Variable compression ratio engine: a future power plant for automobiles – an overview

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Abstract: Increasingly stringent emissions and fuel economy standards have long remained a source of challenges for research in automobile engine technology development towards the more thermally efficient and less polluting engine. Spark ignition (SI) engines have lower part-load efficiency when compared with the diesel engines. The greatest opportunity for improving SI engine efficiency is by way of higher compression ratio, variable valve timing, low friction, reducing throttling losses, boosting, and down-sizing. Variable compression ratio (VCR) technology has long been recognized as a method for improving the fuel economy of SI engines. In order to vary the compression ratio, some method of varying the geometric compression ratio through changing the clearance volume is required. There are several ways of doing this; various patents have been filed and designs presented, including modification of the compression ratio by moving the cylinder head, variation of combustion chamber volume using a secondary piston or valve, variation of piston deck height, modification of connecting rod geometry, moving the crankpin within the crankshaft, and moving the crankshaft axis. The potential of these technologies needs to be evaluated by a trade-off between cost and consumption benefit. This paper reviews the geometric approaches and solutions used to achieve VCR, considers the results of prior research, and forecasts what benefits, if any, a VCR would bring to present engine design.

Keywords: spark ignition (SI) engines, variable compression ratio (VCR), thermal efficiency, fuel economy, clearance volume, knock

1 INTRODUCTION

The concept of variable compression ratio (VCR) promises improved engine performance, efficiency, and reduced emissions. The higher cylinder pressures and temperatures during the early part of combustion and small residual gas fraction owing to higher compression ratio give faster laminar flame speed. Therefore, the ignition delay period is shorter. As a result, at low loads, the greater the compression ratio, the shorter is the combustion time. Time loss is subsequently reduced. Therefore, it seems reasonable that fuel consumption rate is lower with high compression ratios at part load.

The VCR or, more correctly, variable expansion ratio can make a significant contribution to thermodynamic efficiency. The main feature of the VCR engine is to operate at different compression ratios, depending on the vehicle performance needs. A VCR engine can continuously vary the compression ratio by changing the combustion chamber volume. In a VCR engine, thermodynamic benefits appear throughout the engine map. At low power levels, the VCR engine operates at a higher compression ratio to capture high fuel efficiency benefits, while at high power levels the engine operates at low compression ratio to prevent knock. The optimum compression ratio is determined as a function of one or more vehicle operating parameters such as inlet air temperature, engine coolant temperature, exhaust gas temperature, engine knock, fuel type, octane rating of fuel, etc. In a VCR engine, the operating temperature is more or less maintained at optimum, where combustion efficiency is high. It has been proven that a VCR engine develops much more power for the same engine dimensions, i.e. it is very compact.
and has a high power-to-weight ratio without any penalty on specific fuel consumption. In other words, reducing the engine capacity at the same power leads to reduction in fuel consumption owing to reduced pumping, friction, and heat losses.

2 NEED FOR VCR

The present challenge in automotive engine technology is the improvement of thermal efficiency and hence the fuel economy and lower emission levels. One of the key features affecting thermal efficiency is the compression ratio, which is always a compromise in fixed compression ratio spark ignition (SI) engines.

The formula for air standard cycle efficiency is

\[ \eta = 1 - \left( \frac{1}{r} \right)^{k-1} \]

where \( \eta \) is the efficiency of the cycle; \( r \) is the compression ratio; and \( k \) is the ratio of specific heat of air at constant volume to specific heat at constant pressure, or approximately 1.40.

Higher compression ratio results in higher thermal efficiency and improved fuel economy in the internal combustion engine. Generally, the operating conditions of SI engines vary widely, such as stop and go city traffic, highway motoring at constant speed, or high-speed freeway driving. In a conventional SI engine, the maximum compression ratio is set by the conditions in the cylinder at high load, when the fuel and air consumption are at maximum levels. If the compression ratio is higher than the designed limit, the fuel will pre-ignite causing knocking, which could damage the engine. Unfortunately, most of the time SI engines in city driving conditions operate at relatively low power levels under slow accelerations, low speeds, or light loads, which lead to low thermal efficiency and hence higher fuel consumption. As the engine load decreases, the temperature in the end gas drops, so that high compression ratio could be employed without the risk of knocking in naturally aspirated or boosted engines. Raising the compression ratio from 8 to 14 produces an efficiency gain from 50 to 65 per cent (a 15 per cent gain), whereas going from 16 to 20 produces a gain from 67 to 70 per cent (a 3 per cent gain). Figure 1 shows the effects of compression ratio with respect to thermal efficiency.

