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Software Controlled Stepping Valve System for a Modern Car Engine

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Abstract

To address the problem of a piston-valve collision associated with poppet valve engines, we replaced the conventional poppet valve with a solenoid operated stepping valve whose motion is perpendicular to that of the piston. The valve events are software controlled, giving rise to precise intake/exhaust cycles and improved engine efficiency.

Other rotary engine models like the Coates engine suffer from sealing problems and possible valve seizure resulting from excessive frictional forces between valve and seat. The proposed valve on the other hand, is located within the combustion chamber so that the cylinder pressure help seal the valve. To minimize friction, the valve clears its seat before stepping into its next position.

The proposed system was successfully simulated using ALTERA's QUARTUS II Development System. A successful prototype was built using a single piston engine. This is an ongoing project to eventually produce a 4-cylinder engine.

Keywords: poppet valve, stepping valve, valve events, coates engine, valve seizure.

1. Introduction

For the modern car, the sparking and fueling is entirely controlled by the engine control unit. However the valve events are largely controlled mechanically by the camshaft which is in turn driven by a crankshaft, via a timing belt

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or chain. With this arrangement, a mechanical timing failure due to worn-out or broken belt for example, may result in a piston-valve collision, leading to engine damage [1,2]. In this study, we replace poppet valves with rotary stepping valves whose motion is perpendicular to that of the piston. Hence there is no possibility of a piston-valve collision, [2]. The operation of the proposed system is detailed in section 2.

1.1. Conventional Engine Valve Technologies

For almost all its history, the preferred valve for the Internal Combustion engine has been the poppet type, [3,4,5]. A typical poppet valve engine has a camshaft system which controls the opening and closing of the valves. The camshaft itself is timed to a crankshaft via a timing chain or belt. From figure 1b, it can be seen that the poppet valves open into the combustion chamber. The valve closes by pushing against its seat. Therefore the pressure due to compression and power strokes just helps the valve to seal better. The same cannot be said about the Coats valve engine of figure 1a and the Aspin of figure 1c, [6,7].

The Coates engine has two rotating valve cylinders which rotate inwards (as shown in figure 1a) to perform valve events. The valves are located outside the combustion chamber, therefore the valves need to be pressed to maintain seal. The pressing increases valve wear. Furthermore, the persistent pressure from the compression and power strokes eventually weaken the sealing mechanism and the engine efficiency just drops drastically. No production vehicles have ever being made since the introduction of the Coates engine in 2007.

The much older Aspin rotary engine [6] has similar concepts to the Coates engine. It uses a set of gears to drive a whole combustion cylinder. A set of springs and heavy bearings are used to maintain valve seal and smooth valve rotation. As with the Coates, the compression and power stroke forces push the cylinder away from the piston. Persistent spring force which help seal the valve, quickly leads to large frictions and valve seizures.

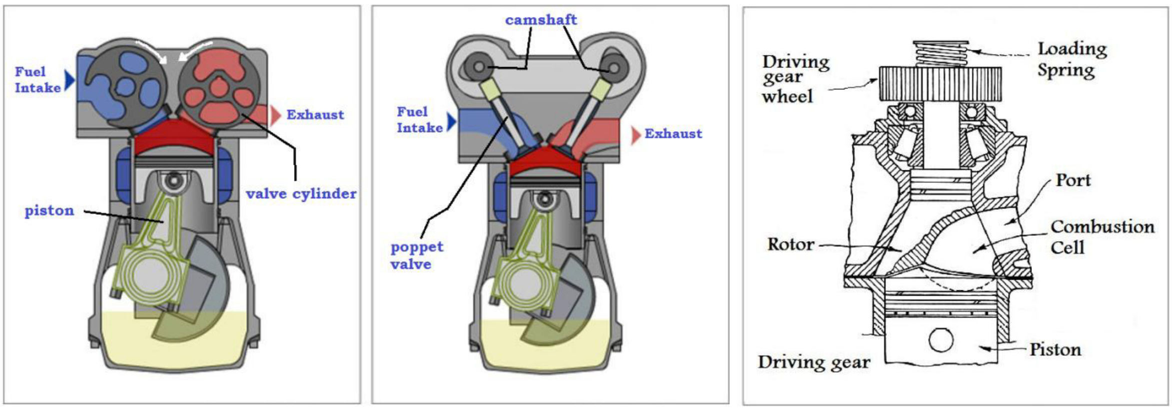

Fig. 1. (a) Coates Overhead Spherical Valve Engine; (b) Overhead Camshaft Poppet Valve Engine; (c) Aspin rotary valve.

