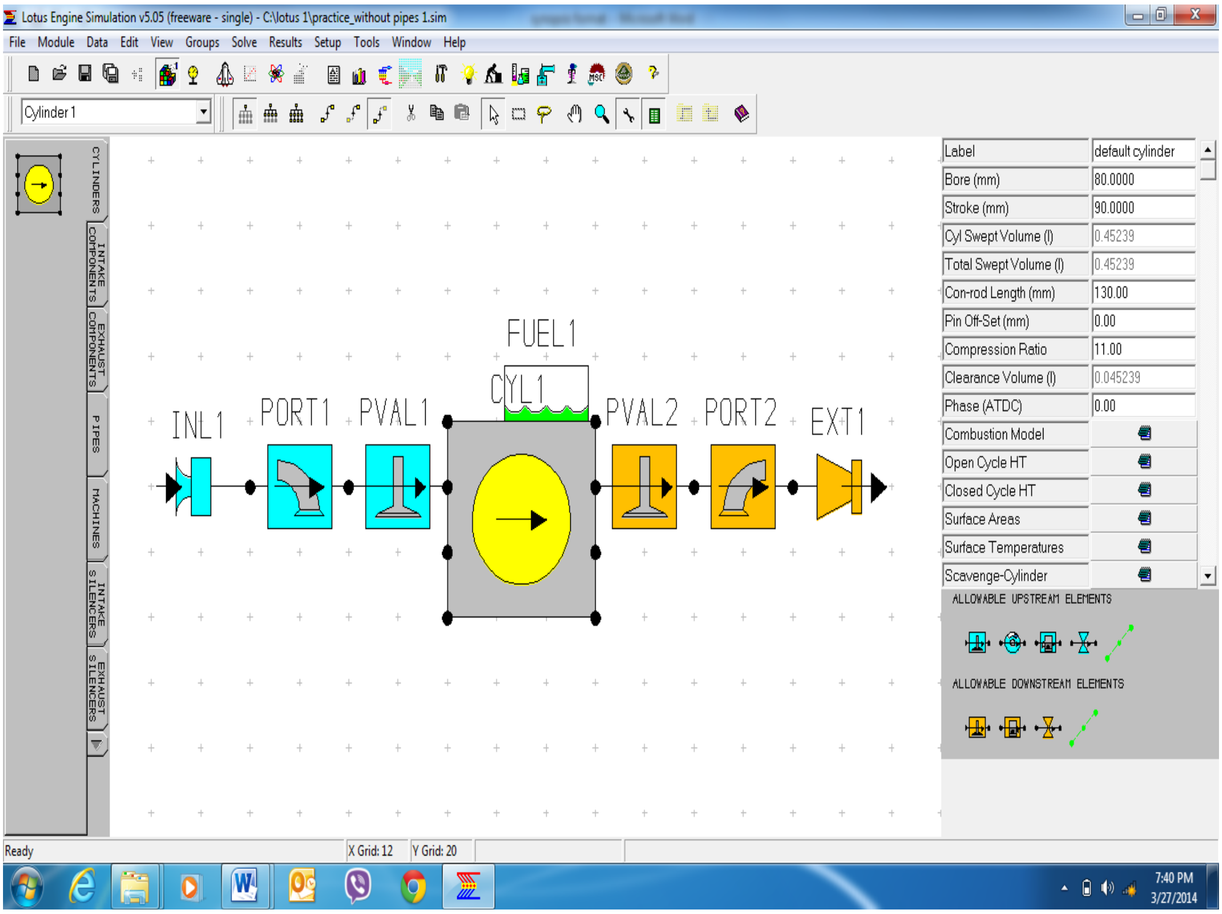


Fig.2- Lotus Software Simulation

5.4) Using the parametric option of the Lotus software, a variable valve timing experiment was carried out in which, keeping all the other parameters constant, the valve opening and closing times and the Valve Lift were varied for a range of Engine rpms and the corresponding change in the Volumetric efficiency noted. (Fig 7).Then the valve opening, closing and Lift Values which provided the maximum volumetric efficiency for each rpm were selected and the corresponding graphs were plotted.(Fig 3)

