The 2-Step VCS-Functional Verification and System Modulariation

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ABSTRACT: Variable Compression Systems for Internal Combustion Engines will become increasingly more important to meet stringent global fuel economy standards. A 2-Step VCS system is in development in cooperation of AVL and IWIS and the basic functionality was described in a technical paper, presented at the JSAE 20175333. The system is based on a hydraulically switched and locked conrod with telescopic shank.

This paper discusses the main development results which have been obtained for the Proof of Concept and for the completion of the functional and design validation as well as the industrialisation concept with a modular production approach.

KEY WORDS: heat engine, spark ignition engine, performance/fuel economy/efficiency, variable compression ratio, 2-Step VCS [A1]

1. Introduction

Future legislation scenarios as well as stringent CO₂ targets, in particular under real driving conditions, will require the introduction of different powertrain technologies (1). Beside the increasing electrification of the powertrain, it will be essential to utilize the full potential of the internal combustion engine. In addition to further optimization of the combustion efficiency and the reduction of mechanical losses, the introduction of Variable Compression Ratio (VCR) is probably the measure with the highest potential for fuel economy improvement (2, 3, 4, 5, 6) in particular in combination with Miller or Atkinson cycles.

A considerable variety of functional principles had been published and developed with the target to achieve variable compression ratio. The main groups of VCR concepts may be characterized by:

- Variable distance between crankshaft and cylinder head
- Articulated, multi-link crank trains
- Variable effective conrod length

Whereas concepts with variable crankshaft to cylinder head distance and in particular articulated crank trains are focusing on continuously variable compression ratio, the variation of the effective conrod length is typically a 2-step approach.

The 2-Step VCS enables a 2-stage variation of the connecting rod length and thus of the compression ratio. The concept allows a modular integration into existing engine families and thus represents a cost-attractive solution (7, 8, 9).

2. The 2-Step VCS Concept

The basic functionality of the 2-Step VCS is a conrod with telescopic shank allowing two extreme length positions (Fig. 1).

Fig. 1 Schematic 2-Step VCS

The VCS actuation system consists of an upper and lower hydraulic chamber, defining the VCR variation range by their respective volumes. The actuation piston is connected to the big end and both parts are connected via a translational joint in the shank area. To achieve the length changes of the 2-Step VCS into the respective directions, the gas and inertia forces are used which are acting on the conrod during engine operation.
VCS control unit and the VCS actuation part are connected via filling and drain bores. If the force applied by the spring is greater than the force being applied by the oil pressure, then the slider moves to the left-hand position and opens the upper chamber drainage. Since the lower chamber drainage is closed by a ball valve, a tensile rod force will pump oil into the lower chamber until the actuation piston reaches the upper limit stop. The "long" position of the VCS is thus hydraulically locked because of a check valve, which prevents drainage via the filling line. If the control pressure is increased until the resulting force on the slider is exceeding the spring force, the slider moves into the right-hand position shown in Fig. 2. The slider is opening the lower chamber drainage and the upper chamber is continuously filled supported by a pressure rod force acting at the shank and subsequently hydraulically blocking the "short" position of the VCS.

3. Operating and Switching Strategy

Comprehensive engine tests with continuously variable VCR systems and corresponding simulations for different vehicles and drive cycles led to the conclusion that the achievable fuel economy improvements are determined more by the optimal definition of the CR spread and less by the decision between a continuously variable or a 2-step VCR system.

While with continuously variable systems the ideal CR and valve lift combination for each application may be optimized during the calibration phase, the parameters for 2-step systems must be determined early in the development phase. This requires an optimized design of the 2-Step VCS and VVL systems, considering all potential engine, transmission and vehicle configurations as early as the design phase, as shown in Fig. 3.

If a WLTC is used as the basis, engine speeds up to 3000 rpm only are relevant and in case of an RDE, aggressive, up to 5400 rpm for a 2.0L TGDI engine in a SUV application. 96% of the run time in the WLTC is spent in the low load area and 89% of the run time in case of RDE. 81% of fuel is burned in the lower load range of the WLTC and 56% in the RDE. Accordingly, the high CR mode, respectively the long position of the 2-Step VCS, is appropriate in the lower left quadrant of the engine map (Fig. 4) while the remaining part is operated with low CR, short position of the VCS.