The characteristics that have the dominant effects on thermal efficiency are compression ratio and air–fuel mixture strength. The fuel–air cycle efficiency increases with the compression ratio in the same manner as the air standard cycle efficiency, principally for the same reason, i.e. more scope for expansion work. Figure 2 shows the influence of 'per cent theoretical fuel' (fuel–air mixture strength) on thermal efficiency at different compression ratios [1]. The 'per cent theoretical fuel' is the ratio of actual fuel–air ratio to chemically correct fuel–air ratio, in percentage terms.

The maximum output is obtained when the air–fuel capacity of the engine is utilized, i.e. when the maximum amount of fuel can be burnt efficiently. The maximum brake mean effective pressure (b.m.e.p.) in SI engines is 12 bar whereas in diesel engines it is 18 bar. A higher compression ratio increases the pressure and temperature of the working air–fuel mixture, which increases the tendency of the engine to knock. Figure 3 shows the comparison of wide
open throttle (WOT) b.m.e.p. versus compression ratio and ignition timing. For knock, key variables are: end-gas temperature, pressure, and composition; time/speed; and fuel octane rating [2].

3 VARIOUS VCR APPROACHES

Designing and successfully developing a production practical, VCR engine has long been a challenge to the automobile industry. Many innovative patents have been filed and different designs developed to modify the compression ratio. A few approaches are discussed below.

3.1 Moving the crankshaft axis

FEV, Germany has chosen to alter the position of the crankshaft. In their engine, crankshaft bearings are carried in an eccentrically mounted carrier that can rotate to raise or lower the top dead centre (TDC) positions of the pistons in the cylinders (Fig. 4). The compression ratio is adjustable by varying the rotation of the eccentric carrier. Mounting the crankshaft on eccentric bearings is simple in that the reciprocating assembly itself is unchanged. In fact, the engine requires an offset fixed-position output shaft, a coupling is required between the movable crankshaft end and the fixed output shaft. The compression ratio is adaptable from 8 to 14 approximately by varying the rotation of the eccentric carriers through 55° [3].

3.2 Modification of the connecting rod geometry

The Nissan project uses a multi-link system to achieve VCR by inserting a control linkage system between the connecting rod and the crankshaft, and connecting this to an actuator shaft, so that the compression ratio can be varied. This project was incorporated in a four-cylinder engine without major modification of the engine block. The shorter crank throw allowed room for the link system, which was anchored by an eccentric rotary actuator. Compression was varied from 10 to 15 approximately by a 70° rotation of the actuator, while at TDC, the piston position was changed by 3.1 mm (Fig. 5). Examining the details of multi-link system operation reveals some advantages. The most striking advantage is that of maximum piston accelerations. Tension forces acting through the connecting rod and piston at TDC represent one of the factors limiting piston speed, so a geometry that reduces the peak piston acceleration would allow either an increase in sustainable engine speed or an increasing stroke, either of which is useful in terms of increasing power output [4].

3.3 Moving the cylinder head

The moving head concept (Saab Automobile AB) combines a cylinder head with cylinder liners into a monohead construction, which pivots with respect to the remainder of the engine. The lower half of the block includes the crankcase and engine mounts, and carries the crankshaft, gear box, oil cooler, and auxiliaries. The upper half includes the cylinders, their
liners, camshafts, and an integrally cast cylinder head. This part is referred to as the monohead (Fig. 6). Saab has enabled a tilting motion to adjust the effective height of the piston crown at TDC. The linkage serves to tilt the monohead relative to the crankcase in order to vary the TDC position of the piston. By means of actuator and linkage mechanism the compression ratio can be varied from 8 to 14. A screw type supercharger provides a 2:1 boost pressure when wide open throttle conditions occur [5]. This system gives wide fuel flexibility, with reduced CO₂ emissions proportional to fuel consumption. Saab recognized that the fuel efficiency of the VCR engine would be low without high-pressure supercharging.