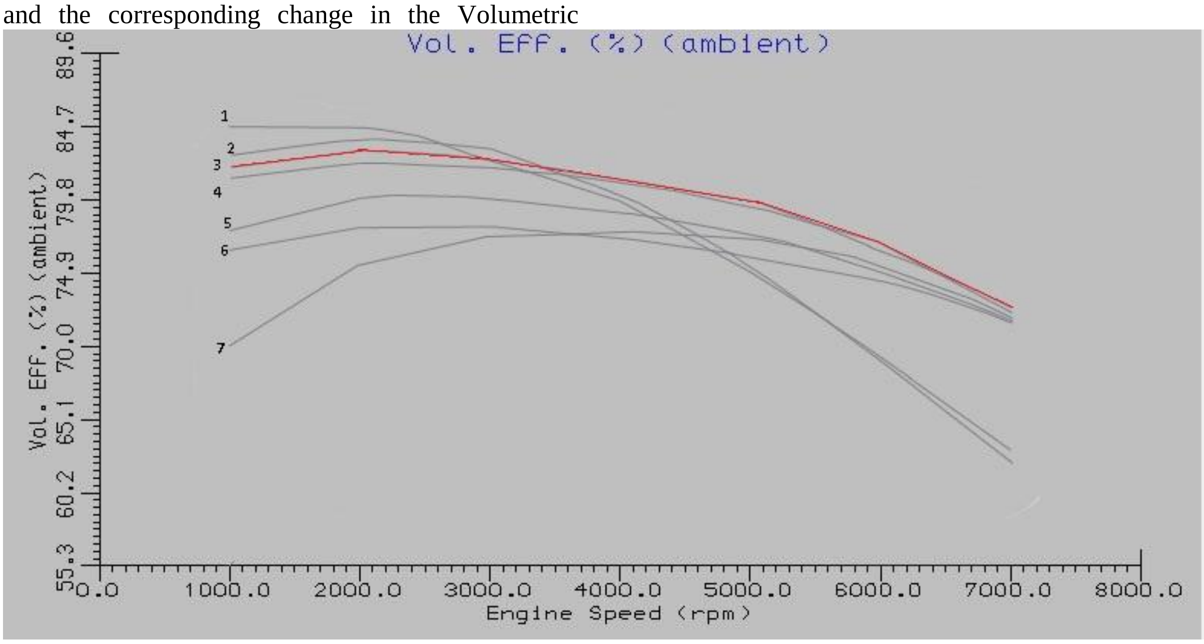


Fig 3 – Volumetric Efficiency curves for optimum Inlet valve opening and closing angles.

Red Line- Overall best Valuesor pre-set Engine Valve timing values (Graph No.3)

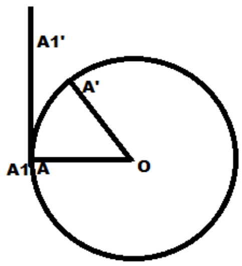
Table 1- Optimum valve Angles for different Engine rpms

Graph No.	Speed	IVO (TDC)	IVC (BDC)	Lift (mm)	N_{vol} (efficiency %)
1	1000	0^0	0^0	6	84.5
2	2000	0^0	0^0	7	84.5
3	3000	10^0	15^0	8	83.5
4	4000	20^0	25^0	9	82
5	5000	20^0	35^0	10	79
6	6000	25^0	45^0	11	77.5
7	7000	25^0	45^0	12	73.5

5.5) Servo Motor Rotation Angle calculations.

For the obtained Valve Lifts of the Inlet Valve at each Engine rpm as mentioned above in the Lotus simulation analysis we now thus need to calculate the extent of rotation required by the servo motor for each of the lifts so as to program the motor accordingly for the desired angle.

A sample calculation for a valve lift reading is as shown below. The other calculations were done in a similar manner and the result thus tabulated.



The above circle represents the pitch circle of the pinion gear and the tangential line drawn to it at the left is the rack respectively. Let A be a point at the circumference of the pinion meshing with the corresponding point A1 on the rack. Thus as the rack moves up linearly due to the servo motor rotation for the valve actuation, the point A1 reaches point A1' and consequently point A reaches point A' on the pinion gear. Thus if A1-A1' represents the rack movement for a particular valve lift, A-A' will represent the corresponding pinion rotation.

Let valve lift, L= 13mm

Lever arm ratio = 4:5

Therefore required lift at the rack end of the lever arm,

$$X = 13 \times 4 \div 5$$
$$=10.5\text{mm}$$

Therefore, A1-A1' = A-A' = 10.5mm

Let us denote A-A', the required arc length by S.

