Development of a Two-stage Variable Compression Ratio Engine

ABSTRACT

Fuel consumption can be reduced in highly boosted gasoline engines with a Variable Compression Ratio (VCR). The increase in fuel economy is the result of operating an engine with higher compression ratios at low load compared to an engine with fixed compression ratio. The two-stage VCR-system provides a high share of the potential fuel savings in comparison to fully variable system.

The two-stage VCR system is proven to be the best concept, considering its low cost to manufacture and the benefit if integration into common engine architectures. The system uses a length-adjustable connecting rod with an eccentric piston pin in the small eye. The compression ratio adjustment is performed through a combination of gas and mass forces.

This study outlines the design of the two-stage VCR-system and describes the functional testing that was conducted under motored and fired engine operating conditions.

INTRODUCTION MOTIVATION AND POTENTIALS

POTENTIAL FOR SI COMBUSTION PROCESSES

Variable compression engine benefits have been widely acknowledged and documented [1, 2, 3, 8, 9, and 11]. Under full load conditions, the performance and efficiency of an engine with a compression ratio that is adapted to load demands is capable of reducing knock susceptibility. In addition, the risk of pre-ignition, mega-knocking effects and engine jerking, as the result of retarded combustion phases, can be reduced. The VCR also provides further potential to control the exhaust gas temperature, contributing to protecting component temperatures.

The potential for fuel savings under part load conditions is shown in Figure 1.

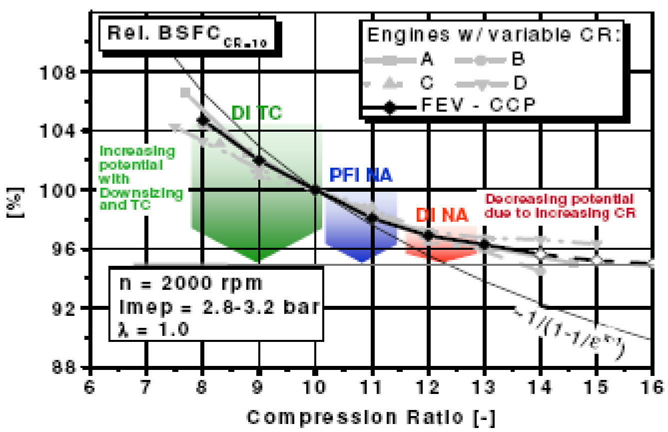

Figure 1: FC Reduction through VCR (Part Load)

For the naturally aspirated engine the potential for CR variability drops because of the increased compression facilitated by gasoline direct injection. However, the benefits of the VCR system can be enhanced through the combination of downsizing and engine charging. This will result in a fuel saving potential of up to 5 to 10%, because the required compression ratio reduction is necessitated by high boost ratios.

Operating the engine under high compression aids in producing higher combustion stability, even under unfavorable thermodynamic conditions (e.g. high amount of residual gas, relative air-fuel ratio). Therefore, the idle speed can be reduced, the valve overlap can be increased, and, if applicable, lean burn limits can be extended. For auto-ignition combustion processes based on the gasoline engine, the auto-ignition operating range can be extended at both higher and lower engine loads.

The potential for increasing the fuel economy of charged engines under various driving cycles in dependence on (mean) driving speed as well as at constant-speed driving is illustrated in Figure 2. Low speed operating conditions can realize benefits of well over 10%, whereas at higher vehicle speeds a benefit of approximately 6% is still possible. The reduction in fuel consumption is not totally dependant upon the VCR system, but also on the characteristics of both engine and vehicle.

The potential fuel economy improvement for a two-stage VCR system is slightly reduced, because the compression ratio cannot be operating point-optimized and due to hysteresis effects.