Each switching event of the VCS, from long to short position and vice versa, requires a corresponding amount of energy. In order to limit the parasitic losses, the idea is to reduce the number of switching events to a minimum taking into account the VCS operating strategy. Fig. 3 shows load (blue color, upper graph) and speed (red color, upper graph) of an aggressive RDE over a period of 900sec. The bottom graph in Fig. 3 shows the number of switching events (trigger 1 = load-controlled event, 1.5 = speed-controlled), green color indicates the accumulated number of cycles required for each switching event, while the red curve represents the accumulated duration. The result is a number of 41 long-to-short switching events and a duration of 124 seconds, corresponding to 14% in short, low compression ratio position. The maximum duration in low compression ratio is 8 seconds, corresponding to 270 cycles. The duration of about 50% of all switching events is less than 50 cycles.

The energy demand in short position is higher compared to the long position due to the higher oil pressure and the requirement of an auxiliary booster oil pump, electrically or mechanically driven. However, due to the low percentage in low compression ratio position in the drive cycle, the impact on cycle losses is negligible.
4. Fuel Efficiency Potential

The VCS system allows the combination of an efficiency engine configuration with high CR, applying Miller cycle and 2-step VVL system and a high performance engine with adapted CR, performance intake cam duration and valve lift providing highest potential in fuel economy. The low CR is optimized for high performance to achieve the competitive torque and power output targets. The high CR level can be increased to about 14, combined with an aggressive intake valve closing strategy. The fuel consumption potential of the 2-step VCR system is estimated from initial MCE test bed measurements. Compared to the "efficiency" base engine, the VCS engine shows slightly increased friction values due to bearings with increased width and a heavier crank train \(^{(10)}\). Considering this effect as well as the increased weight of the VCS requires a modified flywheel layout and adjusted crankshaft counterweights taking into account optimized bearing design, as well as modified NVH. Additionally the friction impact of damping effects due to the elasticity of the VCS hydraulics had to be taken into account.

![BSFC map 2-Step VCS engine](image)

**Fig. 4** BSFC map 2-Step VCS engine (simulation results)

The results, achieved with the VCS engine strategy as the combination of a "fuel efficiency" engine with a "performance" engine are shown in Fig. 4. Compared to the "performance" engine with same torque and power output, the combined engine with 2-Step VCS achieves a significant efficiency improvement at part load with high CR.

5. VCS Development and Testing

The VCS System development is performed in various testing environments to focus on the individual development and validation key areas:

- Hydro-Pulsating and Test Rigs
- Single-Cylinder Engines motored
- Single-Cylinder Engines fired
- Multi-Cylinder Engine fired

The following section covers essential development areas within the advanced development phase.

5.1 Oil investigation

Because of the hydraulic switching and locking of the 2-Step VCS, it becomes very important to investigate and validate all potential oil conditions to ensure the VCS functionality \(^{(11)}\). A test program with defined ICE operating conditions was carried out:

- Different oil temperatures: 50, 70, 90, 110°C
- Different oil viscosities: 5W-30 and 0W-20
- Aged oil
- Oil aeriation: 0%, 5-10%, 15-20% and 20-25%
- Contaminated oil

The oil investigations were performed using a SCE under motored conditions. An oil conditioning and aeration system was installed in the test cell to provide the oil in the required conditions. To alter the piston load, the intake system was connected to a pressure air system providing intake air at 2bar, which allowed to increase cylinder pressures to reach up to 40 bar.

![Eddy current sensors for detection of piston position](image)

**Fig. 5** Eddy current sensors for detection of piston position

Two eddy current sensors located in the cylinder liner were used to measure the piston position and conrod length (Fig. 5). As the piston skirt or crown edge passes the sensor a signal is triggered which, together with amount of Crank Angles (CA) passing between to trigger signals will indicate the piston position and consequently the conrod length and finally the actual Compression Ratio (CR). All motored tests were run in Naturally Aspirated (NA) mode and also with 2 bar air pressure in the
intake system (= Boosted). All test were performed with Wide Open Throttle (WOT). The oil investigations were done in the speed range between 700 and 3500 rpm, since this is the part of the engine operating map, were all the CR switching will occur.