### 3.4 Variation of combustion chamber volume using a secondary piston or valve

Ford have patented a means to vary combustion chamber volume by using a secondary piston or valve (Fig. 7). The piston could be maintained at an intermediate position, corresponding to the optimum
Variable compression ratio engine

The Saab VCR engine to be improved by an efficient cooling system and the auxiliary piston needs proper lubrication for efficient functioning of the VCR engine.

3.5 Variation of piston deck height

The Daimler-Benz VCR piston design shows variation in compression height of the piston and offers potentially the most attractive route to a production VCR engine, since it requires relatively minor changes to the base engine architecture when compared to other options (Fig. 8). Unfortunately, it requires a significant increase in reciprocating mass and, more importantly, a means to activate the height variation within a high-speed reciprocating assembly [7]. This is typically proposed by means of hydraulics using the engine lubricating oil; however, reliable control of the necessary oil flow represents a major challenge. This is claimed to reduce the peak firing loads so that the compression ratio variation becomes self-acting rather than externally controlled. A side-effect would be the momentary variation in clearance volume during the combustion event, which would, in turn, increase, then reduce the volume available to the expanding gases.

3.5.1 Pressure reactive piston

The University of Michigan developed a pressure-reactive piston for SI engines. The pressure-reactive piston assembly consists of a piston crown and a separate piston skirt, with a set of springs contained between them (Fig. 9). This piston configuration allows the piston crown to deflect in response to the cylinder pressure. As a piston crown deflects, the cylinder clearance volume increases, lowering the effective compression ratio and reducing peak cylinder pressure. This mechanism effectively limits the peak compression ratio for a particular condition. The volume of the combustion chamber is increased to reduce the compression ratio by moving a small secondary piston which communicates with the chamber [6]. However, this would require a finite length bore in which the piston could travel, which raises questions of sealing, packaging, and durability. Varying combustion chamber geometry compromises the area available for intake and exhaust valves, while moving the cylinder head and barrel is feasible in a research engine but harder to accomplish in a production vehicle. The cylinder head cooling needs to be improved by an efficient cooling system.
pressures at high loads without an additional control device, while allowing the engine to operate at high compression ratio during low load conditions [8]. It can be easily adapted to the conventional engine with only changes to piston and connecting rod design. Brake specific fuel consumption improvements of the pressure-reactive piston engine over baseline engine at light loads ranges from 8 to 18 per cent. The pressure-reactive piston shows higher heat transfer losses because of higher surface-to-volume ratio and produces higher hydrocarbon emission at part load owing to higher compression ratio and more crevice volume (piston crown design).

3.6 Moving the crankpins

Gomecsys has proposed to move the crankpins eccentrically to effect a stroke change at TDC. Figure 10 shows the Gomecsys VCR engine in which moveable crankpins form an eccentric sleeve around the conventional crankpins and are driven by a large gear [9]. Differences in the TDC position may vary up to 10 mm with a rotation of the ring-gear of only
By rotating the ring-gear slightly to the right or to the left, while the crankshaft is at the TDC position at the end of the compression stroke, the position of the eccentric can be lifted or lowered. Note that lifting the eccentric at one TDC automatically causes the other TDC to be lowered accordingly. In order to effectively downsize the engine, a two-cylinder inline engine is a perfect solution for small cars; the two-cylinder GoEngine concept is small and lightweight, and total powertrain costs are comparable with a small four-cylinder engine. Applications involving staggered crankpin geometry would be less elegant, requiring multiple gear drives.

4 BENEFITS OF VCR

The VCR engine constitutes a major solution for homogeneous lean-burn combustion as it permits an increase in compression pressure and temperature to restore favourable conditions for the combustion process (no misfiring and rapid flame propagation) even under high air-fuel ratio conditions. Thus VCR provides better control over pollutant generation and after-treatment than a conventional fixed compression ratio (FCR) engine. It also extends the life expectancy of a three-way catalytic converter. As the geometrical volumetric ratio is under control on VCR engines, the engine always operates below the knock limit, whatever the load. There should be a compromise between engine compression ratio and ignition advance to obtain the best indicated thermal efficiency. VCR reduces exhaust gas temperature at maximum power, which in turn decreases the engine thermal stresses and avoids charge enrichment at high power. Hence the important benefits of the VCR engine can be summarized as follows:

(a) optimum combustion efficiency in the whole load and speed range;
(b) low fuel consumption and low exhaust emissions;
(c) high fuel flexibility with optimal combustion efficiency;
(d) very smooth idle and full load accelerations are achieved;
(e) provides better indicated thermal efficiency than that of FCR engines;
(f) allows for a significant idle speed reduction because of reduced misfiring and cyclic irregularities, resulting in low vibration levels;
(g) reduction in low-frequency noise because of constant peak pressures;
(h) smoother combustion because the rate of heat release is the same (short) both at low and high compression ratios;
(i) cold starting emissions can be reduced greatly by early catalyst warm-up in the catalytic converter;
(j) improvement in the low end torque of a petrol engine without the risk of detonation;
(k) potential technology for future high-boosting super lean burn engines;
(l) low CO₂ emissions by down-sizing for the same power output;
(m) good idling performance at low ambient temperatures;
(n) constant frictional losses owing to almost constant peak pressures.

5 COMMERCIAL BARRIERS

Variable compression ratio engines have not yet reached the market, despite patents and experiments dating back over decades. Indeed, several prototypes of VCR engines and vehicles have been tested. In many cases, the deviation from conventional production engine structure or layout represents a significant commercial barrier to widespread adoption of the technology. Some of the commercial barriers are listed below.

1. The available methods require major changes to the base engine architecture or layout and represent significant commercial barriers to widespread adoption of the technology.
2. Introduction of additional elements within the crowded combustion chamber environment threatens to compromise ideal geometry and layout of the valves and ports.
3. Engine-out emissions performance is likely to be undermined by additional crevice volumes which obstruct complete burning, thereby increasing hydrocarbon emissions.
4. There is a significant increase in reciprocating mass in the case of a variable height piston.
5. Some approaches lead to an increase in vibrations owing to intermediate members in the connecting rod.
6. In some cases, reworking of the entire engine structure is necessary.
7. Variable compression ratio designs consist of multilink rod-crank mechanisms, which may also present a near-to-sinusoidal motion unfavourable to cylinder filling at low speeds and fine-scale turbulence.
6 SUMMARY OF VARIOUS VCR APPROACHES

All the different approaches for VCR engines, their unique features, and corresponding commercial barriers have been summarized in this section, to assist clear understanding. The authors hope that Table 1 will throw some more light on available VCR technologies in the field of automotive engine research.

7 RELIABILITY, DURABILITY, NOISE AND VIBRATION OF VCR ENGINES

Mass production of robust, reliable, and long-lived VCR engines is subject to implementation of a technical solution to compensate for high loads on high mileages. Variable compression ratio engines are not only more complex than conventional engines, they also pose a number of challenges. High loads essentially impact on cylinder durability, as the higher the average load, the higher the cylinder wear and distortion and associated negative consequences of blow-by, noise, and oil consumption. Other challenges induced by high loads on high mileage are related to engine hydrodynamic bearings, for which a precise and rigid geometrical environment is required, i.e. the appropriate crankshaft and rigid engine block. Variable compression ratio engines present lower cyclic irregularities at idle speed than conventional engines, widely reducing low-frequency vibrations owing to crankshaft torque variations. Variable compression ratio engines permit lower noise levels than diesel engines. However, in order to avoid additional noise emissions owing to their complexity, they must remain highly rigid in that their design must promote noiseless operation.

8 ECONOMICS OF VCR ENGINE

Choosing an appropriate VCR technology is a decisive step to determine the cost of VCR implementation in future vehicles. The different available VCR technologies have to be compared by focusing on all the positive and negative impacts on engine components and their operations. The benefits of VCR also include increased power density, reduced number of cylinders, sophisticated injection technologies, and complex after-treatment. Indeed, to be marketable, the VCR technology has to present