We know that, S = R θ (Arc length to angle conversion formulae)

Where, R=Pitch circle radius of the Pinion gear = 20mm (Assumed) and θ = angle corresponding to arc A-A'

Therefore, $S = R\,\theta$

$10.5 = 20 \times \theta$

Therefore, $\theta = 0.525$ rad $= 30^0$

Therefore, as shown above 30^0 is the rotation required by the servo motor for the valve lift of 13mm. Therefore, similarly we calculate the angles corresponding to other valve lifts and the result is tabulated as shown below.

Table 2- Servo Motor Rotation Angles

Sr. No.	Speed	Lift (mm)	Servo Rotation (degrees)
1	1000	7	16
2	2000	8	18
3	3000	9	20
4	4000	10	23
5	5000	11	25
6	6000	12	27
7	7000	13	30

5.6) Servo Motor Design. After obtaining the required servo motor rotation angles, we need to calculate the torque required by the servo motor so that a servo motor with sufficient torque rating can be obtained. This was done as follows: Since the valve actuates against the cylinder pressure near the end of the exhaust stroke, the servo motor should provide sufficient torque to overcome that pressure. Therefore,

Pressure inside cylinder at Valve opening, P = 0.95 bar (obtained from Lotus Simulation)

~ 1 bar

(higher value assumed)

Area of Valve throat, $A = \pi \div 4 \times D^2 = \pi \div 4 \times (34.1\times10^{-3})^2 = 9.132\times10^{-4} m^2$

Force acting at the Valve Throat, $F = P\times A$

$=10^5 N/m^2 \times 9.132\times10^{-4} m^2 = 91.32 N$

Lever Arm length ratio: = 4:5

Therefore, $F_2 = 91.32\times5\div4 = 114.15$ N

Where, F_2 = Force acting at the connecting rod end of the lever arm

Assuming a service factor, C_s= 1.25 for Light shocks with 8 to 10 hours operation per day, (from Design Data Handbook)

Let F_t = Tangential Tooth Load acting on the Pinion Gear

$F_t = C_s \times F_2 = 143$ N

Assuming the Pinion to have a pitch diameter of 40 mm,

Torque Required T = 143N × 0.02m= 2.86 N-m ~ 30 Kg-cm

Torque required by the Servo Motor = 40 Kg-cm(Higher value assumed for safety)

5.7)Gear Design. The next step was to design the gears accordingly so as to be able to bear the stress produced by the Tangential force F_t acting as calculated above.

As the diameter of the pinion was assumed as 40 mm in the previous step, a module of 2mm was assumed as it is easily available from manufacturing point of view, therefore the number of teeth Z on the pinion is given by:

$z = d \div m = 40 \div 2 = 20$ teeth

The stress induced was accordingly found out by design calculations and was of the order of 20 N/mm^2. Hence, Steel is chosen as the material of choice due to its anti-rusting properties, ease of availability and high permissible stress than the value calculated above.

A rack of around 50mm length was found to be sufficient to provide the desired lift and also accommodate for minor machining operations required to mount it onto the lever arm. An 18mm square cross-section was found to be sufficient to accommodate the stress induced. Thus the preliminary gear design is concluded.

5.8) Ansys Analysis: Furtheran ANSYS analysis using Ansys 14.5 software was performed to validate the results of the manual calculations and to provide more accurate and variety data for the structural fabrication. A screenshot of the analysis is as below

