Valve Control Management - the possibility of improving gas engine performance

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Abstract: ABB Turbocharging presented the electro-hydraulic variable valve timing system VCM® during the 2010 CIMAC congress in Bergen. The VCM® has a considerable degree of flexibility, allowing it to be used on diesel and gas engines of different sizes and for different purposes. The system also has the inherent possibility to be customised in such a way that easy integration without major changes to an existing engine design is feasible. After extensive mechanical testing of the full system, including a validation and qualification programme on a small medium speed diesel engine, the possibility of the VCM® improving the performance of a gas engine has been investigated. On performance we found an improvement in fuel consumption and other engine parameters. The control unit in a conventional high speed pre-mix gas engine consists of a throttle valve and a compressor by pass. Both consume a substantial amount of energy as they provide a pressure reserve for acceleration and control purposes. One concept by which the performance of such an engine could improve is to substitute these control devices with variable inlet valve timing and lift, i.e. the application of VCM®. This paper shows the design of the VCM® unit for a high speed gas engine where the mechanical boundary conditions are discussed, how these could be fulfilled and how they are influencing the performance of the engine with regard to how the engine reacts to certain variations in the system. With regard to thermodynamic performance, the paper considers possible improvements brought by de-throttling and how the engine operates in normal conditions as well as during load changes. The application of skip-firing/cylinder cut-off is also discussed. Furthermore, the paper looks at the required set-up of the inlet valve under changing ambient conditions as well as changing gas qualities and applications with variable engine speed.
INTRODUCTION

The race to improve the engine efficiency and power density has intensified since the application of large spark ignited gas engines takes an ever increasing share in the market of electrical power-generation. Beside this classical application field of gas engines, the interest to use gas-engines for marine applications and higher output compressor drives is permanently increasing. Furthermore the compliance with the continually more stringent emission regulations is viewed as state-of-the art.

Based on present knowledge, both the demand for increased specific output as well as the request for enlarged application possibilities have the uncomfortable drawback of wasting a large part of the turbocharging efficiency if the traditional control strategies like throttle valve with compressor bypass or exhaust waste-gate are applied to stay within emission limits at part load. Therefore it could be concluded that these control and management systems for real high efficiency gas engines have to be replaced sooner or later by more advanced and intelligent solutions.

One such solution is the application of variable inlet valve timing and lift. This allows the replacement of the traditional control elements and at the same time an improvement of the gas exchange work by deletion of the throttle valve resulting in an increase in engine efficiency.

ABB’s VCM® (Valve Control Management) presented to the public during the last CIMAC-congress in Bergen (1) is one practical execution of such a variable valve train configuration. The VCM®-configuration presented was still at the design level of a technology demonstrator with all the imaginable features and control possibilities the VCM® may offer. The VCM®-design discussed in this paper is ready to be industrialized and takes into consideration the specific requirements of a pre-mix/port injection spark ignited gas engine. How the VCM® valve train system functions is principally explained prior to dealing with the specific design of the VCM® for gas-engines itself.

The VCM®-system is based on the design principles of the UniAir-system, produced by Schaeffler Technologies (2, 3). It is an electro-hydraulic-mechanical system, which also allows valve selective control mode when every valve is equipped with its own actuator.

The closing and opening of the solenoid valve allows different operation modes depending on the engine operating and control requirements. (Figure 2)
The valve will follow the mechanical cam profile in full if the solenoid valve is closed. In this case the valve stays open over the longest period. Opening the solenoid valve at different points in time allows selective closing of the valve. It is possible, for example, to apply this operating mode for inlet valve closure timings to realize different Miller-timings or for the exhaust valve control to accomplish varying scavenging periods where applicable. It is also possible to achieve a so-called multi-lift mode, which might be a valuable option for pre-mix gas-engines, by opening and closing the solenoid valve during one cam period. This kind of valve actuation is interesting for creating a certain swirl and/or turbulence inside the cylinder in order to improve combustion or to control the engine behavior at idling or very low loads. The solenoid can obviously also be kept open all the time to avoid any opening of the engine valve. This mode could be used to apply skip-firing (4).

The potential application of this VCM®-design configuration was foreseen from the beginning for a pre-mix gas-engine. Any variability of the scavenging phase was not required, simply because valve overlap simply does not exist on this kind of engine. So the variability is limited to the inlet valve side.

The variability of the inlet valve timing and/or valve lift is in this case only used for replacing the control elements as compressor by-pass and throttle valve and not for more sophisticated features like load dependent variable swirl using valve individual timing and lift. That’s the reason why a mechanical bridge has been applied, which links both inlet valves. It was a logical consequence to install the pump and brake assembly on the push rod side and not above the inlet valves as the original design has had this lay-out already and this mechanical bridge has been activated by the rocker arm. Its position is given due to the fact that this assembly needs to be placed in line with the push rod and rocker cover to avoid lateral forces. At the same time it became obvious that the original push rod could not be used anymore and needs to be shortened. It was necessary to use the cylinder head deck height to locate the pump in an appropriate way based on the required valve lift, which defines the pump capacity. The cylinder head design was given and the only degree of freedom was to machine the cylinder head on the level of the inlet valve push rod openings. The diameter of this opening has been increased as required. An additional bracket has been installed to positively locate the pump unit and properly connect to the main housing.