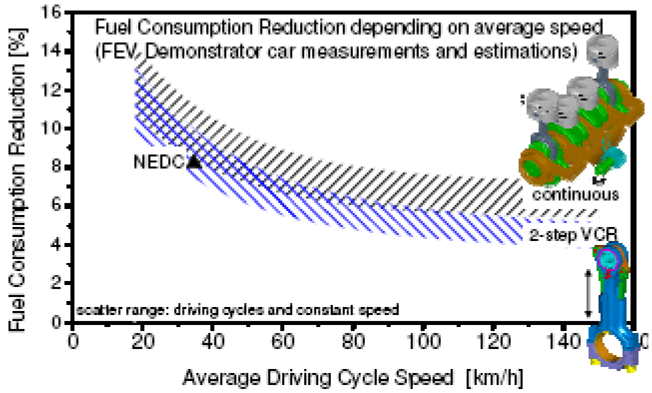

Figure 2: FC Reduction through VCR (On-road)

The calibrated compression ratio in an engine map is displayed in Figure 3. It is calibrated in large areas of the part load range at its maximum. The compression ratio maintains a relatively high value of 14, even at constant-speed driving at 140 km/h. The maximal possible adjustment position is required only for full load accelerations with maximum boost pressure. The adjustment of the compression ratio was integrated into the torque structure to shows a torque neutral behavior and remains inconspicuous while driving. The currently adjusted compression ratio is shown in a bar-graph display, which is located in the center console of the passenger compartment in the vehicle.

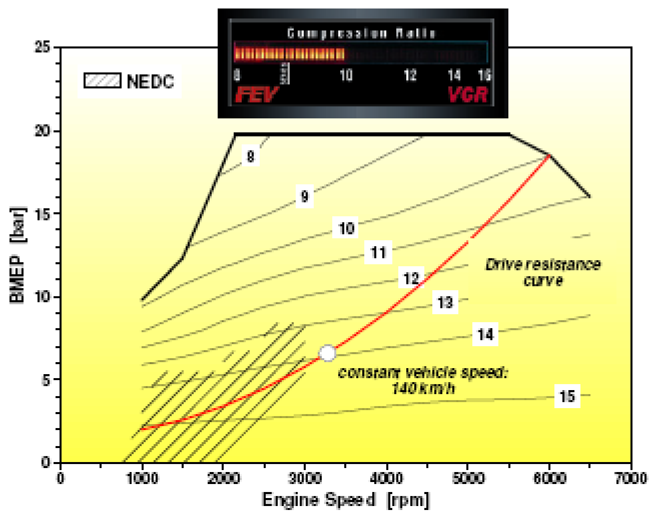

Figure 3: Compression Ratio Operation Map

Therefore, variable compression can be applied in combination with modern SI combustion processes, but it can also facilitate the development of new combustion technologies.

POTENTIAL FOR PASSENGER CAR DIESEL ENGINES

In light of the current debate over carbon dioxide, the development efforts for the combustion process are being directed at reducing fuel consumption. Downsizing, when combined with high-pressure supercharging, is an effective measure to accomplish this goal. [5] [6] Performance and torque must remain at the current high levels though in order for customer to accept them. In order to compensate for the reduction in displacement, the specific power output and the maximum BMEP have to be raised, which can be achieved by an increase in boost pressure. At a constant compression ratio, however, the higher boost pressure can only be effectively utilized in conjunction with an increased peak firing pressure.

A balance must be found between emission output and full load performance when deciding upon a compression ratio. The compression ratio typically used for a passenger car diesel engine lies in the range between 15 and 16.5. A higher CR would result in better combustion stability and can assist in reducing CO and HC emission in the low-load range (especially at low engine and ambient temperatures). A higher CR would also result in a less favorable particulate/NOX trade-off, which is due to a shorter ignition delay and a concomitant decrease in pre-mix combustion. Significant disadvantages are also present with respect to full load behavior, because the higher CR at a constant permissible peak pressure needs to be balanced by a later start of injection or a reduced boost pressure.

Comparing current production engines, it was not possible to demonstrate a better start-up behavior of high-CR systems at very low ambient temperatures. At low ambient temperatures, fuel ignition is largely due to the glow plug, and not to the compression-induced heat, which is CR-dependent.

A reduced CR of below 15 is not only problematic with regard to stable engine operation at low ambient temperatures, but also adversely affects the engine's part load behavior, especially under low and medium load conditions.

Basically, CR variability on a diesel engine can be used to increase or decrease the compression ratio according to demand. Defining the maximum CR (CR-high), however, its impact on the maximum possible combustion chamber recess volume has to be taken into account. Increasing the maximum CR beyond 16.5, a slight benefit at low loads may be achieved, but the free spray lengths as well as the k-factor are very low, due to the small chamber recess – an effect which is especially marked if a lower CR is adjusted. Overall, such a design is not favorable, as small benefits in a small area of the engine map are more than counterbalanced by the negative effects elsewhere in the map.