1.2. Disadvantages of the poppet valve system

The main disadvantages of the poppet valve system are the unreliability of the timing belt/chain, fixed cam profile, inefficient control of the valve events and substantial engine overhead due to spring loaded camshaft system, [5]. Figure 2 shows the basic concept behind the camshaft system. For an interference engine, should the timing belt fail, the valve will come in contact with the piston resulting in a possible damage to the valve, piston and cylinder.

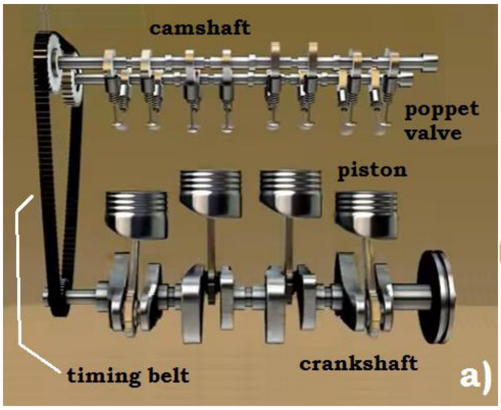

Fig. 2. The Camshaft System.

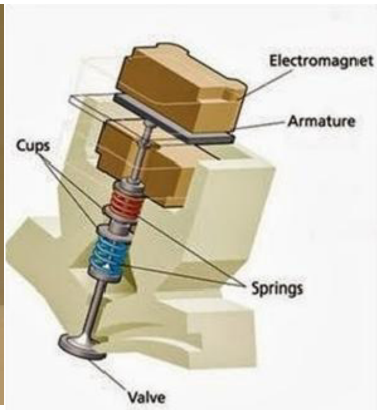

Fig. 3. The EMVA System.

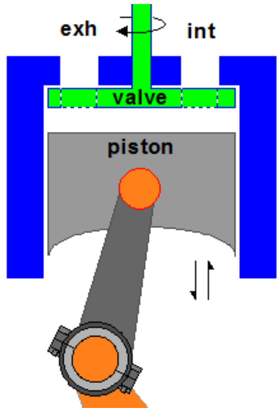

Fig. 4. Stepping Valve Concept.

The basic camshaft comes with a fixed cam profile for engine performance at a specific engine speed. At any other speed, engine performance is compromised. Honda's VTEC system switches between two cam lobes to cater for low speed performance and high speed performance, [8].

Three valve parameters affect engine performance; these are valve lift, lift duration and phase. The air intake into the cylinder can be regulated by the extended to which the valve opens, i.e., valve lift. Valvetronic from BMW varies valve lift so extensively that it replaces the traditional engine throttle butterfly, to allow engine breathing to be entirely controlled by intake valves, [13]. Lift duration means how long the valve stays open. Camless systems are capable of varying lift duration at all engine speeds, torque levels, and temperatures thereby greatly improving the engine performance, including emissions. Such systems include Electro-Magnetic Valve Actuation, EMVA which use electromagnets (figure 3) to open and close the valves, [10]. Pneumatic systems like the Koenigsegg's Camless engine from FreeValve use compressed air to control the valve events, [11].

Change in phase (valve timing) is done by advancing or retarding a valve event to satisfy engine requirements following a change in engine speed. An example is the VVT-i system from Toyota, which continuously varies the timing of the intake (and exhaust) valves by adjusting the camshaft phaser or actuator Advantages include easier starting, quicker, smoother acceleration, better fuel economy and lower emissions, [9].

1.3. Motivation for the proposed stepping valve system

The systems discussed in 1.2 use a poppet valve, hence have the inherent problem of piston-valve collision if the valve driving mechanism fails. This includes systems which drive poppet valves like the EMVA of figure 3. Phaser mechanisms are generally complex, expensive and are subject to oil pressure leaks. A fare amount of energy is required to overcome the restraining springs. Pneumatic systems are generally expensive to maintain and repair air leaks, oil leaks and the pumping mechanisms.

