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Research Article

A Magnetorheological Fluid Based Design of Variable Valve Timing System for Internal Combustion Engine using Axiomatic Design

S. M. Muzakkir†* and Harish Hirani†

†Department of Mechanical Engineering, Indian Institute of Technology Delhi, India

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Abstract

The present engine technology is required to achieve optimum performance under varying load and speed conditions imposed on the vehicle. The variable valve timing systems are employed in conventional engines to ensure optimal performance under varying operating conditions. The Variable Valve Systems (VVS) improves the gasoline-engine fuel economy and reduces emission by controlling the area, time and duration of cylinder opening. The benefits of the VVS technology are however not fully realized because the existing engine valve systems are modified by the addition of the control elements to convert it to VVS. These extensions make the valve system complex and bulky in addition to increasing the cost making it less preferable for implementation in various applications. The present paper emphasizes the design of variable valve systems starting from conceptual design phase to the final design using the axiomatic design. Axiomatic design is a systematic and scientific approach that provides future directions and enhances designers' creativity. Using the axiomatic design, this paper presents two concepts of VVS which involve minimum number of moving parts, causes minimum power loss and provide full flexibility to actuate the valve. These proposed VVS's have less inertia, low noise and high sealing capacity.

Keywords: *Axiomatic Design, Functional requirement, Design Parameters, Design Matrix, Variable Valve System, Optimum Engine Performance, Magnetorheological Fluids*

1. Introduction

A four strokes internal combustion engine converts chemical energy of gasoline-fuel into kinetic energy of crankshaft. Basically such an engine employs two gas-exchange processes, namely exhaust and intake strokes, and two closed cylinder processes, namely compression and power strokes. To run efficiently with minimum exhaust pollutant, the gasoline engine draws stoichiometric mixture of fuel to air during intake stroke. By volume, stoichiometric ratio contains approximately 9500 liters of air and 1 liter of gasoline (Bosch, 2004). As the amount of power produced by an engine is directly related to the rate at which it can burn gasoline, engine-power is governed by volume of fresh-air drawn inside the cylinders during the intake stroke.

Gasoline engines are seldom used at its maximum output. However, they are essentially designed to generate enough power to handle sporadic extreme operating conditions, such as overtaking other vehicles requiring high acceleration, moving out of large pit, or going up very steep hills requiring high torque. One obvious concern in such designs is the non-optimum utilization of the resources being specifically valid when the engine operates most of the time at part loads. This concern is addressed by the designers in three different ways:

1. Utilizing the concept of "Engine down-sizing" by using compressed air to increase the air volume. Since compressed air burns relatively large gasoline in same cylinder volume and generates more power, therefore a smaller engine may be utilized for high power requirements as and when needed. However, this concept of supercharging is fruitful for self-ignited direct injection gasoline engines (diesel engine). In spark ignition (port fired) engines, supercharging reduces the chances of fuel evaporation. Since supercharging increases the temperature of fresh charge therefore the chances of knocking are also increased.
2. Utilizing the "rich mixture strategy" by using slightly rich mixture to produce more power with same amount of air volume. However this "rich mixture strategy" increases the pollutants and therefore the emission regulations put this strategy under question.
3. Producing lesser power at part load conditions using one of the following technique:
    i) Regulation of the air supply to individual cylinder by throttling or variable intake valve

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*Corresponding author: **S. M. Muzakkir**

timings. A major disadvantage of throttled gasoline engine is pressure loss in the engine manifold. This requires additional energy for pumping (termed as 'pumping losses') to increase pressure of inhaled sub-atmospheric fresh air. These pumping losses are high (as shown in Fig. 1 by area covered by red thick line) when the throttle valve tends to close (low load), medium at medium load (as shown in Fig. 1 by area enclosed by pink thick line) and are low at wide-open-throttle (high load). The 'variable intake valve timing' does not require engine throttling and, as a consequence, the intake manifold is at the atmospheric pressure.

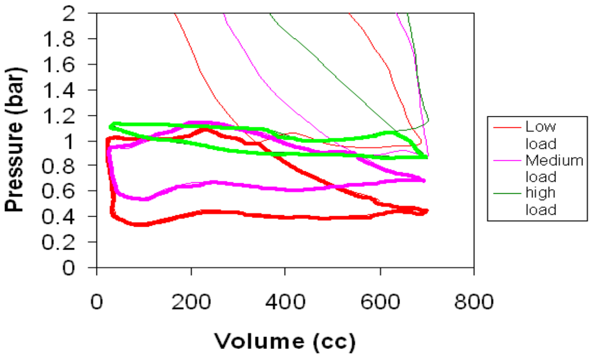

Figure 1 Engine pumping losses at low, medium and high load on engine

ii) Obtaining intake charge dilution by re-circulating the exhaust gases. This is achieved by using an extra valve to regulate the exhaust gases recirculation (termed as "External EGR") or using variable exhaust valve timing (called as "Internal EGR"). The maximum percentage of EGR is typically limited by combustion stability.

iii) Cylinder deactivation by variable intake and exhaust valve actuation systems.