A far greater potential can be demonstrated for a concept which features a conventional recess and combustion chamber geometry and which makes use of the variability to reduce the compression ratio. Taking only the combustion process into account, such a design facilitates an improved part load behavior, as full load characteristics have not to be considered for the determination of the compression ratio. Figure 4 illustrates an example of the design of a two-stage system for a downsizing concept.

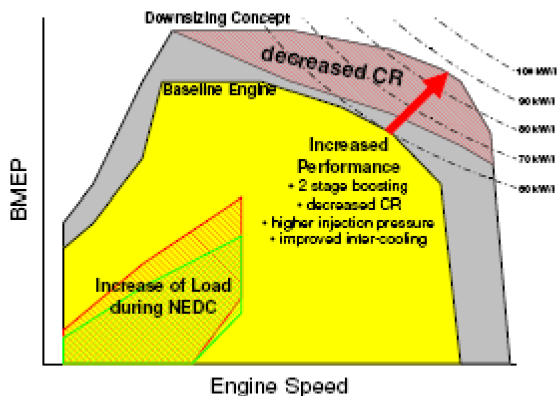

Figure 5: Downsizing Concept with VCR

As the high compression ratio is optimized with regard to part load and warm-up behavior, a value close to the upper limit of the commonly applied range can be selected. Due to the variability there are no negative effects on the combustion process, as the combustion chamber geometry does not differ from that of a conventional (i.e. non-VCR) system.

The low compression ratio (CR-low) is utilized in the full load range, especially at high engine speeds. Even though it results in an enlarged squish, for modern combustion strategies with their optimized air utilization it is usually the maximum permissible exhaust gas temperature that is the limiting factor for full load operation, especially if high-pressure injection systems (1800 bar) are utilized. In this case, a possible slight increase in soot emission due to an enlarged squish is unproblematic: as high exhaust gas temperatures can be expected, any soot particles should be oxidized in the obligatory particulate filter.

With a constant center of combustion, a reduced CR results in a lower peak firing pressure. Thus, the engine can be designed for a lower peak firing pressure, which facilitates a reduction in friction losses and weight and allows more freedom in the design of the ports. As an alternative, an advanced center of combustion can be applied, resulting in higher combustion efficiency. This increase in efficiency has an immediate effect on the specific power output; in addition, at a constant exhaust gas temperature, the injection quantity can be increased.

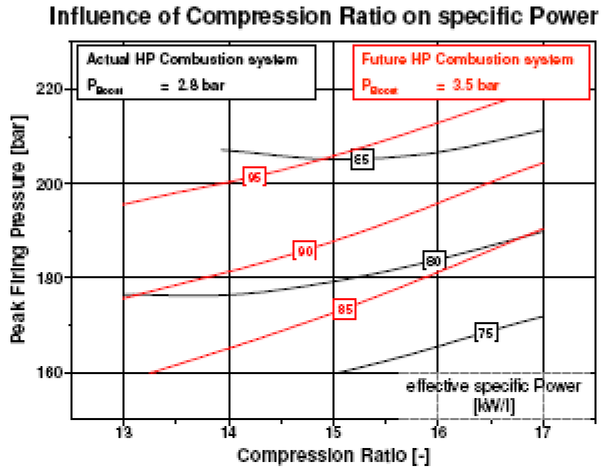

Figure 5: Influence of CR on Peak Firing Pressure and Specific Power Output

Figure 5 shows the results of calculations on the combustion process of an engine with two charging concepts and variable CR. For the calculations, the following boundary conditions were taken into account:

- The boost pressure has been adjusted to achieve constant values
- Via the injection quantity, the exhaust gas temperature was set to a constant 800°C
- A constant progression of the combustion was assumed
- The peak firing pressure was controlled via the center of combustion

As can be seen in the above figure, a variable CR yields only minor benefits for a supercharged concept delivering 2.8 bar at the point of nominal power output. A CR decrease from 16 to 14 at a specific power output of 80 kW/L results in a peak pressure drop of approximately 10 bar. For the 3.5 bar boost pressure curves, however, a much greater benefit can be demonstrated, which can be improved even further by higher boost pressures.

Thus, a variable compression ratio is an adequate measure to limit the required peak firing pressures without negatively affecting the engine's part load behavior. In view of modern commonly used boost pressures (< 3 bar), the benefits of VCR are probably not great enough to justify the expenditures of implementation. With higher boost pressures, however, greater benefits can be achieved.

