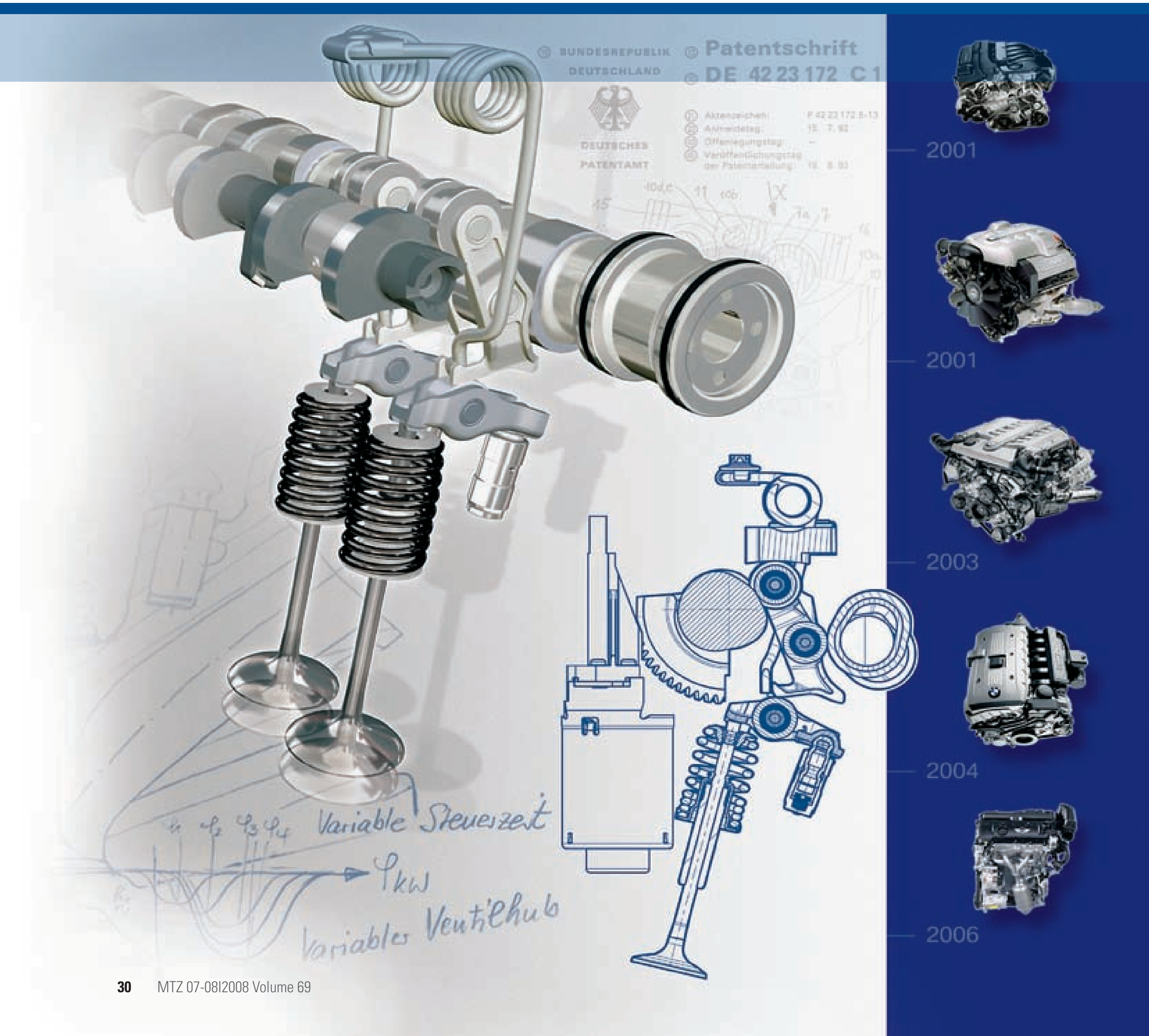
The Valvetronic

Experience from Seven Years of Mass Production and a Discussion of Future Prospects



In 2001, the new four-cylinder engine launched by BMW was the world's first SI engine for cars to have a fully variable valve train, BMW Valvetronic. Compared to its predecessor, it achieved a consumption reduction of 12 % whilst its basic technology provided the pattern for all future BMW SI engines. Since the launch of Valvetronic, its technology has undergone continuous development so that it will continue to meet all the demands placed on it in future at the same time as offering further potential. Mass-producing a system such as Valvetronic has been and remains at least as demanding a challenge as was its development. BMW is the only engine manufacturer to have attempted this feat, and has already produced and sold more than 2.5 million engines with Valvetronic.