A need of variable valve timing is also experienced as a gasoline engine operating at high speed requires different valve settings than the same engine working at low speed. It requires more valve overlap for better scavenging of the residual gases at high speed. But more valve overlap is detrimental during idling speed due to the increased chances of larger amount of residual gases going back into the intake manifold. Similarly high lift of intake valve is desirable in order to achieve complete filling of engine cylinder and consequently generation of excessive power. On the other end, at low engine speeds, small lift is desired in order to increase air velocity as it passes through the valve, which leads to a faster burn rate. These contradictory requirements arise due to the dependence of valve events on crank degrees and gas exchange as a function of time. To sum it up, an engine needs controllable opening and closing valve timings, convenient valve event and suitable valve lift.

The search for solution to address these problems is the motivation behind the development of variable valve actuation systems. Intensive efforts towards this direction are evident by large number of patents related to flexible valve actuation devices. The "fully variable valve actuation" concept permit the best possible cylinder charge, power, and ensure improved air fuel mixing which results in lower toxic emissions in the exhaust gas (Bosch, 2004). However, such devices are complex, bulky and incur additional cost. Therefore, their applications tend to be limited. This indicates that solution to one problem generate associated problem(s). It leads to a vicious cycle of problems and solutions. To break this vicious cycle one needs to turn a new page and view the problem in a larger perspective using a structured design approach, such as axiomatic design, with a target of variable valve actuation without additional cost/complexity.

Axiomatic design has been chosen in this study as a general design frame work as it emphasizes on the functions that product must perform. For example to design a variable valve actuation one might think how to improve the classical camshaft-poppet valve system to make it suitable for variable valve -timings, -lift and -duration. This type of thinking is termed a "mechanical thinking" and it hardly offers any creativity or innovation. However, axiomatic thinking of "control on cylinder opening" and "control on cylinder closing" forces a designer to search out of the box, generate more creative solutions and select the best among feasible proposed designs.

The present paper focuses on an innovative design of valve that is simple and easy to control valve functions and robust against environmental conditions (temperature, wear, etc.). Two concepts of valve actuation are proposed that generate lower noise, reduce power-loss, decrease emission and have lesser moving parts.

2. Approach to Axiomatic Design

Axiomatic design emphasizes on functional requirements needed to be accomplished in a solution neutral environment (Suh, 2001). For example, if one thinks on improving part-load-efficiency of a four-stroke-port-fired-spark-ignition, he/she is committing a mistake by even thinking about a physical entity, spark ignition engine. Options of using engines such as diesel engine, direct ignition engine and/or gas turbine, will never even cross his mind unless he starts thinking out of the box.

In axiomatic design approach there are two fundamental axioms that govern the design process. The first axiom, named "Independent Axiom", states that the independence of functional requirements (FRs) must always be maintained (Suh, 2001). The design solution must be such that each FR is satisfied without affecting the other FRs (Suh, 2001). To exemplify this concept let us consider the same example of "improving part-load-efficiency of a four-stroke-port-fired-spark-ignition". Assuming that a designer is working for a company which produces only port-fired-gasoline-engines, and he/she is bound by this constraint. However, the designer is free to design any engine that operates on four-stroke-cycle and uses port-fired-gasoline. In such a case, the designer needs to maximize efficiency at idle condition f_1, low load f_2, medium load f_3, and full load f_4, which are function of speed and torque. The functional requirements can be set as:

FR_1 Maximize efficiency at idle condition
FR_2 Maximize efficiency at low load condition
FR_3 Maximize efficiency at medium load condition
FR_4 Maximize efficiency at full load condition

Here all four functional requirements are independent. Now there comes the requirement of four physical parameters (may be components, geometric parameters, or control strategies) that maintains the independence of FR_1, FR_2, FR_3 and FR_4. Let us consider a solution (say Solution A) by assigning four cylinders DP_1, DP_2, DP_3 and DP_4 to satisfy FR_1, FR_2, FR_3 and FR_4 respectively. Here DP_1 is smaller in size compared to DP_2. Similarly DP_2 is smaller than DP_3. This solution indicates that the engine operates on:

- DP_1 cylinder for idle operation,
- DP_2 cylinder for low load condition,
- DP_3 cylinder for medium load condition, and
- DP_4 cylinder for full load condition

At first sight this solution appears to be an ideal solution, as there is no contradiction and every function has a separate solution, which can be maximized individually. However, if there is restriction on overall cost, material utilization, engine weight, etc. then one needs to think of different solutions. Here comes another advantage of axiomatic design, which stresses on documentation of constraints for every design and at every design level. This documentation part is essential to review the design in the future. It is particularly important in the case of technological development. Tomorrow's technology can alter today's decision.