POTENTIAL FOR HEAVY-DUTY DIESEL ENGINES

The compliance of today's emission legislations for heavy-duty diesel engines in commercial vehicles demand a reduction of NO_x emissions in the entire engine operating area, also including high load points. A very effective way to reduce the raw NO_x emissions at high loads is to operate the engine with high EGR rates. At the same time the Air Fuel Ratio (AFR) must be kept constant which is needed to hold the particle emissions under the allowed level. Under the boundary condition that the torque output of the engine should be kept unchanged or even increased, a higher boost pressure must be provided. As a result the PFP requirement of the engine will rise, which requires a reinforcement of the engine structure or even a complete new engine design. The VCR technology can be seen here as an alternative solution by decreasing the CR at high loads, so that the PFP does not exceed the allowed level of an existing engine structure.

OVERVIEW AND ASSESSMENT OF VCR SYSTEMS

In order to realize a variable compression ratio the combustion chamber volume has to be varied. Figure 6 shows various design options for VCR systems and offers a classification of approaches. The compression volume variation can be realized by implementing a switchable additional volume within the cylinder head or, alternatively, by varying the TDC position of the pistons. The TDC piston position can be modulated, for example, by utilizing an unconventional cranktrain in combination with a two-piece connecting rod, which is controlled by an additional shaft, or by using a rack-and-pinion gear for the transmission of power from the piston to the crankshaft, [8]. Alternatively, retaining a conventional crankshaft drive, the TDC piston position can be varied by modifying the distance between the crankshaft and the cylinder head or by varying the cinematically effective lengths of the crankshaft drive. The distance between the crankshaft and the cylinder head can be modulated by tilting the cylinder head together with the cylinder barrel relative to the bearing pedestals, as in the VCR system developed by Saab [9], or by means of a translatory mechanism acting on the cylinder head and barrel unit. Utilizing an eccentrically supported crankshaft, the required distance modifications can be realized as well [2], [12]. The variation of cinematically effective lengths opens up the widest range of constructive possibilities: compression height, connecting rod length, and crank radius can be modified by means of eccentric bearings or by using a linear guidance device.

Apart from having the desired VCR capabilities, each of these systems comes with its respective benefits and disadvantages. As the VCR systems can be realized by the most various mechanical devices, it is safe to conclude that their adequacy with regard to requirements such as suitability for engine operation, mass production, etc. varies considerably. Figure 7 shows an evaluation matrix for the various VCR systems. At low-CR engine operation, an increased combustion chamber volume within the cylinder head results in an unfavorable combustion chamber shape, which is due to the large surface-to-volume ratio. Moreover, the additional switchable volume cannot be implemented in today's 4V cylinder heads.

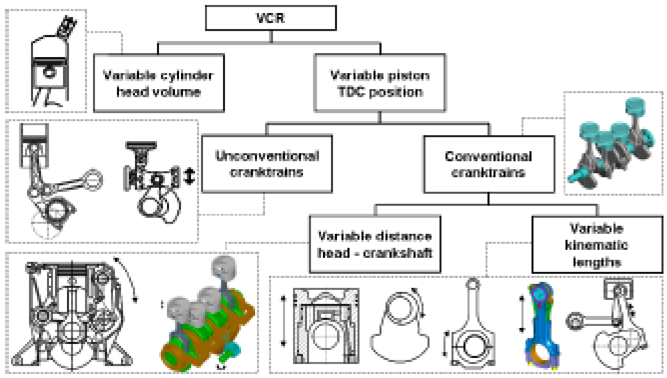

Figure 6: Classification of VCR Systems

System / Criterion				4	5	6	7	8	9	10
Suitability for cont. VCR	Continuous VCR						2-stage VCR			
Determin. of actual CR	+	+	+	+	+	+	-	-	-	-
Combustion chamber shape	–	++	++	++	++	++	++	++	++	++
Impact on package	o	–	–	–	-	-	o	o	o	o
Modification of production	o	–	–	–	-	-	o	o	o	o
Oscillating mass	++	–	–	++	++	–	–	+	+	--
Friction	++	-	-	++	-	-	o	+	–	o
Costs	o	-	–	–	-	-	o	-	-	-

++ very low negative impact + low negative impact o moderate negative impact
-- very high negative impact - high negative impact

Figure 7: Comparison of VCR Systems

Systems which are based on unconventional cranktrains make possible a continuous adjustment and with it a precise CR control, but due to installation space requirements, especially in the engine transverse direction, significant changes to the base engine architecture are required, which have a major impact on the manufacturing process. Higher friction losses through additional bearings and an increased reciprocating mass, however, are compensated to some extent by a lower lateral piston force.