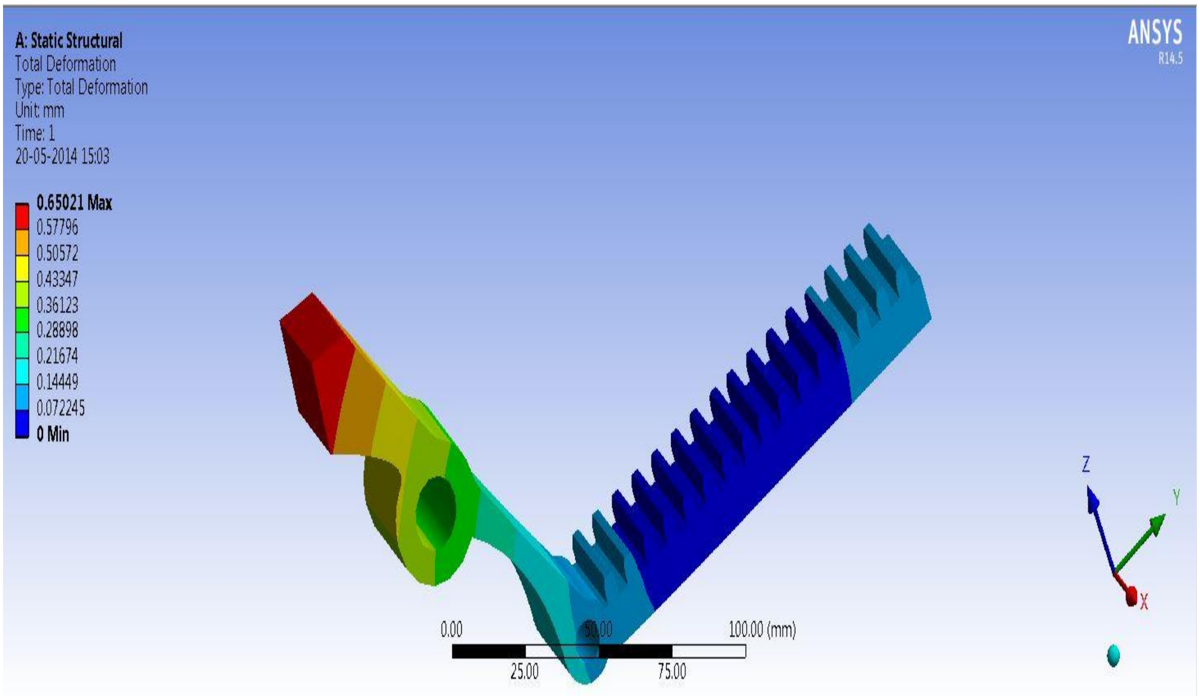


Fig.4-Ansys Structural Deformation Analysis of Rack with Lever Arm

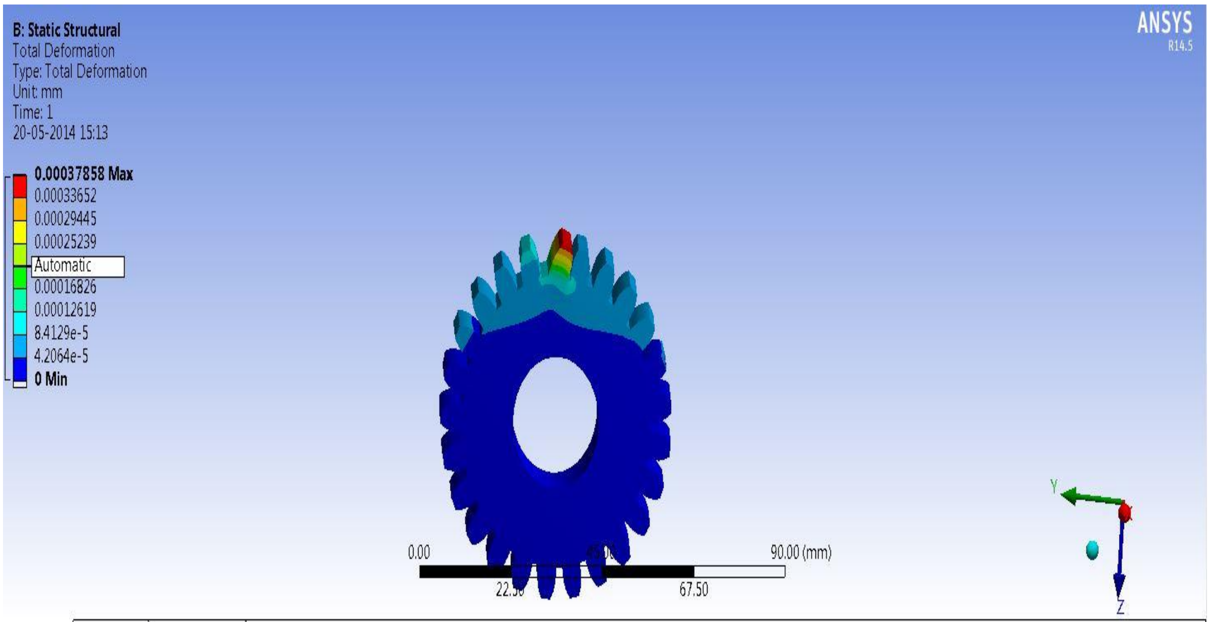


Fig.5- Ansys Structural Deformation Analysis of Pinion Gear

The complete results of the Ansys analysis is as shown in the table below.