Now once limit on overall cost, material utilization, engine weight is described "solution A" needs to be refined. As requirement of independent axiom is independence of functions from each other, not the physical parts, therefore one can think of "solution B", which assigns only one cylinder (of capacity equivalent to that of DP_4 of solution A) for all four FRs. This cylinder has three additional geometric parameters which change the volume of cylinder. In other words to satisfy:

- FR_1, volume of cylinder is made to DP_1
- FR_2, volume of cylinder is made to DP_2
- FR_3, volume of cylinder is made to DP_3
- FR_4, volume of cylinder is made to DP_4

Variable volume of cylinder in "solution B" may be referred as "variable stroke cylinder", "variable compression ratio cylinder" or a "cylinder with variable EGR". Drangel *et al* (Drangel, Olofsson, & Reinmann, 2002) used variable compression ratio approach and varied volume by tilting the "Mono-head" relative to the crankcase.

Large single cylinder engine power is generally detrimental in the view of knocking, weight, vibration, noise, crankshaft balancing, etc. Further relatively large size engine is difficult to fit in a small vehicle demanding large power. Under such additional restrictions, use of multi-cylinder is preferred. Thus "solution B" needs modification. Let us think of "solution C" that provides four cylinders of same volume capacity for four FRs. Designing same capacity cylinders reduces manufacturing cost and helps in engine balancing.

In solution C, FRs and DPs relation can be expressed as:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix} \quad (1)$$

Equation (1) states dependence of FRs on DPs. To satisfy FR_1, DP_1 is sufficient, whereas FR_2 requires DP_1 and DP_2. FR_4 depends on all four DPs. This type of design is termed as "decoupled design" (Suh, 2001). In automotive industry "solution C" is referred as "Cylinder Deactivation". Sandford *et al.* [4] described the design, application and operation of cylinder deactivation using existing engine. They demonstrated 7 to 14% fuel economy using "cylinder deactivation" concept. (Sandford, Allen, & Tudor, 1998) deactivated cylinder during vehicle deceleration. They introduced the 'pneumatic hybridization' concept utilizing deactivated engine cylinders. A supplementary valve, located between the cylinder and a plenum, was used to charge the storage plenum with air compressed in deactivated cylinder. Such stored compressed air was used to boost the engine that augmented the acceleration performance of the vehicle.

These examples indicate axiomatic design is a systematic and scientific approach. It provides future direction and enhances designers' creativity. Due to these advantages, independent axiom of axiomatic design is utilized to design an engine valve in the present paper.

3. Review of Variable Valve Actuation System

In conventional spark ignition engines, camshaft transfers the cam lift to the intake/exhaust poppet valve through a lever mechanism. This lift transformation may be through long push rod-rocker system or through overhead camshaft. The overhead camshaft allows eliminating the pushrod from the system, and permits to operate engine at higher speeds. The engine with two overhead camshafts, which is preferred over one camshaft-engine, uses one camshaft for intake poppet valve(s) and one for exhaust poppet valve(s). In such engines the timing and stroke curves for intake and exhaust valves remain constant for every camshaft-cycle. Notable features of camshaft operated poppet valves are:

1. Self-sealing capability (due to geometry) of poppet valve,
2. Energy storage by spring (Spring performs valve closing) ,
3. Lash adjuster that compensates temperature related expansion and contraction of the valve, eliminates valve unseating during the expansion process and also compensates for cam wear over time.
4. Direct utilization of crankshaft kinetic energy.

These four advantages of poppet valve-camshaft mechanism provide major reluctance to switch over to any other mechanism. To overcome drawback of invariable valve actuation of this system, designers have proposed a number of valve extension mechanisms, which can be grouped in following categories:

- Control at camshaft level
  - Camshaft phasing
  - Variable valve lift
  - Full flexible variable valve actuation
- Control at the valve train (excluding poppet valves and camshaft)
- Cam-less valve actuation

3.1.1 Camshaft phasing

Camshaft phasing (rotation of camshaft relative to crankshaft) is adjusted using electrical or electric-hydraulic actuators (Bosch, 2004). Retarding the intake camshaft leads to intake valve opening later so that valve overlap is reduced or minimized to zero. At low engine speeds, the low valve overlap results in very little residual gas content in A/F mixture, leading to a more efficient combustion process. This reduces idle engine speed, which is in favor of fuel consumption. However, the “valve closing” depends on the “valve openings” and this invariable coupling cannot be removed by camshaft phasing.

3.1.2 Variable valve lift

Variable valve lift involves switching of the cam contours. Contours can be designed for various speed ranges. Two-steps cam (Sellnau & Rask, 2003) utilizes two discrete valve-lift profiles. The first cam contour defines, the optimum valve timing and lift, for the intake and exhaust valves in the low to medium power ranges (Bosch, 2004). The second cam contour controls the increased valve lift and longer valve open duration needed at higher speed (Bosch, 2004). This improves the classic tradeoff between low-speed low-load operation, and high-speed full-load operation. By combining two step cam profiles with cam phasing (such as shown in Fig. 2), Sellnau and Rask (Sellnau & Rask, 2003) demonstrated improvement in the fuel economy and emissions. However, this type of mechanism cannot replace engine throttle valve and thus cannot reduce pumping loss. Further, cam-phasing and axial movement of camshaft consumes extra-power, reduce upper speed-limit of engine, and increases the cost. Moreover, these mechanisms do not provide full optimization over the whole load and speed ranges.