The proposed stepping valve system promises to solve the fundamental problems associated with poppet valve systems and legendry rotary systems of figure 1. Figure 4 implies that the stepping valve moves perpendicular to the piston, ruling out any possibility of a piston-valve collision. Unlike the Coates and the Aspin engines, the stepping valve is located inside the combustion chamber. As a result, the cylinder pressure forces help seal the valve. Furthermore, the stepping valve 'floats' to its new position rather than merely rotating, thereby minimising wear.

Since the motion of the valves is perpendicular to that of the piston, the valves can be opened or closed even if the crankshaft is stationary. Therefore engine cranking can be done electronically without using a mechanical starter. In a conventional cylinder-head, the poppet valves are spring loaded, therefore they require a lot of effort to move them. On the contrary, the stepping valve doesn't require a lot of effort to operate. The next section details the design of the stepping valve system. The design is based on a single piston engine.

2. Design of the Software Controlled Stepping Valve (SCSV) System

The stepping valve is designed using an axial motor concept. As the rotor moves from one pole position (or state) to the next, the rotor is pushed outwards and then inwards again. The outwards push is useful for un-sitting a valve when it needs to change state. For purposes of valve stability during rotation, a 4-holed valve has been used with a matching 12 pole axial rotor and stator. A model of the proposed rotor-valve assembly and a specially built cylinder-head is shown in figure 6b.

2.1. System Operation

Figure 5 shows the stator and rotor at different pole positions or states. For purposes of explanation, the rotor and stator are placed radial rather than axial. The stator coils are labeled A1 to A12. The rotor magnets are labeled RA1 to RA12. A North pole is placed after every two consecutive South poles. The stator coils as energized in Figure 5a shows a stable state since each rotor magnet is paired to a coil of the correct polarity. For correct operation, the rotor and stator should be in the same state. However loss of synchronism can occur especially at start-up. Figure 5b and 5c are examples of such situations. The notation used here is as follows;

A rotor magnet or stator electromagnet is referred to as a node.
● *means two nodes attract each other.*
◄●► *means two nodes repel each other with no 'preferred' direction of rotor repulsion.*
●► *means nodes repel each other and direction of rotor repulsion shown by direction of the arrow.*

Suppose at start-up RA1 of the rotor is facing A2 of the stator, (figure 5b). When the stator is then energized as in figure 5a, RA1 will be attracted to both A1 & A3, R12 will stay attracted to A1, R2 will be attracted to A2 (because it's nearer to it) and will tend to turn the rotor disc to the default position/state of figure 5a. Rotor nodes with ◄●► and ◄● collectively lift the valve against few nodes with ● which tends to pull the valve back. Rotor nodes with ◄● will turn the rotor anticlockwise so that it returns to the stable state of figure 5a.

Suppose the rotor's RA1 is facing A3 as in figure 5c. Analyzing the circuit as we did in figure 5b, we will find that the rotor will move clockwise so that RA1 faces A4. This is another stable situation. The conclusion which can be drawn here is that if RA1 lies within the first quadrant, A1 to A4, it will go to the nearest of A1, A4. The same argument holds for the other 3 quadrants.

In-fact, the cylinder-head floor plan of Figure 6a shows all the possible 4 positions RA1 will go to at startup. The 4 positions are labeled e1,e2,e3&e4. They are all identical and are connected to the exhaust channel.

Similarly for the intake stroke, the stator's A1 could be in any of the i(intake) positions. For the power/compression stroke, the stator's A1 could be in any of the c(closed) positions. Figure 6a shows a high degree of symmetry which will be used to simplify the valve control algorithm. Figure 6b shows how the physical cylinder-head will look like.

2.2. The Design of the SCSV System

The scsv algorithm is represented in table 1. Notice that the scsv state ci is common to Otto Cycle States pwri and cmpri, (the valve is closed for both power and compression strokes).

