

engine technology INTERNATIONAL

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Honda diesel

The Japanese firm finally does a compression engine all by itself – well, almost...

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Is the manual gearbox dead?

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The greatest engine in the world

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More variables

We've reviewed Saab's concept and checked out FEV's take, but what of the Innovation Engineering variable compression axial engine – can it really make the grade?

by Art Shulenberger

The compression ratio of an ICE ranks right up there with bore, stroke and number of cylinders as a key parameter in determining performance. Higher compression ratios, up to the point of pre-ignition, increase output and efficiency in petrol engines.

In comparison with diesels, petrol engine efficiencies suffer due to lower compression ratios. The effective compression ratio in petrol engines is much lower than the nominal (or geometric) compression ratio during part load operation – the predominate mode of operation in automobiles and most other engine applications.

Premixing of the air and fuel in petrol engines gives a power to displacement advantage over the diesel engine through the higher fuel:air ratio possible, and by faster combustion, which leads to higher engine speeds. Thermodynamically, fuel-air premixing is a disadvantage due to the need for intake throttling to provide for part load operation. At a compression ratio of 10:1, the full-throttle limiting thermal efficiency is 60.2 per cent and

half throttle (50 per cent of full charge) has a limiting thermal efficiency of 47.5 per cent.

Ideally, a petrol engine would have a constant effective compression

ratio throughout its operating range, keeping the limiting thermal efficiency at the maximum now seen only at full throttle. In the 50 per cent throttle case mentioned, this corresponds to a 26.7 per cent improvement in efficiency.

Variable Compression Ratio (VCR) makes it possible to maintain an optimum compression ratio from 50 to 100 per cent of maximum load. Below 50 per cent, the effective compression ratio is still two times higher than in a non-VCR engine, maintaining a thermal efficiency advantage all the way down to idle. It has been found that VCR works very well in combination with engine boosting and downsizing.

With Variable Valve Actuation (VVA), the effective compression ratio can be varied with reduced throttling losses as compared to a standard engine. High-efficiency Miller and Atkinson cycles are possible, where the expansion ratio is greater than the effective compression ratio. However, VVA does not make it possible to maintain a constant effective compression ratio over a wide load range as VCR does. VVA and VCR offer complementary benefits and can be used together to achieve even greater improvements to petrol engine efficiency.

Many different approaches have been taken to implementing VCR in prototype engines, with varying degrees of success. Notable efforts include: connecting rods

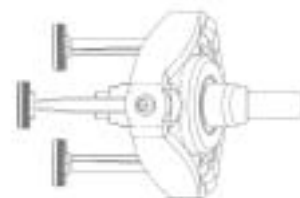
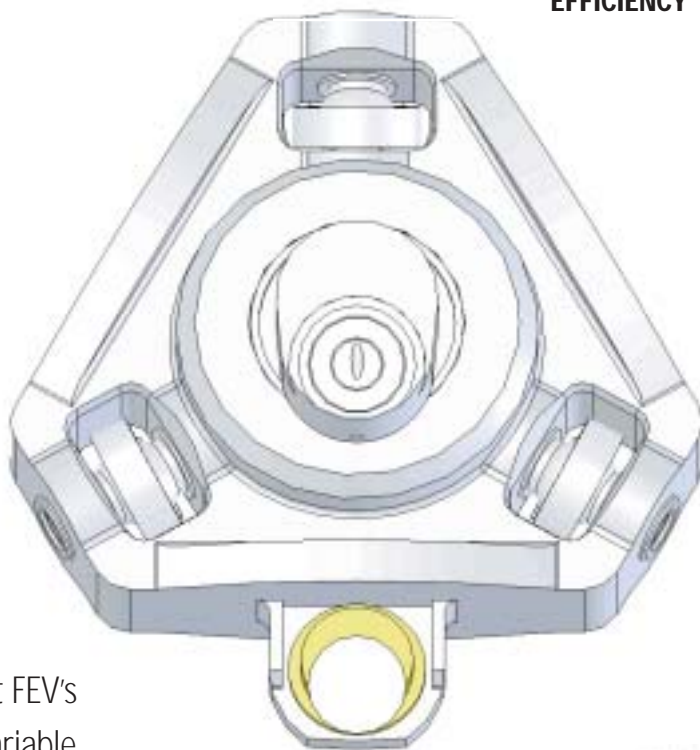
with unconventional linkages developed by Nissan, PSA, Mayflower and Rapan; hydraulically controlled (variable height) two-piece pistons developed by BICERA, Ford and Daimler-Benz; Ford and Volvo/Alvar have developed mechanisms with secondary pistons in the head; Saab has developed a hinged crankcase engine; and FEV and Envera have developed VCR engines with movable crankshaft main bearings.