Systems which vary the distance between the crankshaft and the cylinder head are also well suited to implement a continuously variable CR; in addition, they offer the advantage that an existing cranktrain can be retained "as is" and fully carried over.

With tilting or translatory moving of the cylinder head and barrel compound, the base engine design has to be extensively modified. The installation expenditure for the actuation mechanism, the sealing of the crankcase as well as the coupling for the moved intake and exhaust systems is considerable and adversely affects production costs and vehicle packaging.

An eccentric bearing crankshaft, by contrast, requires far less modification to the engine design, which is hardly affected at all; the offset between the crankshaft and the gearbox input shaft, however, has to be bridged by a compensation gear, a device which introduces additional frictional losses and also increases the overall engine length.

Most systems which modulate the cinematically effective lengths are not suitable for the realization of a continuously variable CR. These systems, however, have the advantage that they require only minor modifications to the base engine design and that the impact on the production process is comparatively low. As an exception, the system which features a permanently controlled, eccentrically positioned piston pin can be named [11], as it enables a continuous CR variation but again, as a drawback, has a major impact on the engine design as well as on the production process. Comparing the other systems shown here – preferably realized as two-step designs – the system with variable connecting rod length by an eccentrically mounted piston pin can be considered superior with regard to integration and production costs. As a disadvantage, however, this approach results in an increase in reciprocating mass. The variable-length connecting rod with an eccentric bearing in the connecting rod big end can as well be easily integrated into existing engine designs, with only a minor increase in reciprocating mass. Due to the usual one-piece crankshafts, however, the system requires a two-piece eccentric, which increases the constructional expenditure and thus the manufacturing costs. The realization of a variable crank radius using an eccentric on the crankpin results in a significant increase of the connecting rod diameter and an attendant increase in cranktrain friction. Utilizing a piston with variable compression height, sealing and the actuating mechanism have to be integrated in the mechanically and thermally highly loaded piston, a solution which poses a major technological challenge.

For a concluding assessment of the various VCR mechanisms, a weighting of the various evaluation criteria would be necessary. The weighting of the criteria, however, would depend on the respective demands of the manufacturers; therefore, a universally valid weighting system cannot be devised.

In FEV's view, systems are to be preferred which can be easily integrated into conventional engine architecture and which do not significantly increase production costs. Thus a VCR variant of a conventional engine can be produced without requiring special manufacturing facilities. As a prerequisite for such a variant, however, the VCR-specific components should be packaged in modules which substitute for conventional components in the assembly process [4]. In order to be competitive with other fuel saving technologies, the benefits of the VCR system for the customer should outweigh the additional production costs. Thus, taking into account the tension between technological possibilities and economic demands, FEV has been focusing its development activities on two VCR systems:

For the realization of a continuously variable compression, FEV is investigating a system fitted with an eccentrically supported crankshaft, the so-called "crankshaft shift" system [1], [2], [4], [12].

As a two-stage solution, FEV is working on a system fitted with a variable-length connecting rod, realized by an eccentric piston pin suspension, which utilizes cranktrain forces to adjust the compression ratio. This system is called the "variable-length conrod" system or “VCRconrod”.

FEV has developed this two-stage VCR-system for a passenger car gasoline engine application as well as for a heavy-duty diesel engine application, which is described in more detail in the following sections of the present paper.

TWO-STAGE VCR-SYSTEM "VARIABLE-LENGTH CONROD"

WORKING PRINCIPLE / DESIGN

The connecting rod length variation is realized by means of a rotation of an eccentric bearing in the connecting rod small end. The moment acting on the eccentric, resulting from superimposed gas and inertia forces, is used to adjust the connecting rod length. This is the key feature to meet a cost effective VCR solution, because no expensive and power consuming actuators are needed and all functional elements are concentrated into only one component, the connecting rod. As shown in figure 8, the eccentric moment takes on positive as well as negative values during a combustion cycle, making possible an adjustment in both directions.