To find the equation for the vector A, we use the default setting of the stator found in figure 5a. For the default scsv state e1, to find A[e1], we simply read clockwise the stator nodes from A1, (North Pole as logic 1 and South Pole as logic 0). Therefore A[e1]=[101101101101]. To rotate the rotor to the next state i1, we rotate the magnetic field on the stator so that A12 and A1 will now appear to occupy the position of A1 and A2 respectively. The vector A[i1] will still be read from position of A1 going clockwise to give A[i1]=[110110110110]. The easiest way to find valve state equations is to use the following; Looking at figure 6a, the equations for the valve states on the right of the axis e1-e3 are read starting from the left e1-e3 reflection, going clockwise, and vice versa. For example, to get the equation for i2, read the stator node values clockwise starting from position c4 (since i2 reflects to c4). The calculated values appear in table 1.

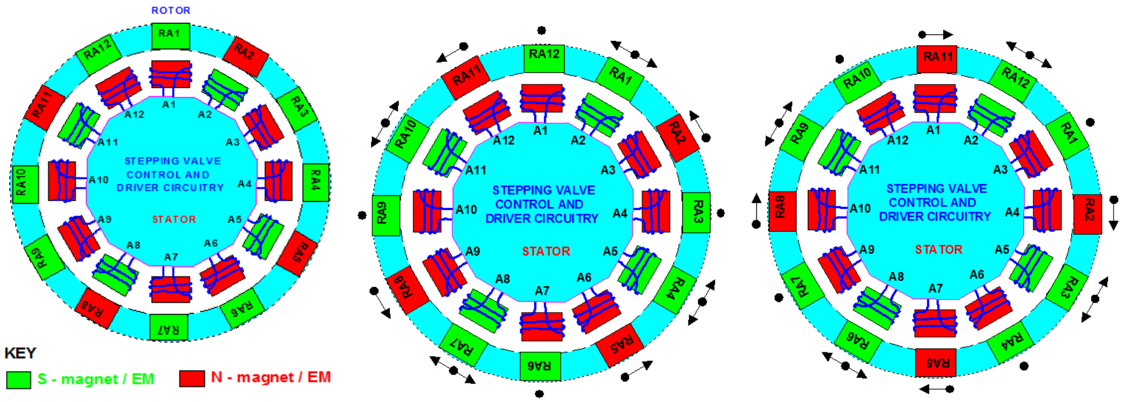

Fig. 5. (a) Rotor-Stator in default state; (b) Rotor at 1 state away from stator; (c) Rotor at 2 states away from stator.

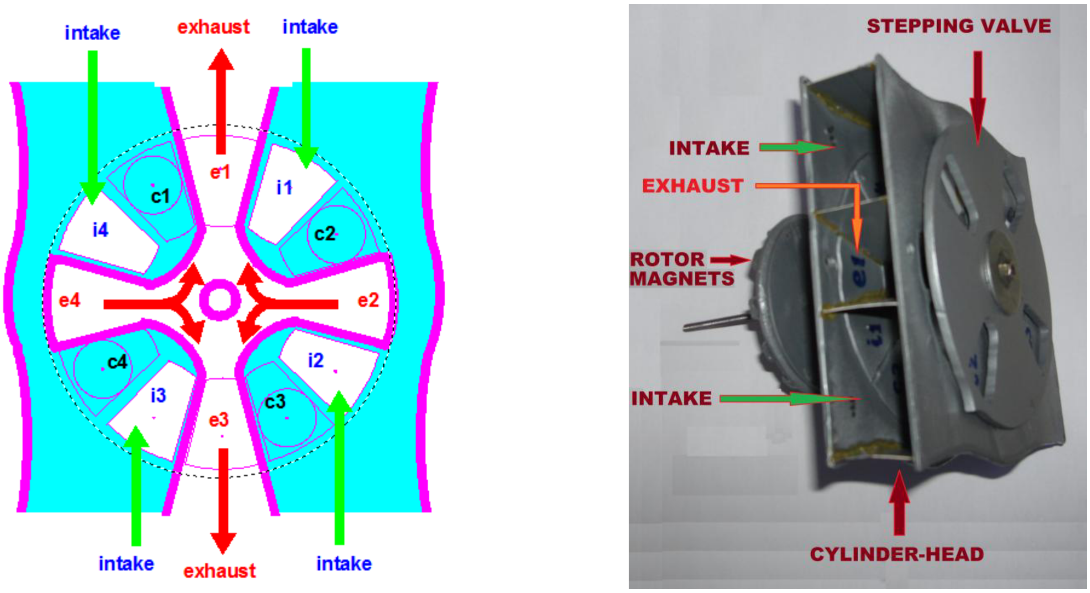

Fig. 6. (a) Cylinder-Head Floor Plan Showing valve states. (b) Cylinder-Head and stepping valve model.