5.2 Test Results – Oil Temperature Variation

The 2-Step VCS was investigated with fresh SAE 5W-30 and 50, 70, 90 and 110°C oil temperature. Fig. 6 shows the average number of engine cycles needed to expand the VCS from short to long position, after the oil pressure signal has been given to initiate a CR switch.

![Fig. 6 Average number of cycles needed to expand – 5W30 - 50, 70, 90, 110°C](image)

The increase in oil temperature leads to a reduction in oil viscosity, which accounts for the slight decrease in engine cycles needed to extend the conrod from short to long. The number of engine cycles needed to expand were consistently between 5 and 16 depending on engine speed (excluding 700rpm boosted mode), which equates to maximum switching times of 0.6 - 2sec at 1000 rpm (at 1000 rpm the time for a length change is the longest). Fig. 7 shows the average number of cycles needed to collapse to VCS from long to short position, after the oil pressure change to initiate the switch.

![Fig. 7 Average number of cycles needed to collapse – 5W30 - 50, 70, 90, 110°C](image)

The VCS collapses to the short position within 2-3 engine cycles almost inde-pendent from engine speed (0.24sec at 1000rpm). The variation of oil temperature also did not make a difference which would be of any significance during engine operation. The very short conrod switching response from long to short is very important for immediate knock mitigation during a driver tip-in (=sudden load increase). Since the 2-Step VCS is using hydraulic chambers for the length change it is of high interest to keep the elasticity of the system at low levels, especially when the load path is transferring forces through the hydraulic chambers.

There is a difference in VCS conrod length between the gas exchange TDC with the conrod in long positions too, due to the fact, that the VCS has some flexibility under the influence of the forces acting on the small end. The elasticity in gas exchange TDC with the conrod in short position is larger, because in this case the upper hydraulic chamber gets pressure loaded and this chamber is contained by 2 hydraulic seals which causes a higher flexibility and potential leakage.

In the other case the bottom hydraulic chamber gets pressure loaded, which only has one hydraulic seal and therefore a lower elasticity and also lower leakage rates. In general it can be concluded that the oil temperature levels show very little influence on in-cycle length change during operation and the load magnitudes over en-gine speed are the dominant influence. It was confirmed that the 2-Step VCS is fully functional in the 700-3500rpm speed range with all oil temperatures tested.

5.3 Test Results – Oil Viscosity Variation

A comparison between fresh 5W-30 and 0W-20 oil grades was performed and a variation of oil temperature between 90°C and 110°C was also included. Fig. 8 shows the same trends as the variation of the oil temperature with 5W-30, the influence of the load conditions acting on the VCS have a larger impact on the conrod behavior than the oil viscosity. The number of engine cycles needed to expand the VCS from short to long are slightly higher with 0W-20 compared to 5W-30.

![Fig. 8 Average number of cycles to expand – 5W30 vs. 0W-20 at 90 and 110°C](image)

Overall the expansion from short to long takes between 5 and 17 engine cycles, which equates to 0.7 – 2sec at 1000rpm. The number of engine cycles to collapse are very low and basically identical between 0W-20 and 5W30. A full collapse from long to
short position takes mostly 2 – 3 engine cycles, which is equivalent to 0.24sec at 1000rpm. The elasticity of the VCS with 0W-20 due to forces acting on the oil chambers is also in similar ranges compared to the results with 5W-30. The results show that the 2-Step VCS conrod is fully functional in the 700-3500rpm speed range with SAE 5W-30 and SAE 0W-20 under 90°C and 110°C.

5.4 Test Results – Aged Oil

Engines can add a large amount of combustion particles into the oil which can affect wear on sliding contact surfaces as well as oil dilution by fuel. Therefore, the testing of the 2-Step VCS with aged oil was important. 5W-30 oil was aged and collected from high load / high speed TGDI engine dyno durability testing. The aged oil was used at 90°C to conduct the VCS tests. The results also show that the 2-Step VCS is fully functional in the 700-3500rpm speed range with aged 5W-30 oil. The number of engine cycles needed to expand and to collapse and also the elasticity behavior of the VCS are very similar to the previous tests described in this chapter.