The main casing acts as the housing for the control valves including a solenoid valve, for the oil piping, for the pressure accumulator and as rocker arm post. It replaces the original one and acts as interface to the cylinder head. The connection to the cylinder head is executed as in the original design, i.e. the same bolt, which fixed the rocker post screws in the original design, now fixes the whole VCM®-unit to the cylinder head. The oil supply to the VCM® is assured by the same supply system, which delivers the oil for the rocker arm bushes. Contrary to the design applied in automotive engines, the control unit consists of a pre-stage with the solenoid valve and a main-stage. This configuration has been chosen to minimize the space requirements and to assure the required time to release the pressure from the high pressure chamber. Figure 3 shows the final design.

EXAMPLE OF A VCM®-DESIGN

In an ideal case the designer starts with a white sheet of paper and integrates the VCM®-device into the whole engine configuration but such a situation does not occur too often in the real world of engine design. Normally the first applications of new technologies are used on existing engine designs, in this case the VCM® variable valve train. So there are constraints regarding the available space, the feasible modifications to the cylinder head and also the design criteria of the engine builder that need to be fulfilled.
The design features of a VCM® integration into the cylinder head resolve into:

- Cylinder head remains virtually untouched except for a limited machining operation
- Original fixation and assembly procedure is retained
- Existing parts including mechanical bridge, rocker arm, rocker shaft are re-used

The only modified components beside the new VCM®-unit are the shortened push rod, cam profile and the rocker cover with its gaskets.

The VCM®-unit can be designed in such a way, that the required modifications as well as newly required parts are kept to a minimum even if the available space is limited. With the chosen design it is even possible to apply the same VCM®-unit for a possible diesel version of this engine.

**CAMSHAFT LAY-OUT AND DESIGN**

The camshaft lay-out differs in comparison with a mechanical valve train due to the requirements and possibilities of the hydraulic system. First it needs to be said that the application of the VCM® allows a camshaft design with a much higher cam lift potential as is feasible with a conventional configuration. The main reason for this increased lift is the fact that the shape of the closing lobe has not to be taken into consideration. The VCM® hydraulic elements permit the separation of the mechanical link between the camshaft and the engine valves. The valve closing movement with the solenoid opened is only dependent on the gas- and spring-forces, the masses of the valve train and the damping action of the brake element. A small spring is integrated into the pump unit, which puts all moving parts between the camshaft and the pump unit under a certain pre-load and avoids any kind of contact loss between the camshaft, swing arm, push rod and pump unit. The risk that the components lose contact, which could lead to disastrous consequences, is circumvented.

It is important to specify the load control philosophy at idling and low load operation besides the normal opening and closing timings that occur during normal engine operation to assure the required load control of the engine. The issue here is that the trapped air-gas amount in the cylinder is so small that even a small deviation would lead to a relatively large change in engine output respectively engine speed. VCM® offers different modes to manage the mixture mass flow since the mixture mass flow into the cylinder is only controlled by the timing/lift of the inlet valve. With the presented configuration we have in principal 3 modes (Figure 4):

- Fixed valve opening, very early valve closing (bBDC; Miller)
- Late valve opening (bBDC), early valve closing (bBDC)
- Fixed valve opening (bBDC), very late valve closing (aBDC; Atkinson)
Analyzing the low pressure cycle of the engine shows how different the amount of the mixture mass flows in and out of the cylinder is, even if the final trapped mass in the cylinder is the same at the end of the compression stroke (Figure 5). It seems to be logical to select the configuration with the highest mass movement for the engine control, bearing in mind that the absolute mass in the cylinder is very small to assure satisfactory operation of the engine at these load points and because the impact of tolerances, clearances and other influencing parameters might be considerably lower. A further argument that speaks for the application of a cam-shape with the possibility to apply Atkinson timings is the fact that the concerned cylinder could not run into overload operation but falls back into the idling mode in the unlikely case of a failure of the solenoid or an interruption of the electrical supply to this part.

Figure 5 – Low pressure cycle

Another key issue is the system robustness with respect to consistent valve closing time. Therefore the closing timing with activated VCM® was measured over 200 cycles to address the issue. The maximum deviation recorded was 0.3 °CA, which is considered sufficient for controlling a gas-engine.

This VCM®-design underwent in total more than 2000 h on the mechanical test-rig and the fired 1-cylinder engine.