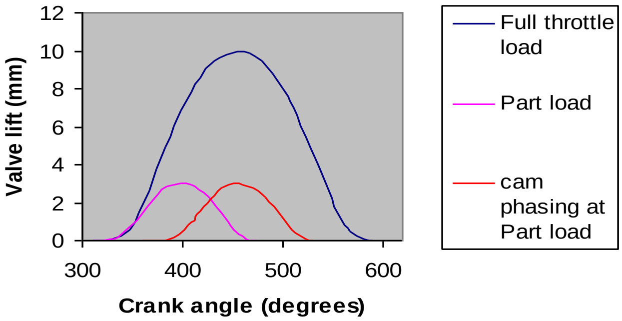

Figure 2 Two steps VVA

3.1.3 Full flexible variable valve actuation

A camshaft utilizing three-dimensional cams (used in Ferrari engines) provides a continuously variable valve lift and timing. However, the restriction in such design occurs, with the increase of camshaft rotation that causes interference of three-dimensional cam with valve lifter. Moreover, movement of the shaft in the axial direction is limited by the design of cylinder head. Further restriction arises from growing trends towards higher engine speed. To overcome problems related to 3-D camshaft valve actuation, Ogura and Sasaki (Ogura & Sasaki, 2003) developed a continuous variable valve timing mechanism by combining three-dimensional cam and the rocker arm movement. This mechanism makes possible the continuous variance of the valve timing by moving rocker arm parallel to the three-dimensional cam. These mechanisms require additional movements in valve-systems and thus increase the weight and results in higher frictional losses.

3.2 Controls on Intermediate Linkage (Valve Train)

Control at the valve train level is exercised by employing an additional subassembly named as “lost motion device”. The cam-phasing mechanism provides the phases for the camshaft of a single high lift (required for high speed operation) contour whereas the lost motion devices control various transmission elements between cam and valve to impart the required displacement, velocity and acceleration to the valve. The lost motion device may be applied directly between overhead cam and valve, or to any of the transmission elements (rocker arm, pusher, pivot location, etc.). Basic aim of these mechanisms is to regulate valve timing and lift as per cylinder requirements that develop power efficiently with minimum emissions. Kreuter *et al*. (Kreuter, Heuser, Murmann, Erz, & Peter, 1999) described various mechanical valve mechanisms to continuously control intake valve lift from zero to maximum. Such mechanisms allow an un-throttled load control of spark ignition engines. Leslie *et al*. (Leslie, Abdulkadir, & Hamid, 2003) utilized magnetorheological (MR) fluid to control the timing and/or the lift of valve motion. MR fluids show a transition from a liquid behavior to a solid one upon application of a magnetic field. The applied magnetic field intensity is controlled by the electric current supplied to electromagnet(s). These MR fluids change their stiffness and damping properties as a function of supplied control current (Hirani & Manjunatha, 2007; Sukhwani, Hirani, & Singh, 2007, 2008; Sukhwani, Vijaya, & Hirani, 2006; Sukhwani & Hirani, 2008).

3.3 Cam-Less Valve Actuation

This subheading highlights the valve mechanisms that open and close engine valves using a computer control rather than relying on a camshaft. Such cam-less valve trains (Chang W. S., Parlikar T., Kassakian J. G., 2003; Okada, Marumo, & Konno, 2004; Pischinger, Salber, Staay, Baumgarten, & Kemper, 2000) adjust valve motion parameters to get maximum engine performance at every engine revolution, offer much more flexibility and solve load vs. efficiency contradictions.

Cam-less valve train does not mean absence of cam in the valve actuation system rather it means a system devoid of camshaft. More precisely cam-less valve actuation means a valve actuation system without any geometric relation to the crankshaft rotation. Cam-less valve actuation is based on “magnetic levitation” and is shown in Fig. 3. In this figure two sets of electromagnets are used to control the reciprocating motion of valve. Retainer springs are used to avoid any jerk motion.

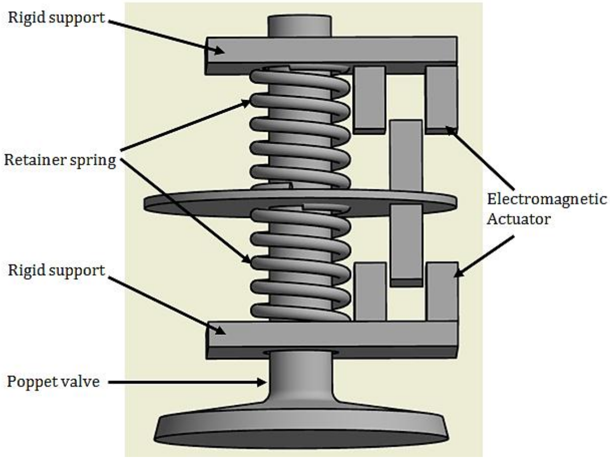

Figure 3 Cam-less valve actuation using magnetic levitation principle

These mechanisms are often termed as “individual drive mechanisms”. An electric-motor or a battery is used to activate the (mechanical, hydraulic or electro-magnetic) valve system. Synchronization, soft valve landing (for poppet valve configuration), and high response time of closed feed loop controller are essential requirements of such cam-less devices. The control of valve seating velocity (to minimize valve hits against its metallic seat that produce unacceptable levels of stress and audible noise), high power consumption, control-speed limitations, and high cost continue to present significant challenges for cam-less continuously variable valve actuation systems. Recently, Chang *et al*. (Chang W. S., Parlikar T., Kassakian J. G., 2003) tried to overcome the soft landing problem of electromagnetically-actuated poppet valve using a motor driven modified mechanical cam-disk, to regulate the valve lift. The opening and closing instances of the valve was regulated by controlling the motor speed.