5.5 Test Results – Oil Aeriation

Due to the load transfer path of the VCS through hydraulic oil chambers the potential influence of oil aeriation and the impact on conrod elasticity under load needed to be investigated. The aeriation system installed in the engine test cell is able to provide oil aeriation levels between 0 to 25%. The actual aeriation level was measured with a Coriolis meter and the aeriation level was determined as a ratio of real time oil density measurement to calculated oil density corrected for actual temperature and pressure. The oil aeriation tests were performed with fresh 5W-30 oil at 90°C. The oil aeriation test, as all other tests before showed very good functionality of the conrod with almost no influence of the aeriation level (Fig. 9).

It can be concluded the oil pressure levels inside the hydraulic system of the VCS are high enough, so that any air is compressed to very small volumes or goes into solution and does not have an impact on the VCS function. In general the aeriation level shows very little difference in-cycle length change during operation.

5.6 Test Results – Contaminated Oil

The hydraulic circuit of the 2-Step VCS consists of passages, valves and seals, which potentially could be sensitive to oil contamination. To choose the right contamination in terms of particle types, size distribution and concentration, oil analysis data from an engine durability development program was used. The average contamination level found was doubled for the oil contamination test. As contamination source A2 Ultrafine test dust (ISO 12103-1) was used. For the oil contamination test the SCE was operated in motored condition, NA mode, 2000rpm constant speed and the VCS was switched every 15 sec during the first 2 h and then every 5 sec for the rest of the test. After 5.7h the control over the VCS length switching was lost and the conrod could not be moved into short position anymore.

Fig. 10 Engine cycles to expand - Contaminated oil at 90°C and 2000rpm const.

After VCS conrod tear-down some uncritical internal wear was discovered in the VCS and the root cause for the loss of function was determined as increased wear of the conrod big end bearing shells, which led to increased bearing clearance and increased oil loss through the bearing gap. Until the loss of switching control the VCS conrod did not show any different behavior compared to the other oil tests performed before as shown in Fig. 10 and Fig. 11.

Fig. 11 Engine cycles to collapse - Contaminated oil at 90°C and 2000rpm const.
The VCS and the SCE were subsequently cleaned and reassembled with new bearing shells. VCS conrod function was completely restored in the new testing program, which confirmed the root cause analysis. It can be concluded that the VCS is sufficiently robust against oil contamination and other established engine systems (e.g. conrod big end bearing shells) seem to fail before the VCS.

5.7 Dynamic Measurement of VCS

For detailed investigations of the behavior of the VCS an instrumented VCS was developed and equipped with sensors for the high and low pressure systems and thermocouples to observe any temperature difference over time and sensors for measuring displacements between VCS parts. The measurement VCS was installed in the fired SCE together with a linkage for extracting all data via cables.

Fig. 12 shows the instrumented VCS with linkage arm, which was designed to run up to 6000 rpm. CA based pressure in the lower high pressure chamber of the VCS (LC) for different load points (speed and BMEP) is given in Fig. 13 as one example of the data obtained.

5.8 VCS Initial durability screening

The initial durability screening run (IDS) is defined as a preliminary Generation - 1 VCS - Test to be conducted under fired conditions at low to mid speeds where the combination of high gas forces and (relatively) low inertia forces result in the largest negative (downwards) VCS forces over spark top dead center, when the VCS is in the long position. This test is designed to test the VCS under the maximum normal loads that it will see in the long position, and therefore the highest lower chamber pressures. Initial durability screening at high speeds shall be conducted to assess the VCS’ ability to hold a short and stable position at high engine speeds (6500 rpm) for a defined period.

The load point definition can be seen in Fig. 14 whereas the gathered timings, respectively number of switching events are shown in Fig. 15. The Engine load points are results from AVL Load Matrix simulation. Fig. 14 shows the switching thresholds for both switching directions. The percentage circles at the 4 relevant load points indicate the duration in high and low compression ratio (CR), the higher value for high CR throughout.

High speed events are covered by final high speed robustness test. The test shall provide the following information:

1. the durability of the VCS and its sub components at medium to high loads,
2. the switching functionality and extension/deflection up to 4000 rpm at medium to high loads over time,
3. information according stability of short VCS position under high speeds,
4. the switching functionality and extension/deflection up to 4500 rpm post high speed testing,
5. the conrod and sub component wear.