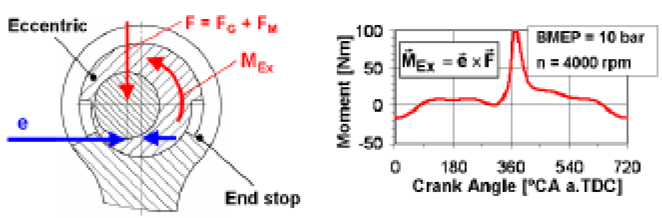

Figure 8: Formation of the Eccentric Moment

SUPPORT MECHANISM

Figure 9 shows cross sections for a VCR connecting rod design for use in a passenger car SI engine. The moment acting on the eccentric is supported via linkages by hydraulic pistons.

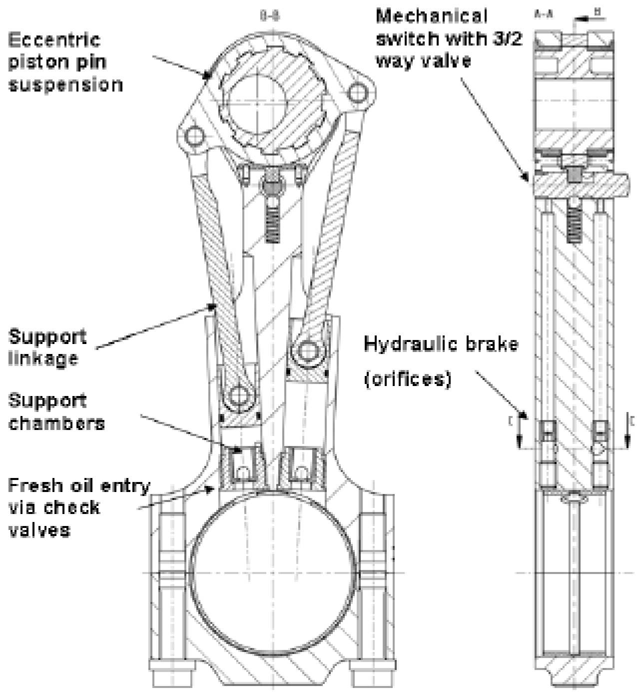

Figure 9: Layout of the VCR Connecting Rod

The two support chambers are connected to the oil circuit via one check valve each, and by means of a 3/2 check valve, a passage from the chamber to the crankcase can be opened. Thus it is possible for one hydraulic piston to enter more deeply into its support chamber, displacing oil from it in the process, while the other support chamber is being filled with oil. Consequently, the eccentric is able to rotate in one direction only. The adjustment process takes several working cycles to conclude; the number of cycles required for the adjustment depends on the operating point as well as the hydraulic resistance. The hydraulic resistance, which can be controlled by means of orifices, is to be adjusted in such a way that the adjustment process is finished as quick as possible, so as to avoid engine knocking during step load changes from part load to full load and, in addition, to be able to make immediate use of the improved efficiency of the higher compression at load changes to part load. The adjustment time must not be too short, however, so as to avoid the following undesired side effects:

- Cavitation at the check valve of the enlarging support chamber
- Inordinately high impact loads on the support mechanism when the end stops are reached

Calculations have demonstrated that it is possible to achieve switch-over times of less than one second.

INITIATION OF CR TRANSITION

The reversal of the eccentric's direction of rotation can be triggered by actuating the 3/2 way valve, which is designed as a mechanical switch. The reversal is executed by actuating two cam discs in such a way that the valve is axially moved in either the "CR-low" or in the "CR-high" direction (figure 10). The actuation process itself is concluded within one engine revolution. As the valve body is arrested in the respective end position by means of a combination of spring-and-ball catches, any further impacts through subsequent engine revolutions are prevented.