There is therefore a need to design a suitable variable valve actuation system. In order to conceive this design a complete understanding of the various strategies of valve timings, lift and duration will be required.

4. Effect of Variable Valve Actuation on Engine Performance

The valve timing influences the engine performance in many ways. It affects engine power, torque, idle quality (fuel is used to keep the engine running while not actually doing useful work to move the vehicle), thermal efficiency and emission. A sound decision on valve timings and opening area, along with fuel injection and ignition timings, brings forth a win-win (high thermal efficiency, least emission, minimum fuel consumption and maximum driving comfort) situation. For 2-valves/cylinder engine there are four cases for variable valve actuation to be examined: Inlet valve opening (IVO), Inlet valve closing (IVC), Exhaust valve opening (EVO) and Exhaust valve closing (EVC).

4.1 Intake Valve Opening (IVO)

In conventional engine, generally opening of the intake valve takes place at around 10 degrees before TDC. This valve timing or any other early inlet valve opening (EIVO) is preferred at high speed and high load to refill the engine cylinder with fresh charge to its maximum capacity. However, at part load, volume of engine cylinders is much larger than required for air-intake. Therefore, late intake valve opening (LIVO) will be a good strategy. LIVO timing reduces HC emissions under cold start situation, by lowering the chances of cylinder wall wetting and increasing in-cylinder gas motion that helps ignition and combustion.

4.2 Intake Valve Closing (IVC)

Generally closing of the inlet valve represents the end of the intake stroke and the start of the compression stroke. For a conventional engine with fixed intake cam timing, intake valve closing (IVC) timing is a trade-off between low speed torque and high speed power. In variable valve actuated engine, IVC helps to eliminate this trade off. Modulation of IVC timings controls the cylinder filling, so there is no need of throttling operation. The strategies such as early intake valve closing, late intake valve closing and variable valve lift are used to limit the pumping loss.

4.2.1 Early intake valve closing (EIVC)

In EIVC, the intake valve is closed early during the suction stroke of the engine, when the desired fresh air mass has been introduced into the cylinder. During warmed up (part load) conditions, a limited fraction of the intake stroke is used to introduce air fuel charge. As a result, the pumping requirement is greatly reduced as compared to traditional throttled engine, which increases engine efficiency at partial loads. To understand this, let us consider pressure (P_{intake}) at which fresh charge is taken in to the cylinder, and pressure ($P_{exhaust}$) at which combustion products are exhausted. Based on intake and exhaust pressures, pumping work is given as:

$$W_{pump} = (P_{exhaust} - P_{intake}) * V_s \quad (2)$$

Where V_s is the swept volume. As is apparent from the Eq. (2), the decreasing difference between intake and exhaust pressure reduces the pumping work. At full load conditions, $P_{intake} \approx P_{exhaust} \approx P_{atm}$. In a throttled engine at part load, $P_{intake} \approx 0.25 P_{atm}$. For variable inlet closing timing, P_{intake} remains atmospheric pressure. Once inlet valve is closed, adiabatic expansion process occurs and pressure and temperature are reduced. This contributes to lower heat losses, lesser NO_x emissions and reduced pumping losses. However, this strategy has two disadvantages:

- The manifold pressure remains high, which reduces pressure difference required for liquid fuel to get evaporated. Liquid droplets cause poor combustion. EIVC engines can overcome this penalty by reducing intake valve lift to a reasonable value (too low valve height eats away all the benefits of un-throttled engine operation). Low valve height causes higher intake air-fuel mixture velocity. This higher velocity creates turbulence for good fuel vaporization.
- The intake valve closing before bottom dead center results in a nearly adiabatic expansion inside the cylinder. Because of this the fresh charge cools down, resulting in air fuel mixture cooler than that in a conventional engine. Cooler charge is detrimental to the fuel atomization. Therefore this strategy cannot be used in cold-start engine case.

4.2.2 Late intake valve closing (LIVC)

The late intake valve closing is characterized by the intake valve remaining open during the complete suction stroke. It cannot be closed before of the excess charge is pushed back into the intake manifold during the compression stroke of the piston. In throttled and un-throttled engine LIVC plays different roles. In throttled engine with LIVC timing, some of the charge is expelled back into the intake manifold. The pressure of the entrapped charge is little more than the atmospheric pressure. During the subsequent induction stroke the entrapped charge gets readmitted at a pressure above that of the air-fuel mixture in conventional engines. This means that the suction pressure line deviates very little from the atmospheric line. Thus, the negative area is almost nil, which results in reduced pumping losses. On the other hand, in the absence of the throttle body, LIVC strategy causes very high flow losses because of the air fuel reverse flow. This increases hydrocarbon emissions and fuel consumption.