Table 3- Ansys Structural Analysis Results

Rack	Pinion
Maximum Stress Induced = 116.39Mpa	Maximum Stress Induced = 5.08Mpa
Maximum Strain Induced=5.81×10^{-4}mm/mm	Maximum Strain Induced =2.6×10^{-5}mm/mm
Maximum Deformation = 0.6502mm	Maximum Deformation = 3.8×10^{-4}mm

The Ansys analysis pointed to maximum stress and strain values well within the permissible range of the material chosen. Also it is to be noted that maximum stress/strain and deformation occurs at the point of contact of the Rack and Pinion meshing tooth. This concludes the end of the design stage which was then followed by fabrication and assembly.

5.9) Fabrication and Assembly. As the designing stage was concluded and the chosen design values found safe, the required components i.e. the Servo Motor, Rack and Pinion Gear pair etc. were obtained and assembled. A Universal Joint was incorporated between the rack and the lever arm to compensate for the angular motion of the lever arm and cause the rack to slide linearly. The Arduino Microcontroller powering the Servo Motor was programmed according to the values obtained in table. The system after assembling on the Ganga Diesel Engine cylinder head is as shown in the Figure below

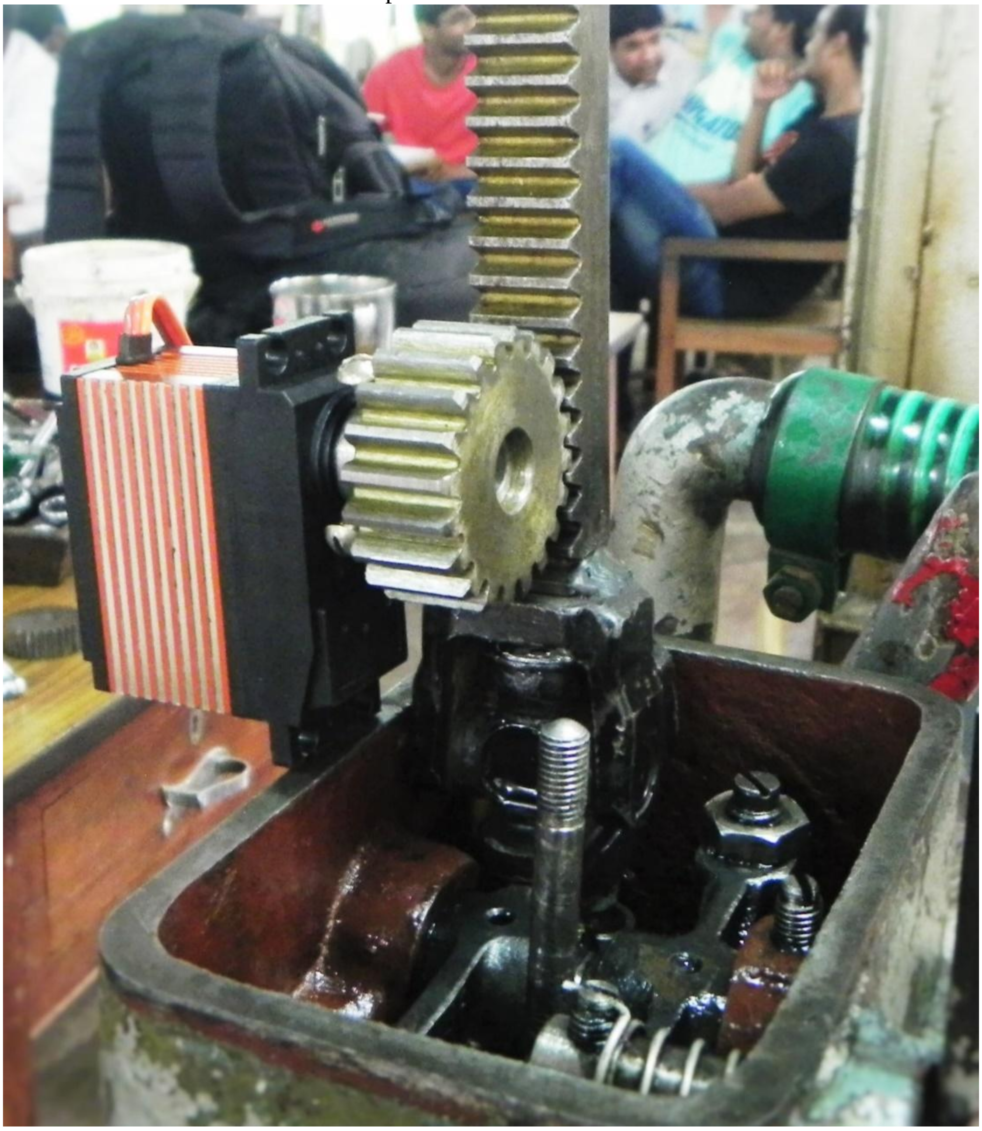
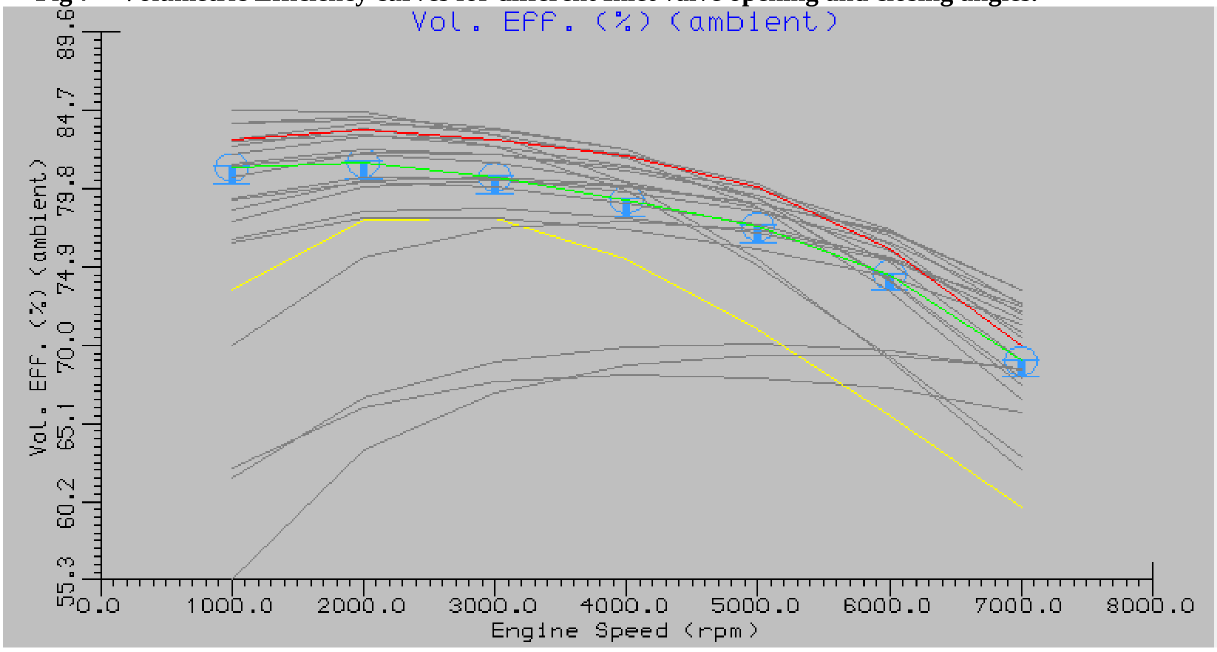