Figure 6a is highly symmetrical, so is Flow Table 1. From the table, we can observe that;

A1=A4=A7=A10; *A2=A5=A8=A11;* *A3=A6=A9=A12.*

Also to notice is that the output vector, A[] is the same for identical valve states, i.e.,

A[exh1]=A[exh2]=A[exh3]=A[exh4]; *A[int1]=A[int2]=A[int3]=A[int4];*
A[pwr1]=A[pwr2]=A[pwr3]=A[pwr4]= A[cmpr1]=A[cmpr2]=A[cmpr3]=A[cmpr4].

Furthermore, all identical Otto Cycle states can be identified by a single state, i.e.,

exh1=exh2=exh3=exh4=exh; *cmpr1=cmpr2=cmpr3=cmpr4=cmpr;* *pwr1=pwr2=pwr3=pwr4=pwr;*

By taking advantage of this high degree of symmetry, we can reduce table1 to table 2. Notice that we have added Spark and Fuel outputs to form a complete engine control unit, ECU for a single cylinder.

Although the ECU has been reduced to 4 states, the physical valve still goes through its 12 states. To see how this is so, let's focus on RA1 of the rotor (figure 5a). After the four states of the controller, RA1 will be where RA4 is now. Because of the symmetry, the rotor will seem to be in the original position. So when the controller goes through the states for the second time, RA1 will now advance to A7. Eventually RA1 will reach its original position after 4 Otto cycles (a total of 16 cycles).

Table 1. Flow Table for the Valve Control Algorithm (SCSV system).

Otto-Cycle State Assignment	Otto-Cycle State	SCSV State	Output Vector, A (=valve control inputs) A[] = A1 A2 A3 A4 A5 A6 A7 A8 A9 A10 A11 A12
S1	exh1	e1	$B6D_H$ = 1 0 1 1 0 1 1 0 1 1 0 1
S2	int1	i1	$DB6_H$ = 1 1 0 1 1 0 1 1 0 1 1 0
S3	cmpr1	c2	$6DB_H$ = 0 1 1 0 1 1 0 1 1 0 1 1
S4	pwr2	c2	$6DB_H$ = 0 1 1 0 1 1 0 1 1 0 1 1
S5	exh2	e2	$B6D_H$ = 1 0 1 1 0 1 1 0 1 1 0 1
S6	int2	i2	$DB6_H$ = 1 1 0 1 1 0 1 1 0 1 1 0
S7	cmpr2	c3	$6DB_H$ = 0 1 1 0 1 1 0 1 1 0 1 1
S8	pwr3	c3	$6DB_H$ = 0 1 1 0 1 1 0 1 1 0 1 1
S9	exh3	e3	$B6D_H$ = 1 0 1 1 0 1 1 0 1 1 0 1
S10	int3	i3	$DB6_H$ = 1 1 0 1 1 0 1 1 0 1 1 0
S11	cmpr3	c4	$6DB_H$ = 0 1 1 0 1 1 0 1 1 0 1 1
S12	pwr4	c4	$6DB_H$ = 0 1 1 0 1 1 0 1 1 0 1 1
S13	exh4	e4	$B6D_H$ = 1 0 1 1 0 1 1 0 1 1 0 1
S14	int4	i4	$DB6_H$ = 1 1 0 1 1 0 1 1 0 1 1 0
S15	cmpr4	c1	$6DB_H$ = 0 1 1 0 1 1 0 1 1 0 1 1
S16	Pwr1	c1	$6DB_H$ = 0 1 1 0 1 1 0 1 1 0 1 1

2.3. Simulation and prototyping using Quartus II

Quartus II is a simulation and prototyping software tool from Altera. It can compile VHDL, AHDL design text files and produce corresponding output waveforms. It can program FPGAs, XYLINX or MAX Plus II devices using

ALTERA Development Boards as programming platforms. For this project, we used UP1 Development Board to prototype our control unit, [14].