In summary LIVO and EIVC with reduced valve lift are preferred strategies at the engine start, during warm-up period and part load conditions.

4.3 Exhaust Valve Opening (EVO)

For a conventional engine with single cam profile, timing of exhaust valve opening (EVO) is a trade-off between high speed exhaust stroke and low speed expansion work. In conventional engines EVO takes place at around 60 degrees before BDC. Early opening of exhaust valve (EEVO) generally results in losses in the expansion stroke, while late exhaust valve opening (LEVO) causes increase in temperature of exhaust gases and more chances of NO_x emission. Variable exhaust valve actuation tries to improve such tradeoff and allows EEVO for high speed and load conditions, while LEVO for partial load situations.

4.4 Exhaust Valve Closing (EVC)

Generally, closing of the exhaust valve in conventional engine takes place at around 10 degrees after TDC during the intake stroke. This late closing requires expelling out all the residual gases from the cylinder and bring-in new fresh charge for full load conditions. However, late exhaust valve closing (LEVC) allows an engine torque reduction, under partial load operation. Early exhaust valve closing (EEVC) seems a better strategy for part load circumstances. To understand the requirement of EEVC, let us study the engine start-up and warm-up states.

During gasoline engine starting, almost five times of the required fuel-quantity is injected in the first cycle and nearly two to five times is injected in the second cycle. This large amount of fuel is injected into the intake port to get the engine started as quickly as possible. A large fraction (50 -75%) of this fuel ends up as a liquid film on the intake valve, cylinder wall and in the piston-ring-cylinder clearance. Majority of this liquid fuel drifts away (without burning or after partial burning), with exhaust gases during the first few seconds of engine operation. To neutralize the hydrocarbons of the exhaust gases, the use of catalyst is the one of remedies. However, catalyst requires some time before it is warm enough to be effective, and cannot restricts hydrocarbon going to environment for first few cycles. The results are high level of hydrocarbon emissions in first few seconds of engine start. In order to meet the most stringent upcoming environmental standards, it is a must to reduce hydrocarbon emissions during startup period. A number of strategies are suggested (Bosch, 2004) to deal with the cold start emission problem. In authors view one possible method to control such emissions is to explore the exhaust valve closing timings.

The development of any strategy to deal with cold start problem requires a cycle-by-cycle analysis during gasoline engine starting. In the first cycle of engine (Sampson, 1994) all of the cylinders show a negative work output, therefore the first cycle is a cranking cycle. The cranking phase commonly lasts for less than two cycles before a significant firing of cylinders. Unstable combustion occurs in the following three to five cycles, as manifold pressure rapidly drops and the fuel and air flow rapidly change. Between the third cycle and the tenth cycle hydrocarbon emissions shoot-up, touch maxima and drop down. Only a small portion of injected excessive fuel, in first two cycles, is recovered for combustion, but the majority remains “unaccounted”. On major reason is the relatively high temperature of exhaust gases that evaporates the liquid fuel from cylinder walls and crevices and takes away fuel vapor during exhaust stroke. Remaining fuel is left into the crankcase and absorbed by oil lubricant. However, mass of unaccounted fuel can be reduced by providing warm intake air (at temperature nearly 400 K). This warm start up strategy reduces hydrocarbon emissions (Sampson, 1994).

On careful observation following points can be summarized:

- Temperature 300K is insufficient to evaporate the liquid fuel. At this temperature combustion is relatively unstable.
- There is relatively large clearance between piston and cylinder.
- Cold cylinder walls condense the vapor fuel in liquid droplet.
- Last part of exhaust stroke carries the (unburned or partial-burned) hydrocarbons to the exhaust manifold.

5. Design of Engine Valve using Axiomatic Design

Engine valves are devices that start/stop flow, regulate flow and prevent backflow. All these requirements are fulfilled by a number of mechanisms (Skosen, 1998). However, for engine cylinder proper sealing is a crucial requirement, particularly during compression and expansion strokes. To seal and unseal a passage, three most commonly used ports are illustrated in Fig. 5. Port shown in Fig 5C cannot prevent backflow, therefore it can never be recommended for an engine valve.