Fig. 12 Measurement VCS

Fig. 13 Measurement VCS – Linkage Results

Fig. 14 VCS initial durability screening (IDS) Load point definition

Fig. 15 VCS initial durability screening test definition - duration of 1 cycle [Sec]
The telescopic rod assembly of the VCS as a module includes mainly the small end which is connected to a rod via a thread.

![Image of telescopic rod assembly]

Fig. 16 VCS telescopic rod module after initial durability screening

As an example, an optimised design of thread and rod end connection, using a convex top end shape, had been developed to prevent structural damage in that area. To define that connection regarding small end tolerances, like admissible angle deviation, a contact area between the two main parts is present that determines the relative position of each part to the other one.

One optimization area within the IDS was the geometry and surface improvement in the contact area between small end and rod. The surface roughness had been redefined and a coating introduced to avoid local fretting. Fig. 16 shows the result of the optimized area after initial durability screening run.

6. Industrialization of 2-Step VCS for Modular Engine Platforms

The most important concept decision criterion is the application of the 2-Step VCS into existing engine architectures allowing modular engine variants with and without VCR.

![Diagram of 2-Step VCS modular design]

Fig. 17 2-Step VCS modular design

The 2-Step VCS approach considers parametric application for specific power range, displacement per cylinder, bore stroke ratio and conrod ratio as measure for kinetic and kinematic aspects.

The base 2-Step VCS used for scaling to other engine families is currently designed for 0.5L per cylinder engines with specific power ranging from 80 kW/l to 180 kW/l and a stroke / bore ratio reaching from 1.05 to about 1.20.

The second engine class of main interest for VCS application is the 1.5L- 4 cylinder class resulting in displacement / cylinder values in the range of 400 cc, stroke / bore span similar from 1.1 to 1.2. The compression ratio spread target range is 8 to 10 for the low CR and approx. 14 for the high CR.

Modular VCS engine families influence the design of the 2-Step VCS regarding strength, space, to implement it into power cells with changed bore, different con rod length and varying crank radius. The adjustment also must consider the VCS width to apply it on different crankshafts with different offsets (usually from 0 mm to 12 mm). Also, the piston pin diameter must be considered to be different for the different engine families.

The 2-Step VCS has the following modules (Fig. 17):
1. Con rod Upper and Lower
2. Telescopic Rod
3. Valves

The defined interface and main design parameters enable fast and simple engine application as well as cost effective production.

During functional development prototypes are assembled in a pure manual process. Subsequently the workflow is improved with specific tools to support single steps in the workflow. Based on the experiences collected here the general assembly principle was chosen. For the small series production, a One-Piece Flow concept was evaluated as the most efficient possibility. Therefore, the first concepts are already defined and will be build up step by step. The approach as shown in Fig. 18, will be continuously reviewed according to the experience gained from a semi manual prototype production.

![Diagram of One piece flow approach for small series production]

Fig. 18 One piece flow approach for small series production
However, the one-piece flow approach will not satisfy the requirements of a high-volume series production for several million products per annum, especially when several high-volume variants must be considered simultaneously.

Assuming high volume production, full use of capacity and estimation based on current design, the 2-Step VCS can be considered as a VCR System with very competitive cost benefit ratio in the range of 30-40 €/g CO2.

7. Conclusion

The development of the 2-Step VCS system is in progress and the POC milestone has been successfully achieved in 2017. Major development results can be summarized as follows:

- Full functionality in the engine speed range 1000 – 6500 rpm and under loads to be expected in a 2.0L TGDI state-of-the-art passenger car engine.
- Very fast switching times from L2S and fast switching times from S2L.
- Very consistent and repeatable switching behavior.
- Functionality assured for SAE 5W-30 and SAE 0W-20 oils, robustness against oil aeration and oil contamination.
- Minor parasitic losses (especially in WLTC drive cycle operation).

Due to the target achievements so far, the 2-Step VCS development has been transferred into a production development program. The modular design approach of the 2-Step VCS provides high flexibility and cost efficiency for the application in modular engine families.

Fig. 19 shows the comparison of the 2-Step VCS with alternative VCR concepts. VCR 1 is the cost calculation for a fully variable system, already introduced to the market, VCR 2 is the related cost calculation for an alternative 2-Step system.

This paper is written based on a proceeding paper No.2018-5161 presented at JSAE Annual Spring Conference May, 2018.

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