Advancement of a Two-stage Variable Compression Ratio Engine

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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.

Index Terms— Variable Compression Ratio, Wide Open Throttle, New European Driving Cycle.

I. INTRODUCTION

The search for a feasible VCR engine has been driven by the compromise between WOT (Wide Open Throttle) and part-throttle which exists on any fixed CR engine. Detonation thresholds at WOT limit the maximum useable CR to a value lower than could be sustained at part throttle. Comparison of BMEP figures shows that increasing CR becomes counterproductive at values typically above 11~12:1 since the reduction in spark advance negates the benefit from higher CR Potential benefits in fuel consumption and CO_2 emissions are, however, to be expected from running at higher CR during part throttle operation. The detonation limits identified at WOT do not apply to part throttle operation as the in-cylinder temperatures and pressures are so much lower. As the majority of engine running time occurs in this mode, real world improvements should be enabled, not just theoretical or experimental gains.

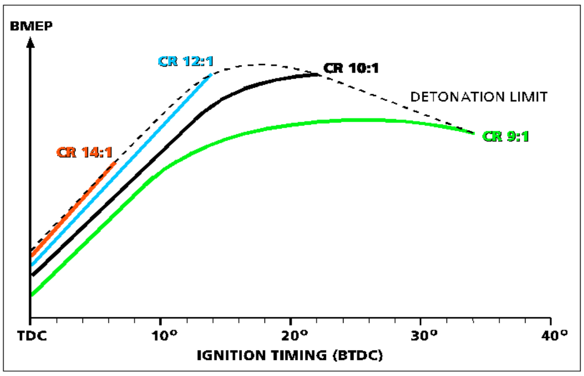

Fig.1 Comparison of W.O.T. BMEP versus compression ratio and ignition timing

One method of solving the high peak pressure problem on counted when the specific output is increase to reduce the compression ratio at full load but at the same time keeping the compression ratio sufficient high for good starting and part load operation thus, it is clear that a fixed compression ratio engine cannot meet these requirement of high specific output. Hence, the development of a variable compression ratio engine.

II. MOTIVATION AND POTENTIALS

A. Potential for SI combustion processes

Variable compression engine benefits have been widely acknowledged and documented. 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.

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. 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.

B. 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. 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. Comparing current production engines, it was not possible to demonstrate a better start-up behavior of high-CR systems at very low ambient temperatures. 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.

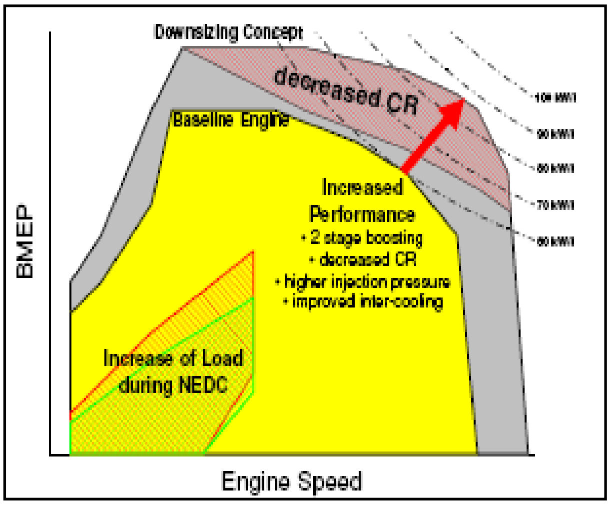

Fig.2 Downsizing Concept with VCR

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. The low compression ratio is utilized in the full load range, especially at high engine speeds. 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. 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.

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. A variable compression ratio is an adequate measure to limit the required peak firing pressures without negatively affecting the engine's part load behavior.

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

A. 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 Fig. the eccentric moment takes on positive as well as negative values during a combustion cycle, making possible an adjustment in both directions.

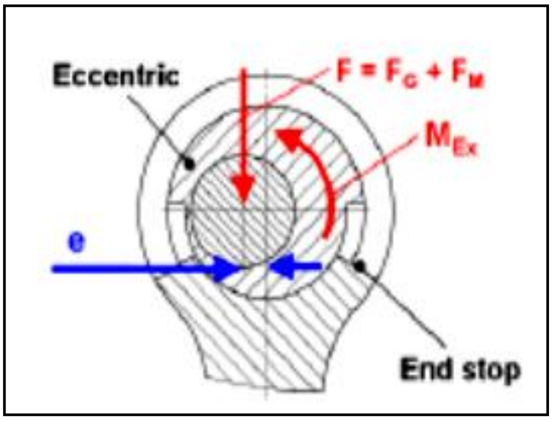

Fig.3 Formation of the Eccentric Moment

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.

B. System Properties of the Two-Stage VCR System

The presented connecting rod belongs to the group of VCR systems with variable kinematic lengths and has been developed over the past few years, shows a cross section of the actual connecting rod. The small end is equipped with an eccentric sleeve which houses the wrist pin. By rotating the eccentric sleeve the effective connecting rod length and thus compression ratio can be varied. To adapt the system to existing engine architecture requires only relatively small changes to existing parts as compared to the requirements of other VCR systems at acceptable additional manufacturing costs. The reduction of moving masses is part of current development activities. For engines with a cylinder displacement of approximately 0.4 l the oscillating mass increases by 30 to 50 % depending on stroke-to-bore ratio. Simulation results have shown that optimizing the design and utilizing high-strength steel significantly reduces the mass of the conrod.