The simplified engine control unit, ECU, of table 2 can be represented by the flow chart of figure 7. The piston direction sensor, PDS, changes value as the piston changes direction. The ECU is event driven by the PDS. Table 3 shows AHDL text design file derived from the flow chart algorithm of figure 7. The text file was used for simulation. The simulation results are shown by the simulation channel file of figure 8. The reset input is active high, so it has been kept low. The system moves to the next state on the low to high clock transition. The state transitions and outputs on figure 8 are the same as for the flow chart. As an example, the curser has been placed at the 200ns mark and the state of the system is indicated under column value and is given as; ss=cmpr, A1=Spark=0, A2=A3=Fuel=1. These results confirm table 2 and figure 7.

Table 2. Reduced Flow Table for the original Valve Control Algorithm

<table>
<tr><th rowspan="2">Otto-Cycle State</th><th rowspan="2">SCSV State</th><th rowspan="2">Spark</th><th rowspan="2">Fuel</th><th colspan="3">(valve control inputs)</th></tr>
<tr><th>A1,A4 A7 A10</th><th>A2,A5 A10,A11</th><th>A3, A6 A9, A12</th></tr>
<tr><td>exh</td><td>e</td><td rowspan="3">0</td><td rowspan="2">0</td><td rowspan="2">1</td><td>0</td><td>1</td></tr>
<tr><td>int</td><td>i</td><td>1</td><td>0</td></tr>
<tr><td>cmpr</td><td>c</td><td>1</td><td rowspan="2">0</td><td rowspan="2">1</td><td rowspan="2">1</td></tr>
<tr><td>Pwr</td><td>c</td><td>1</td><td>0</td></tr>
</table>

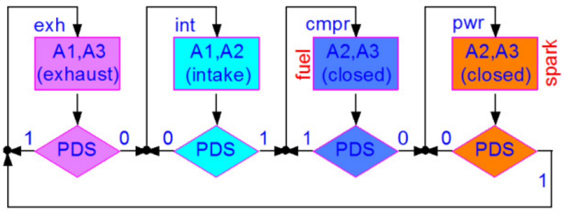

Fig. 7. Equivalent Flow Chart

Table 3 AHDL text design file

```
% algorithm.tdf %

SUBDESIGN algorithm
(
clk, reset                    :INPUT;

A1, A2, A3, Fuel, Spark       :OUTPUT;
)
VARIABLE
ss:MACHINE WITH STATES(exh, int, cmpr, pwr);

BEGIN
ss.clk=clk;
ss.reset=reset;

TABLE
% present                                    next %
% state.     Outputs                         state. %
ss         => A1, A2, A3, Fuel, Spark,        ss;

exh        => 1,  0,  1,  0,    0,           int;

int        => 1,  1,  0,  0,    0,           cmpr;

cmpr       => 0,  1,  1,  1,    0,           pwr;

pwr        => 0,  1,  1,  0,    1,           exh;


END TABLE;
END;
```

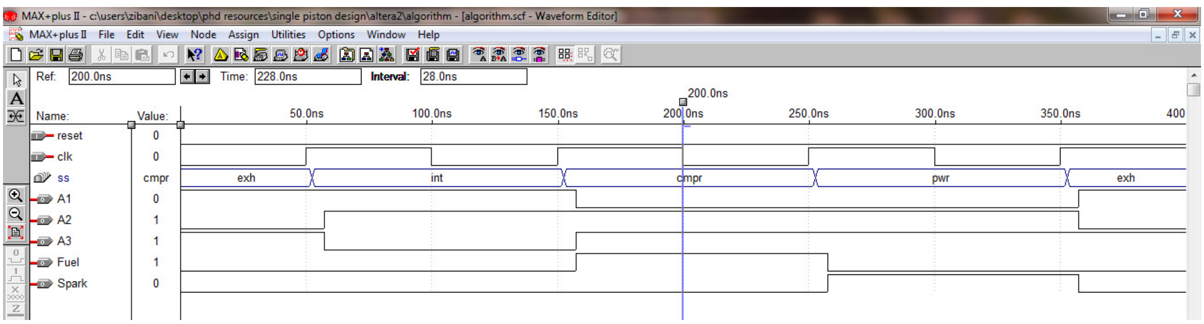

Fig. 8. Simulation Channel File for the valve control algorithm. Simulation time = 400ns. Grid size = 50ns.