TESTING OF THE VCM®-UNIT

Several mechanical tests were performed on a special test-rig prior to the VCM®-unit being installed on a fired engine. The VCM®-unit was fixed to this test-rig in the same way as on a real engine. The relevant dimensions and masses as in a real engine were set up to simulate the real operational conditions as closely as possible. Consequently the same cooling fluid temperatures, pressure and temperature levels of the lubrication oil as in a real engine were used. An endurance test over 1,000 h was run to demonstrate a high level of reliability. The distribution of the different load set-ups is schematically shown in Figure 6. It is worth mentioning that half of the test was performed with new lubrication oil and the other half with used oil from an engine after a recommended exchange interval. The oil properties caused no detectable difference on the VCM® behavior due to oil aging. The operating parameters of the VCM® didn’t change during the endurance test as well.

Figure 6 – Test cycle

The main target of this investigation is to give an answer to the question: "Could the VCM®-unit replace the conventional control elements of a gas-engine?".

It was decided to keep the mean effective pressure at today’s level and head for the same temperature of the trapped mixture at the bottom dead center to make a fair comparison between a conventional control strategy using compressor by-pass with throttle valve and the application of variable inlet valve closure. This way the influence of the engine’s high pressure cycle could be eliminated. The boundary conditions before and after the cylinder head of the 1-cyl.-engine were chosen in

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such a way that a turbocharged complete engine could fulfill the emission requirements with NOx at 100% and 50% load on a constant speed operation line. The advance of the inlet valve closure timing was less than 10° CA for the 50% load point.

The engine efficiency gain at full load was 0.5% points with the applied VCM®-set-up. This efficiency gain is due to the application of the advanced Miller-timing as well as taking full profit from the supercharging efficiency by replacing the compressor by-pass and throttle valve. The conclusion is that a gas-engine output can be controlled with sufficient precision and improve the engine efficiency at the same time.

Figure 7 shows the mixture temperature at the start of combustion. The experienced temperature reduction could be used for increasing the output and efficiency as discussed in the next chapter or as a reserve for compensating changing ambient conditions due to the increased knock-margin, gas qualities or performance deterioration due to fouling.

Figure 7 – Temperature at start of combustion

OUTPUT INCREASE AND ENGINE EFFICIENCY IMPROVEMENT

It is viable to increase the mean effective pressure, i.e. output, and search for further engine efficiency improvements in order to benefit as much as possible from the possibilities of very advanced Miller-timing with the consequential low temperature at BDC and of the thereby required pressure ratios. These are only feasible with 2-stage turbocharging and its high turbocharging efficiencies.

Increasing the engine output by 15% and improving the efficiency of the turbocharging unit by around 7%-points shows an improvement of engine efficiency by roughly 0.6%-points already with the conventional control system. Applying VCM® using an engine set-up with increased compression ratio, advanced Miller-timing, increased boost pressure and advanced ignition timing resulted in a further engine efficiency improvement by at least 1.4%-points as shown in Figure 8. The advanced Miller-timing and the resulting low temperature level of the mixture at BDC assured a knocking-free operation of the engine including supplementary margin at this higher output level. The analysis of the test results showed some additional potential regarding efficiency optimization achieved by increasing the geometrical compression ratio and corresponding inlet valve closure timing. Unfortunately it was not possible to verify this potential at the moment due to mechanical constraints.

Figure 8 – Efficiency improvements

CONCLUSIONS AND OUTLOOK

The investigated case study shows in theory and practice that:

- a compact and simple to install VCM®-design can be realized with minimal engine modifications
- the application of VCM® in place of conventional control elements improves the engine efficiency of a gas engine and allows the full benefit of the 2-stage turbocharging potential
- the application of VCM® allows additional engine efficiency improvements by optimizing the high pressure cycle with
increased compression ratio, ignition timing, Miller-timing etc.

In the near future the above mentioned optimization process will be followed. Then the application of VCM® to control a gas-engine with variable speed as in marine-applications or compressor-drives will be investigated as well as the required timing changes with variable methane numbers or changing ambient conditions.

It is also foreseen to study the possibilities to realize a cylinder selective control algorithm with VCM® to further enhance the engine efficiency.

The progress already made justifies the statement that the application of VCM® in connection with 2-stage turbocharging allows a big step forward in improving the efficiency of gas-engines and their application range. Further benefits for the OEM and enduser will be proven by the coming investigations.

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(1) Mathey, Ch.; Variable Valve Timing – A necessity for future large diesel and gas engines, paper no. 298, 26th CIMAC World Congress in Bergen, Norway, 2010
(2) Michael Haas; Martin Rauch; Elektrohydraulischer vollvariable Ventiltrieb; MTZ 03/2010
(3) Bernard, L. et alii; Elekrohydraulische Ventilsteuering mit dem „MultiAir“-Verfahren; MTZ 12/ 2009