The hinged crankcase and movable main bearing configurations appear to be the most practical, although both add weight and complexity.

It has been difficult to implement VCR largely because piston motion is perpendicular to the axis of rotation of the crankshaft. This is true in all types of conventional piston engines: in-line, vee, horizontally opposed (boxer) and radial.

Is there another possible arrangement that would be better for VCR? If piston motion were parallel to the axis of the output shaft, then it would be possible to shift the piston driving mechanism slightly during operation to vary the compression ratio while maintaining power and auxiliary output connections through splined shafts.

There have been engines built in this axial configuration. As a group they are referred to as barrel engines, and include cam, swash plate and wobble plate drives. Cam-type axial engines suffer

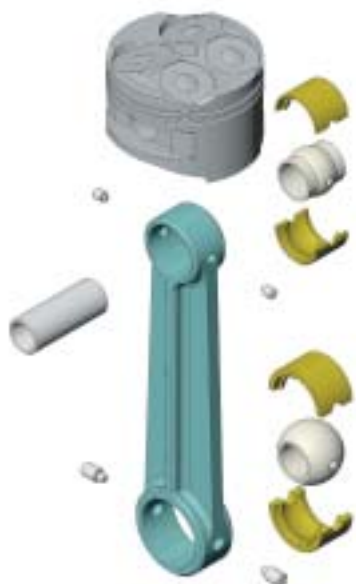


from the need for cam-following rollers that are highly stressed and rotate at a multiple of engine speed. Both cam-type and swash plate-type axial engines have unacceptably high frictional losses. Wobble plate axial engines have lacked a simple, robust and geometrically accurate mechanism for counteracting the reaction torque that tends to cause rotation of the wobble plate.

Innovation Engineering, Inc., has developed an axial engine design of the wobble plate type that overcomes past limitations. Adding variable compression capability to the axial engine results in the Variable Compression Axial Piston (VCAP) engine concept.

Each piston is attached through its connecting rod to a single motion converter, or wobble plate, which wobbles (the technical term for this is nutation) as the Z-crank rotates. The nutation of the motion converter as the Z-crank rotates drives each of the pistons in a sinusoidal motion. Rotation of the motion converter is prevented by the reaction control bearing, which rides on the reaction control shaft. The reaction control shaft has a slight eccentricity and rotates at twice the speed of the Z-crank.

The VCAP is a simple, geometrically correct implementation of the wobble plate concept where each connecting rod pivot point at the motion converter follows a perfect lemniscate (figure eight-type) path. Geometrically correct motion makes it possible for the inertial vibration forces to be perfectly balanced, resulting in an engine where only the torsional vibration caused by the power pulses of individual pistons remains.



Exploded view of the VCAP engine piston assembly

The VCR mechanism can be located in the main block, between the cylinders, with the Z-crank carrying the piston thrust load in tension. This saves space and reduces stresses at the output end of the engine. Both ends of the Z-crank are splined to allow for VCR axial displacement. At the output end the Z-crank drives a flywheel/counterbalance module, and at the cylinder end the Z-crank drives valves and auxiliaries.

With the high specific power output due to the boost pressures possible with VCR, only three- and five-cylinder configurations will be needed. In a three-cylinder VCAP, the valvetrain drive requirements are not overly difficult. A five-cylinder VCAP engine design will benefit from electronic valve actuation or other unconventional valve gear.

A possible valve gear solution is to have a pair of multi-lobe cams, one each for intake and exhaust, that operate all of the valves. The cams, concentric to the main axis of the engine, would have lobes, equal in number to the number of cylinders minus one, and would rotate in the opposite direction to the Z-crank at a fraction of the Z-crank's speed. The reduction ratio is two times the number of lobes. The drive ratio is $-1/[2 \times (N-1)]$, where N = the number of cylinders. For three-cylinder VCAPs the number of cam lobes is two per cam and the rotational speed is a quarter of the Z-crank speed in the opposite direction. For five-cylinder VCAPs, the number of cam lobes is four per cam and the rotational speed is an eighth of the Z-crank. For VVT, a phasing mechanism can be added, for instance shifting of the location of a planetary gear in the reduction gear train.

What advantages does the concept offer? There's simplified implementation of VCR, with improved thermodynamic and mechanical efficiencies and no inertial vibration. The compact, low-vibration package can offer new options to vehicle designers in addition to the ability to be automatically optimized for bi-fuel and multi-fuel operation and to reduce friction and wear between the piston skirt and cylinder walls. Uniform temperatures from cylinder to cylinder due to symmetry are another bonus, while peak accelerations of the pistons and rings can be reduced by about 25 per cent. Lastly, the small angle between the connecting rod and the cylinder axis may make it possible to combine the piston and connecting rod into one piece, or two pieces rigidly attached together.