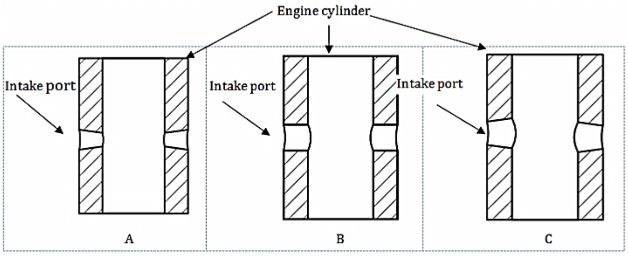

Figure 5 Port geometries

Response time is a second criterion to narrow down the search space. The engine valve opens, remains open and closes within a range of 150 to 280 crank degrees. In terms of time span a valve gets only 5 to 10 milliseconds to perform all these functions. This arduous requirement imposes a severe restriction on the selection of a valve. Most of pneumatic linear actuators and metallic bellow devices are slow to moderate in their response time. Relatively fast response of a valve system requires minimum number of movements, and insignificant system inertia. Other functional requirements, which limit the valve systems, are related to economics and society, such as: sufficiently resistant to wear, maintenance free throughout their operating life, high natural frequency (rigid-structure), light in weight, minimum power loss, robust design (consistent performance) and minimum noise. To maximize the volumetric efficiency and the idle smoothness, valve should acts as an ideal check-valve: fully open and close as soon as possible. Above all any new development/design should be consistent with favorable fuel consumption and emission levels from the viewpoint of the global environment.

Based on this description, the FRs and DPs of an engine valve system may be summarized as:

Table 1: FRs and DPs for Engine Valves

FRs	DPs
1. Open the valve 1.1 start opening 1.2 displace contacting bodies	1. Force signal 1.1 Signal from controller 1.2 Force that overcome sealing force, inertia of valve assembly and friction.
2. Regulate the opening area	2. Controllable valve area
3. Close the valve 3.1 start closing 3.2 bring two surfaces in contact 3.3 minimize wear	3. Signal from controller 3.1 closing signal from controller 3.2 force to close valve 3.3 relative velocity between contacting bodies
4. Minimize backflow	4. Seal
5. Minimize variability due to temperature, wear and misalignment	5. Compensating device

Five functional requirements stated in the Table 1 are independent. Opening of valve means to unseal two surfaces. Once surfaces are unsealed, essential requirement is to regulate the flow area to control the mass flow rate. Subsequent closing of the valve is an essential requisite. Similarly minimizing backflow and providing robust performance are important to gain maximum engine work. However, overall performance of valve system depends on the choice of physical parameters/entities/subassemblies (DPs) to fulfill the functional requirement.

Mixing of air/fuel charge, valve cooling, and avoiding valve-jamming are other three functional requirements. However, literature does not provide much information on these topics. Similarly supporting valve assembly is a requirement, which is targeted at engine assembly level.

To understand these FRs and DPs let us consider three examples: a rotary valve system (Muroki, Moriyoshi, & Sekizuka, 1999; Paul, 2003), an electromechanical cam-less actuation (Chang W. S., Parlikar T., Kassakian J. G., 2003), and a magnetorheological fluid based lost motion control device (Leslie *et al*., 2003).

Example 1: Rotary Valve (Muroki *et al*., 1999; Paul, 2003)

Muroki *et al*. (Muroki *et al*., 1999) performed laboratory experiments using rotary valve. A variable speed drive and four apex seals were used. A single valve body was used to inhale fresh air and exhale combustion products. Such a device does not satisfy all FRs listed in the Table 1.

Table 2: FRs and DPs for Muroki *et al*. (Muroki *et al*., 1999) rotary valve

FRs	DPs
1. Open the valve 1.1 start opening 1.2 displace contacting bodies	1. Motor drive 1.1 Variable speed drive 1.2 Driving torque of electric-motor.
2. Regulate the opening area	2. Notch (recess) on the rotor surface
3. Close the valve 3.1 start closing 3.2 bring two surfaces in contact 3.3 minimize wear	3. Motor drive 3.1 Variable speed drive 3.2 Driving torque of electric-motor 3.3 Constant rotational motion
4. Minimize backflow	4. Four Apex Seals
5. Minimize variability due to temperature, wear and misalignment	No functional requirements were identified by Muroki *et al*. (Muroki *et al*., 1999)

FR 1.1 (start opening) and 3.1 (start closing) are coupled, like in conventional engines. Second FR was not considered properly. Apex seals are contact seals and wear out slowly and so lack consistent performance. One advantage of this device is low friction which ultimately consumes less power.

Paul (Paul, 2003) presented a rotary valve assembly with variable timing controls on the intake and exhaust fluid flow. Cogged belt drive, operated by crankshaft, was used to alternately block or permit flow along the intake or exhaust manifold. The amount of overlap, and variation in start and closing timings were adjusted using relative motion between core and throttle body subassembly. A schematic of such a rotary valve is shown in Fig. 6.