Fig.6- Picture of the System installed on the Engine Head

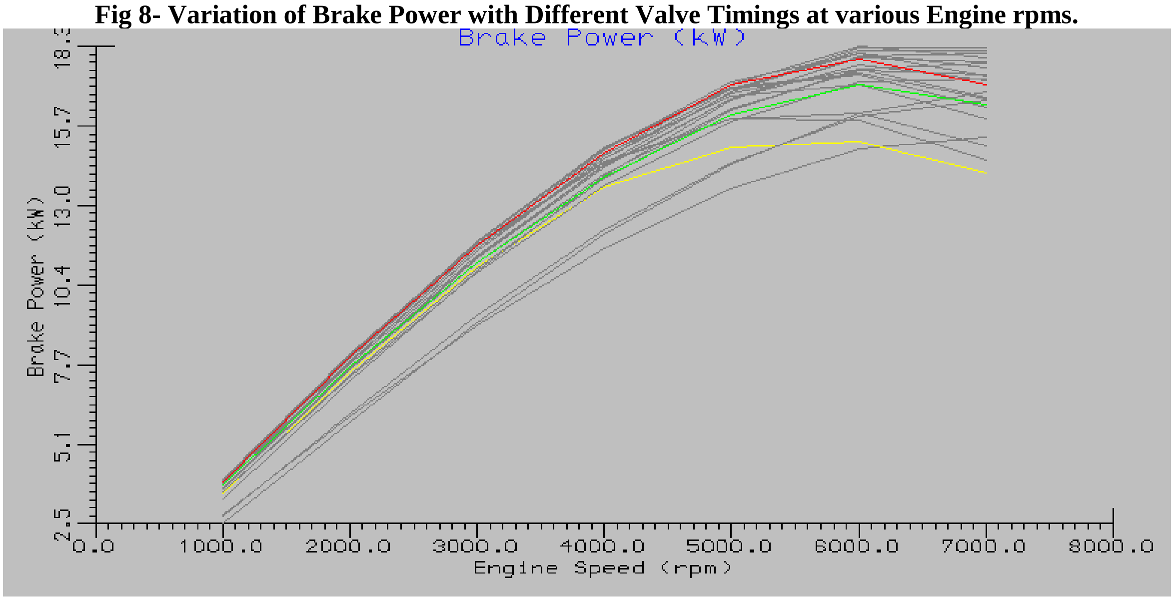
VI. Results

Fig 7 – Volumetric Efficiency curves for different Inlet valve opening and closing angles.



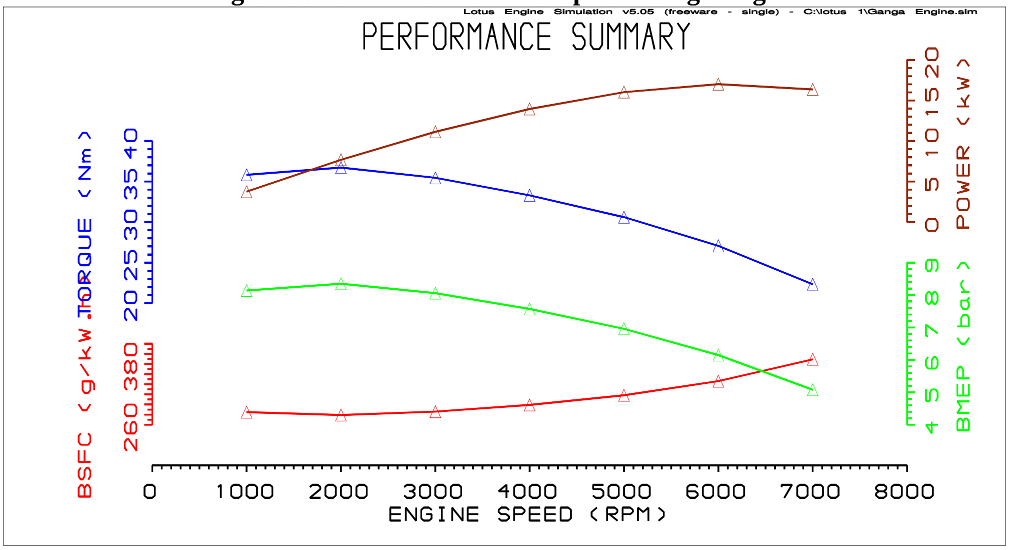
The optimum 9 curves in **Fig.2**earlier are selected from these curves.
Variation of Valve timing done: IVO: 0-50^0 IVC: 0-90^{0}Valve Lift: 6-12mm
Red Line- Overall best Values   Green line- Default Engine Values
Yellow line- Picked Value (Current)

Fig 8- Variation of Brake Power with Different Valve Timings at various Engine rpms.