There are many challenges in VCAP engine design: hydrodynamic thrust

Diesel variables

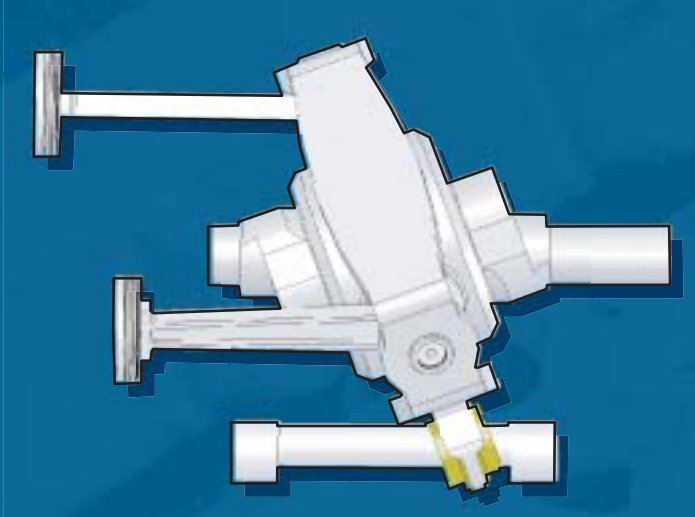
The VCAP concept can also be applied to diesels. The primary benefit is a better power to weight ratio. VCR in a diesel engine allows for variable boosting, from no boost in the low power ranges to high boost ratios at upper output levels. VCR (and VCAP) may be an enabler in HCCI applications, since HCCI depends on the effective compression ratio for ignition and many operating parameters (such as engine temperature, power setting, and engine speed) are involved.

bearings have a much lower load-carrying capacity than standard journal bearings; laying out the heads and intake runners for optimum flow in such a compact arrangement; providing adequate lubrication for the bearings; building a sufficiently rugged and precise VCR mechanism that can be operated quickly without excessive power; and connecting rods need double-articulated bearings at one or both ends.

Unlike the Wankel and other rotaries that have challenged conventional crankshaft and piston mechanism, the VCAP engine uses completely conventional technologies in the area of the combustion chamber. This is a huge advantage in terms of compatibility with the existing supply chain and for performance and reliability. Pistons, rings, valves, cylinders, ignition and fuel systems, and many more components of the engine, are essentially conventional. The heads, blocks and manifolds of the VCAP engine will be unusual but can be manufactured using conventional processes and existing equipment.

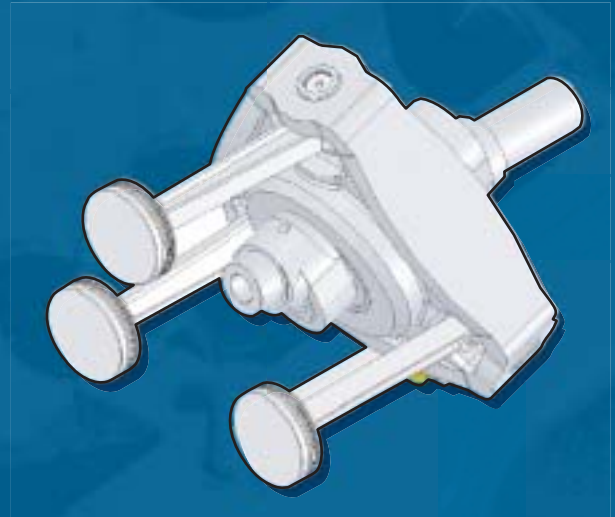
VCR has been shown to produce real-world fuel consumption reductions of 25 per cent or better, on a par with those made by going to hybrid-electric with conventional engines. The cost of switching to a smaller, more efficient VCAP engine of equal or greater performance to an existing engine will be much less for the vehicle manufacturer than the cost of totally redesigning and equipping a vehicle for hybrid-electric. The hybrid-electric system requires the addition of high-power motors, controllers and massive batteries, leading to increased weight and requiring frame and chassis redesign. A final point is that VCAP can also be used *in conjunction* with mild hybrid-electrics for even greater efficiency gains. *ETi*

Art Shulenberg is president and CEO of Innovation Engineering, Inc., in the US



Variable Compression Axial Piston (VCAP™) engine technologies utilize an axial configuration to make the implementation of Variable Compression Ratio (VCR) simple and compact.

- Axial piston arrangement for simple and compact VCR
- VCR and downsizing provide 25% or greater thermodynamic efficiency gain
- Piston side load friction eliminated
- Pure harmonic (sinusoidal) piston motion
- Elimination of vibration



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