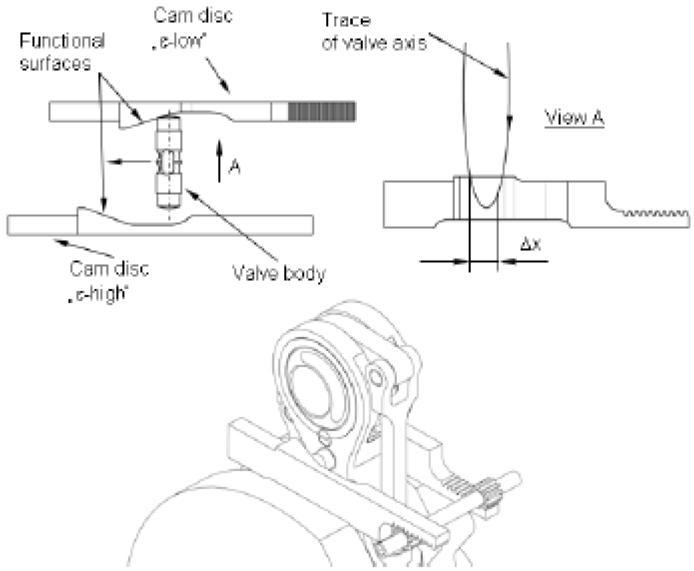

Figure 10: Actuation with Cam Discs

In the shown embodiment the mechanical switch is located just underneath the connecting rod's small eye. The cam discs are located between the envelope of the counterweights of the crankshaft and the piston pin boss. This arrangement has the advantage that the velocity of the valve body is relatively small when getting in contact with the cam discs. On the other hand it requires that the sufficient clearance is available between the counterweight envelope and piston pin boss in BDC position.

In general there are plenty of other solutions to actuate the mechanical switch from outside the moving connecting rod. From the big variety of solutions the cam disc actuation is considered as the most robust one.

FUNCTIONAL TESTING OF A VCR-CONROD FOR GASOLINE ENGINES UNDER MOTORED OPERATING CONDITIONS

In a first step the functionality of the variable-length connecting rod was investigated in dynamometer tests under motored conditions. During this test phase, switch-over operations were performed at various engine speeds. It is expected that the transition times are shorter under fired operating conditions, as a higher gas pressure benefits the adjustment process toward the lower compression ratio.

After the basic functionality of the mechanism was confirmed over the entire engine speed range and for different manifold air pressures, the reproducibility of the measured transition times as well as the system's durability had to be investigated. For this purpose, approximately 70,000 switch events were performed at varying engine speeds, recording the transition times at fixed intervals. Only slight transition time variations were detected in the tests that were conducted.

Subsequently, the components were disassembled for inspection. The parts did not show any significant signs of wear.

REFINED DESIGN OF A VCR-CONROD FOR GASOLINE ENGINES

With the design of the 1st prototype, the demonstration of the functioning was focused in an initial approach. Structural optimizations toward a maximum lightweight design have not been completed so far.

After the general functioning of the VCR-conrod was demonstrated under motored operating conditions, the design was further refined. Major development targets are:

- Reduction of the oscillating mass
- Reinforcement of the structure to withstand the PFP demand of future gasoline combustion processes

These conflicting targets were fulfilled by using advanced CAE methods and by substituting steel by aluminum for the eccentric. Figure 11 shows the latest design.

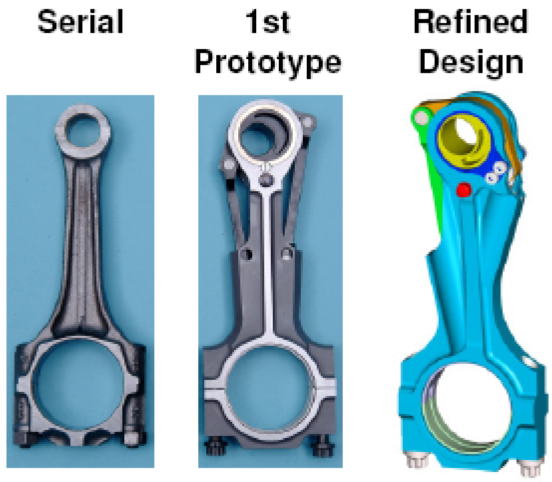

Figure 11: Refined Design for a VCR-conrod for Gasoline Engines

The connecting rod structure and the support mechanism protect for a PFP of 140 bar. An important design feature is the asymmetric design of the support chambers in order to meet the different maximum amount of eccentric moment to support caused by gas and mass forces. The targeted transition time from high to low CR is less than 1 sec.

The 1st prototype VCR-conrod led to an increase of the total oscillating masses of approximately 45%. The total amount of the total oscillating masses is considered as the oscillating fraction of the connecting rod mass and the mass of the piston, pin and ring assembly. With the refined design the increase of the total oscillating masses is reduced to approximately 30%.