The above Graph indicates that Brake Power, BSFC and BMEP are indeed dependent on the Volumetric Efficiency as the graph with higher BP indeed is the one with higher Volumetric Efficiency (Red)

Fig 9- Overall Performance Graph of Ganga Engine



VII. Results Analysis

1. The valve timing values which give the highest volumetric efficiency at a given speed is indeed the one which gives the highest Brake Power, Highest BMEP and in turn lower BSFC. Thus maximizing the Volumetric Efficiency was indeed made the aim of experimentation.(Fig 8)
2. Increasing the valve lift compensates the need for higher Inlet Valve opening and closing angles at higher rpms ie.in the sample run without varying the valve lift IVO and IVC values as high as 55^0 and 90^0 respectively were obtained for maximum efficiency curves which could be contained to 25^0 and 45^0 upon increasing the Lift. (Table 1)
3. The Volumetric Efficiency at Higher Engine rpms decreases in general. This result is in accordance with the wire drawing effect theory in IC engines. (Fig 7)
4. There was found to be an approximately 10% increase in the volumetric efficiency of the Engine towards both the low and high ends of the speed spectrum on using the optimum VVT values at each rpm than the original single value pre-set by the manufacturer as is evident from the Volumetric efficiency graphs in fig.7.

VIII. Conclusion

1) It was evident from the research by A.H. Khakee and M. Pishgooie in their paper "Determination of optimal valve timing for internal combustion engines using parameter estimation method" [1] that the variation of engine performance is less affected by the exhaust valve timing than the inlet valve timing. Thus the fulcrum of design synthesis and simulation and the eventual mounting on the engine is based on varying the inlet valve timing event for the sake of simplicity and convenience. But the system can be advanced further to vary both the Inlet and Exhaust Valve Timings by accommodating specific gear train for the exhaust valve variation.
2) Thus the system can be used to alter the Timing, Duration as well as the Lift of a valve event, all the three independently of each other, something which has never been achieved till date.
3) As shown in the design, a rack of around 50mm length and a pinion of diameter 40mm can be easily used to serve the purpose. Including the servo motor the overall space required for mounting the system is around 100mm×50mm×70 mm which can be easily accommodated in the cylinder head itself or nearby and is quite expendable for the improvement in Efficiency achieved. Also by using special purpose brushless motors and precision helical gears the system can be made even more compact.

References

[1] H. Kakaee and M. Pishgooie, Iran University of Science and technology, "*Determination of optimal valve timing for internal combustion engines using parameter estimation method*", International Journal of Automotive Engineering.
[2] Osama H.M. Ghazal, Mohammad S.H. Dado, "*Gear Drive Mechanism for Continuous valve timing of IC Engines*". Scientific Research Journal, Paper No-245-250
[3] Chun Tai, Tsu-Chin Tsao, " *Control of an Electromechanical Actuator for Camless Engines*" SAE paper-780413

[4] Chihaya Sugimoto, Hisao Sakai, Atsushi Umemoto, Yasuo Shimizu and Hidetaka Ozawa, Honda R&D international Ltd. "*Study on Variable Valve Timing System UsingElectromagnetic Mechanism*", SAE paper- 2004-01-1869

[5] Osama H. M. Ghazal, Yousef S. H. Najjar, Kutaeba J. M. Al-Khishali, University of Jordan, "*Modeling the Effect of Variable Timing of the Exhaust Valves on SI Engine Emissions for Greener Vehicles*", Scientific Research Journal, Paper No- 2013, 5, 181-189. http://dx.doi.org/10.4236/epe.2013.53018

[6] S.ChakradharGoud, G.SureshPatil, Dr.D.Maheshwar, Dr. B. Anjaneya Prasad, "*An Investigation of Variable Valve Timing application for controlling the HCCI Combustion.* International Journal of Engineering Research & Applications(IJERA) ISSN:2248-9622

[7] C. Gray, "*A Review of Variable Engine Valve Timing*," SAE Technical Paper No. 880386, 1988.

[8] T. Dresner and P. Barkan, "*A Review and Classification of Variable Valve Timing Mechanisms,*" SAE Paper, No. 890667, 1989

[9] H. Hong, G. B. Parvate-Patil and B. Gordon, "*Review and Analysis of Variable Valve Timing Strategies-Eight Ways to Approach*," *Proceedings of the Institution of Mechanical Engineers, Part D*: *Journal of Automobile Engineering*, Vol. 218, No. 10, 2004, pp. 1179-1200. doi:10.1177/095440700421801013

[10] H. S. Yan and W. R. Chen, "*On the Output Motion Characteristics of Variable Speed Input Servo-Controlled Slider- Crank Mechanisms,*" Mechanism and Machine Theory, Vol. 35, No. 4, 2000, pp. 541-561. doi:10.1016/S0094-114X(99)00023-3