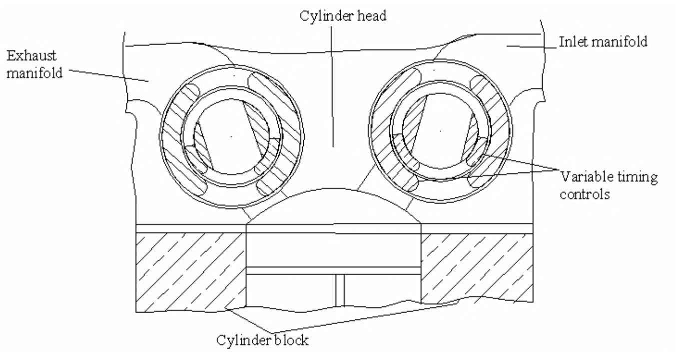

Figure 6 Rotary valve

Table 3: FRs and DPs for Paul's (Paul, 2003) rotary valve

FRs	DPs
1. Open the valve 1.1 start opening 1.2 displace contacting bodies	1. Crankshaft rotation 1.1 Core and throttle sleeve arrangement 1.2 Cogged timing belt drive.
2. Regulate the opening area	2. Core and throttle sleeve arrangement
3. Close the valve 3.1 start closing 3.2 bring two surfaces in contact 3.3 minimize wear	3. Crankshaft rotation 3.1 Core and throttle sleeve arrangement 3.2 Cogged timing belt drive 3.3 Uni-directional rotational motion
4. Minimize backflow	4. Circumferential and longitudinal seals
5. Minimize variability due to temperature, wear and misalignment	5. Elongated spring washers

Example 2: Electromechanical Cam-less Actuation (Chang W. S., Parlikar T., Kassakian J. G., 2003)

Chang *et al* (Chang W. S., Parlikar T., Kassakian J. G., 2003) used an independent electromechanical device to actuate the poppet valve, which satisfies FR 1. Poppet valve geometry inhibits back flow, so this design satisfies FR4. A nonlinear mechanical transfer operated by electric motor was designed in the view of valve's soft landing. The soft landing minimizes valve wear, therefore FR 1.3 is satisfied.

However, fixed characteristics of the mechanical device restrict total valve open duration. This couples the opening and closing of the valve. Closing of a valve is dependent on opening of a valve. Two functional requirements, FR2 and FR5 were not considered.

Example 3: Magnetorheological Control on Camshaft Operated Valve (Leslie *et al*., 2003)

Leslie *et al*. (Leslie *et al*., 2003) considered a very simple mechanism. They used a variable stiffness semisolid, which changes stiffness with magnetic field. A lost motion device was used between cam and valve. Cam and valve operated in the usual conventional manner. Lost motion device works as a mediator between cam and valve, and transfers cam lift in a range from zero to a significant portion of maximum lift. In the absence of magnetic field, lost motion device damps all the cam's signals without discomforting valve. Thus the valve remains closed. At the other extreme, the MR fluid is made stiff by turning the magnetic field on and lift is transferred to the valve.

Table 4: FRs and DPs for Leslie *et al*. (Leslie *et al*., 2003) MR fluid valve

FRs	DPs
1. Open the valve 1.1 start opening 1.2 displace contacting bodies	1. Crankshaft rotation 1.1 Energizing the coil 1.2 Reciprocating piston.
2. Regulate the opening area	2. Core and throttle sleeve arrangement
3. Close the valve 3.1 start closing 3.2 bring two surfaces in contact 3.3 minimize wear	3. Crankshaft rotation 3.1 De-energizing the coil 3.2 Spring force 3.3 Almost zero velocity at valve closing
4. Minimize backflow	4. Poppet valve-seat arrangement
5. Minimize variability due to temperature, wear and misalignment	5. Lash adjuster

Leslie *et al*. (Leslie *et al*., 2003) considered a classical poppet valve in their invention, which satisfies FR4. Lost motion device regulated the valve lift. Further, energizing and de-energizing of coil was kept under control. This regulates the opening and closing timing of the valve. Therefore all five major FRs are satisfied. However, major problem with this valve actuation is relying too much on MR fluid stiffness. As per authors' knowledge MR fluid can never achieve stiffness equivalent to a solid valve system. This stiffness is a function of volume percentage of magnetic particles in the liquid carrier. Generally this volume percentage is kept below 50 percent. Therefore, at most 50 percent of stiffness is achievable by MR fluid semi-solid. Hence, MR fluid based valve actuation system need a cam with lift profile of 200%. High lift cam requires very stiff return spring, particularly at full engine speed. Stiffer spring provides more friction. Moreover, this lost motion device uses two additional pistons, which further increase the friction of device. The effect of particle size on the MR fluid performance was investigated by Sarkar and Hirani and other applications employing MR fluids were reported (Sarkar & Hirani, 2008, 2009, 2013a, 2013b, 2013c, 2013d, 2014a, 2014b).

Conclusions

An axiomatic approach is applied to design an engine valve. Examples to illustrate the creativity potential of axiomatic design are presented. For smooth and emission free engine start "early closing of exhaust valve" strategy is recommended. To support this strategy enveloping of fresh charge with exhaust gases is presented. Three existing valve systems are analyzed viewing their advantages and disadvantages for potential candidate for full variable valve actuation system. Two concepts for variable valve system are proposed which involves minimum number of parts, consumes minimum power loss, and provide full flexibility to actuate the valve. Both the systems are based on variable stiffness magnetorheological fluids. First system utilizes the design of hollow poppet valve, filled with MR fluids. Variable stiffness of valve is used to regulate the flow area. Second system uses concept of eccentric valve, filled with MR fluid. The MR fluid facilitates to seal and unseal the valve.

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