3. Conclusions and Future Work

The software controlled stepping valve, scsv has demonstrated its feasibility through simulations and modelling. Poor valve sealing and excessive valve-seat friction hampered previous attempts by other designers to implement rotary valve systems. These include Coats and Aspin designs discussed in section 1.1. The stepping valve lifts up, moves to the desired position before resting on its seat. It does this in between strokes to minimise pressure on the valve (eg compression/power stroke) which would otherwise offer resistance to the valve's lifting action.

As an attempt to improve control of valve events, a number of variable valve timing techniques have been developed, including Toyota's VVT-i, Honda's VTEC. Cameless systems have done away with the valve train. They control the poppet valve directly using a hydraulic, pneumatic or electromagnetic system. In all these systems, the valve will come in conflict with the piston should the valve control mechanism fail. Hence for proper operation, the valve motion should be synchronized to the piston and the valve lift profile should be sinusoidal at least during the piston's TDC.

The stepping valve moves perpendicular to the piston, thereby eliminating the inherent problem of piston-valve collision. The scsv system has the ideal square wave valve lift profile which is the most efficient. It also has a fast valve event execution for all engine speeds, leading to efficient, environmentally friendly system.

The scsv concept can easily be migrated to multi piston engines as in cars. A starterless engine improves drivability and comfort. With the absence of valve train, the engine loading is drastically reduced, resulting in improved efficiency.

Acknowledgements

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References

[1] S.A.G Mir Saied, S.A. Jazayeri, A.H. Shamekhi, Modeling of Variable Intake Timing in SI Engine. Proceedings ICES ASME, Aachen, Germany, 8-10 May 2006.

[2] I. Zibani, J. Chuma, R. Marumo, The Effect of Valve Control on a motor vehicle engine performance. Proceedings IASTED, Gaborone, Botswana, 3-5 September 2012.

[3] S. Fernando, Internal Combustion Engines. Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, 2006.

[4] S.A.G. Saied, S.A. Jazayeri, A.H. Shamekhi, Modeling of Variable Intake Timing in SI Engine. Proceedngs of ICES2006, ASME International Combustion Engine Division 2006 Spring Technical Conference, Aachen, Germany, 2006.

[5] J.K. Taylor, The Internal Combustion Engine in Theory and Practice. MIT Press, 1985.

[6] http://www.douglas-self.com/MUSEUM/POWER/unusualICeng/RotaryValveIC/RotaryValveIC.htm#crs

[7] http://www.thetruthaboutcars.com/2007/12/coates-spherical-rotary-valve-system-let-the-rivet-counting-begin/.

[8] http://www.superstreetonline.com/howto/engine/1306howvtecivtecworks/.

[9] http://wayananang.blogspot.com/#!/tcmbck.

[10] J. Zhao, R.J. Seethaler, A Fully Flexible Valve Actuation System for Internal Combustion Engines, IEEE/ASME Transactions on Mechatronics, Vol 16, No. 2, April 2011, pp 362-363.

[11] http://www.motorauthority.com/news/1101737_video-shows-inner-workings-of-koenigseggs-camless-engine.

[12] A. Parviainen, Design Of Axial-Flux Permanent-Magnet Low-Speed Machines And Performance Comparison Between Radial-Flux And Axial-Flux Machines, PhD Thesis, Lappeenranta University of Technology, Finland, 2005. Chapter 1.3, pp 16-23.

[13] http://www.autospeed.com/cms/article.html?&A=111539.

[14] http://www.site.uottawa.ca/~rabielmo/miniCourse06/tutorial.pdf.