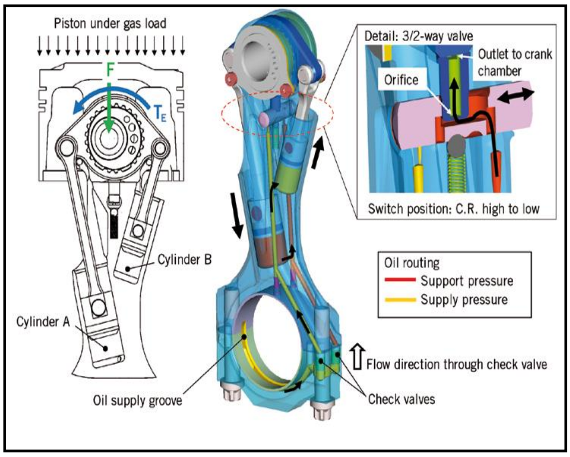

Fig. 4 Functionality of the two-stage VCR system

C. 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 and 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 shows the latest design.

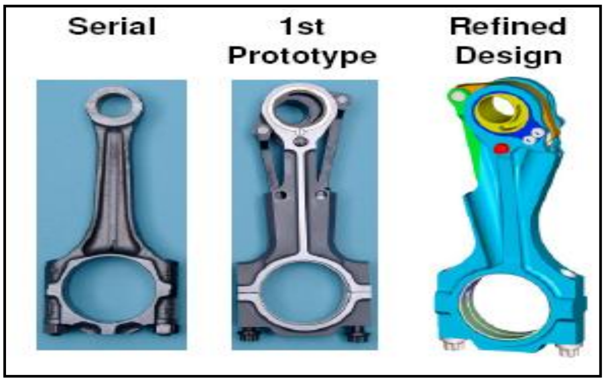

Fig. 5 Refined Design for a VCR-conrod for Gasoline Engines

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 crank train 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.

IV. COMBINATION WITH FUTURE TECHNOLOGIES

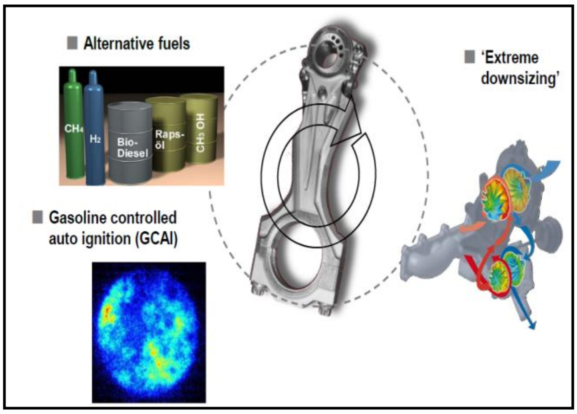

Fig. 6 Combinations With Future Technologies

A. Extreme Downsizing

The example of downsizing (1.5L) results in 120 kW/l specific power to offer identical drive power. While the fuel consumption benefit of the extreme downsizing without VCR over the NEDC still reaches about 3 to 4 %, it has to be stated that with the two-step VCR fuel efficiency can be increased between 6 and 7 % for both investigated driving profiles. In comparison to the base variant with 2.0 l displacement the further potential of a two-step VCR will be higher for the extremely downsized engine with operation at higher engine load.

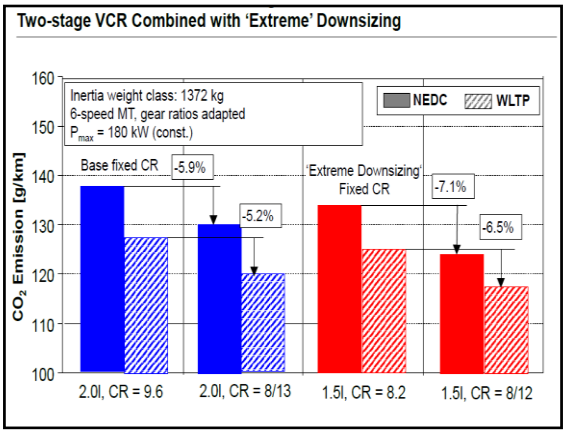

Fig. 7 Extreme Downsizing

B. Alternative Fuels With High Knock Resistance

Achieving a drastic reduction in CO_2 emissions make alternative fuels a suitable option. Besides CNG, Ethanol represents a meaningful alternative to conventional gasoline fuel combining the CO_2 reduction potential gained from a partially closed carbon cycle with high knock resistance. This provides the opportunity to select a higher compression ratio and significantly enhance the efficiency over the entire engine map particularly for boosted applications. As a result, the fuel consumption improvement potential is not being fully taken advantage of while using these knock resistant fuels.

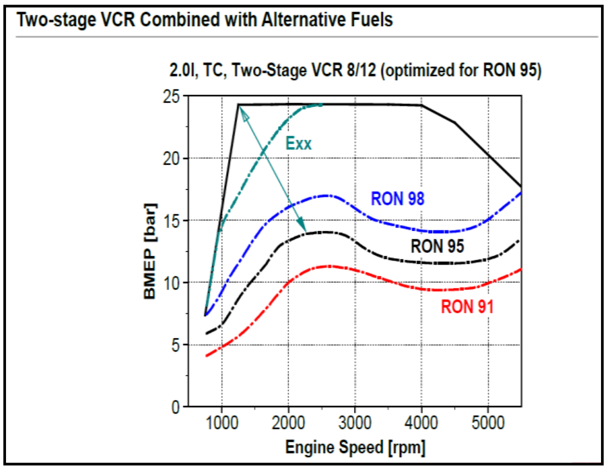

Fig.8 Possible variation of the two-stage VCR system transition depending on fuel quality

V. CONCLUSION

The Variable Compression Ratio 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.

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. The presented two-stage VCR system can be integrated into existing engine families with competitive additional costs. VCR can help to resolve the conflict between part load and full load CR layout especially for boosted downsized gasoline engines

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