In order to quantify the impact of the increased oscillating mass on the engine's friction behavior, friction measurements were conducted on a cranktrain whose oscillating mass was increased by 50%: at the 2000 rpm / 2 bar operating point, the overall engine friction is increased by less than 3%, resulting in a fuel consumption increase of under 1%. Thus, the additional oscillating mass only slightly impairs the efficiency benefits of the variable compression.

DESIGN OF A VCR-CONROD FOR A HEAVY-DUTY DIESEL ENGINE

In a further project a VCR-conrod was designed for a heavy-duty diesel engine application. The structure protects for a PFP of 180 bar and allows the compression ratio stages 14 and 17. A very challenging task was to package the support mechanism within the given space in the piston. The realized design of this system is shown in figure 12.

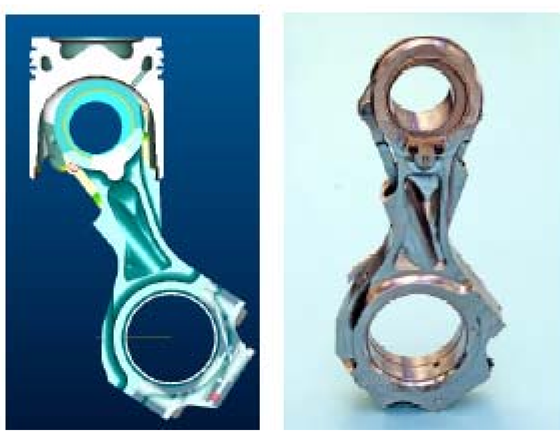

Figure 12: Realized Design of a VCR Connecting Rod for a Truck Application and Prototype

The piston and piston pin of the production engine were retained almost unmodified. In the given case the eccentric moment caused by gas forces is approximately 10 times higher than the moment caused by the mass forces during the gas exchange phase in TDC. Therefore the “gas force” support chamber is made bigger in diameter. The basic principle of the actuation mechanism was retained; the 3/2-way valve, however, was integrated into the connecting rod bearing cap and the actuating cam discs were positioned below the crankshaft, due to package constraints. The increase in the cylinder unit's oscillating mass amounted to 19%.

FUNCTIONAL TESTING OF A VCR-CONROD FOR HEAVY-DUTY DIESEL ENGINES UNDER FIRED OPERATING CONDITIONS

Test runs under fired conditions were conducted on a 6-cylinder in-line engine for use in a diesel utility vehicle, examining the engine's CR transition behavior over the entire engine speed and load range. The measured transition times from CR-14 to CR-17 and vice versa were in the range of 1 to 2 seconds.

A peak pressure curve over a number of working cycles for a selected high-load operating point was created. As in the motored test runs, the transition between the two CR stages under fired operating conditions turned out to be monotonic and steady.

In order to arrive at a deeper understanding of the mechanism's systemic behavior, the rotating angle of the eccentric was measured as a function of crank angle. The measurements were conducted by means of travel sensors attached to the connecting rod. A curve was created to represent the length variation of the connecting rod, which can be calculated from the measured rotating angle of the eccentric, for a cycle in the above mentioned operating point within a high-to-low CR transition phase. The curve illustrates the marked variation in connecting rod length close to the ignition TDC; elsewhere in the crank angle range, the connecting rod length remains constant. The other recorded transition processes show comparable length adjustment characteristics.

CONCLUSION

The Variable Compression Ratio (VCR) engine is definitely a key to improving engine efficiency will be the subject of increased in focus. The current trend for SI engines is toward higher degrees of downsizing of systems which have the capacity for adapting the compression ratio to load conditions throughout the entire engine map. Further optimization of the VCR system is possible in combination with future combustion process advancement, such as CAI or in tandem with alternative fuels.

In diesel engine application, the VCR system can provide a suitable means of reducing the peak pressures required by the highly charged diesel engine (with boost pressures above 3 bar), without adversely affecting part load behavior.

A two-stage VCR-system was developed as a result of this study, which functions by adjusting an eccentric in the small end of the connecting rod. The system was implemented in test engines and the function could be further proven with a significant amount of testing. The results of this study illustrate that promising steps are being made towards a VCR production engine, which are especially relevant in view of the increasing concerns presented for a reduction of carbon dioxide emissions.

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