<table>
<thead>
<tr>
<th>Serial no.</th>
<th>Geometric approach</th>
<th>Unique feature</th>
<th>Commercial barrier</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Moving the crankshaft axis</td>
<td>The engine crankshaft bearings are carried in an eccentrically mounted carrier and the compression ratio is adjustable by varying the rotation of the eccentric carrier</td>
<td>The engine requires an offset fixed-position output shaft; a coupling is required between the movable crankshaft and the fixed output shaft</td>
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<td>2</td>
<td>Modification of connecting rod geometry</td>
<td>Effective length of the connecting rod is varied by a multi-link system to change the compression ratio of the engine</td>
<td>Leads to increase in vibration owing to intermediate members in the connecting rod</td>
</tr>
<tr>
<td>3</td>
<td>Moving the cylinder head</td>
<td>The compression ratio of the engine is varied by adjusting the slope of the upper half of the engine in relation to the lower half</td>
<td>Reworking of the entire engine structure is necessary</td>
</tr>
<tr>
<td>4</td>
<td>Variation of combustion chamber volume using a secondary piston or valve</td>
<td>The volume of the combustion chamber is varied by moving a small secondary piston or valve, which communicates with the chamber</td>
<td>Introduction of additional elements within the crowded combustion chamber environment threatens to compromise ideal geometry and layout of the valves and ports. Engine-out emission performance is likely to be undetermined by additional crevice volumes</td>
</tr>
<tr>
<td>5</td>
<td>Variation of piston deck height</td>
<td>Variation in total height of the piston by means of hydraulics or springs to change the cylinder clearance volume</td>
<td>Significant increase in reciprocating mass and higher heat transfer losses owing to higher surface-to-volume ratio</td>
</tr>
<tr>
<td>6</td>
<td>Moving the crankpin</td>
<td>Vary the TDC positions by moveable crankpins, driven by large ring-gears</td>
<td>Staggered crankpin geometry would be less elegant, requiring multiple gear drives</td>
</tr>
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indispensable features such as robustness, durability, easy integration into all vehicles and low noise and vibration levels.

The real potential of VCR engines will be realized when they are used in combination with down-sizing and supercharging. It may also be stated that only with VCR technology can extremely downsized engines with high-pressure supercharging be realized [9]. As knocking is under control on VCR engines, VCR technology can be combined with supercharger/turbocharger to increase further the power output, or the same combined technology can be used to downsize the engine without loss of the output power; this concept yields reduced heat and frictional losses, reduced pumping losses, and a lighter engine. In addition, VCR provides a further efficiency gain thanks to high expansion ratios at part loads, which compensate for pumping losses. Even if VCR engines are intended for down-sizing strategy implementation, their rotational speed range must be comparable to that of existing SI engines.

Variable compression ratio technology will allow implementation of the adaptive Atkinson cycle. It will also permit increasing load–speed range of effectiveness for lean-mixture strategies such as lean-burn and stratified charge or compression ignition. In future Otto–Atkinson VCR engines, high expansion ratios at part loads will allow benefits to be gained from a better efficiency at low loads than at high loads [10].

The VCR engine provides excellent fuel flexibility, since the compression ratio can be varied and adjusted to suit the properties of the fuel, and therefore the engine will always run at the compression ratio best suited to the fuel being used. For bi-fuel (compressed natural gas (CNG)/gasoline) powertrains, the realization of VCR is of specific interest. Moreover, lean burn technology is a perfect match for CNG engines. This concept can be integrated into existing engine designs, while retaining the existing production and assembly equipment [11]. Among the alternative fuels, liquefied petroleum gas (LPG) has potential for use in internal combustion engines with a lower level of engine modifications required. The conventional FCR engine has not been utilized at optimum specific output most of the time, hence to achieve optimum performance, a VCR engine is necessary [12].

In the near future, fuel-consuming vehicles will not only be penalized by markets, but also by governments. In addition to preservation of the environment, reducing fuel consumption reduces the national oil bill and promotes economic growth and associated tax revenues.

9 CONCLUSION

The VCR engine has great potential for improving part-load thermal efficiency and reducing greenhouse gas emissions. As VCR is a geometric approach to improve all existing engine strategies, it is potentially one of the profitable sources to investigate for the automotive industry. Variable compression ratio promises more efficient operation, the ability to down-size the engine, multi-fuel flexibility, and the potential to revise emission characteristics. The full potential of variable compression can only be realized when it is used in combination with reduced engine displacement and high supercharging pressure. The biggest challenge in adoption of the VCR is incompatibility with major components in current production. In short, VCR features will permit SI engines significantly to reduce fuel consumption and emissions. Purchasing fuel-efficient, clean vehicles would be greatly encouraged by tax breaks and subsidies by government.

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