1 Introduction

To meet demands for reduced fuel consumption, BMW started basic investigations into developing a fully variable valve train back at the start of the 1990s. The first step involved was finding out which physical principle was best suited for implementation in a series production project. Mechanical, hydraulic and electrical approaches were available for selection, as well as combinations of these. Following theoretical considerations and practical tests, the decision was made in favour of a mechanical valve train with an electrical actuator and electronic control. The fact that today, even 15 years after this decision, no other systems have emerged on the market in spite of extremely varied development activities indicates that this decision was correct. Series development of the valve train now referred to as Valvetronic began in the mid-1990s.

Implementing this technology in mass production not only required significant development efforts, it was also necessary to overcome the most demanding technical production challenges. For specific components tolerances had to be significantly redefined, which were presumed to be uncontrollable in mass production until then. In view of the large number of development projects in fully variable valve trains all over the world and comparing this with the result in terms of the number of systems that have gone into series production, it often appears that the production technology required for mass production represents the decisive obstacle to market launch.

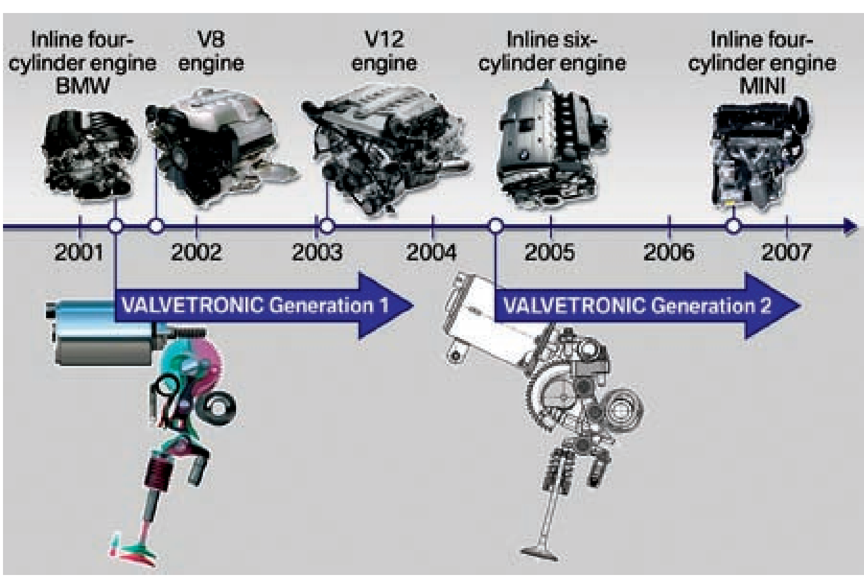
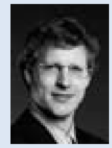


Figure 1: Use of Valvetronic technology

The Authors



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Following the initial series production start-up with the four-cylinder engine in 2001, all SI engines were equipped with Valvetronic shortly afterwards. At the present time, Valvetronic can now be found in five engine series, therefore in all BMW cars as well as in the Mini and Rolls Royce. More than 2.5 million units have been sold since the inception. In 2004, to coincide with the introduction of a new generation of six-cylinder engines, the second generation of Valvetronic was introduced featuring significant optimisations, for example optimising the combustion process meant that it was also possible for a Valvetronic engine to comply with SULEV regulations, and this engine has been available on the market since 2006, **Figure 1**.

The continuing importance of Valvetronic results from two factors. First, compared to the direct injection lean burn petrol engines Valvetronic is by far the economically better priced. Secondly, Valvetronic is worldwide applicable since it does not make great demands on the sulphur-concentration of the fuel and is able to comply with the strictest emission legislations (e.g. SULEV in USA).

Development activity is continuing without restriction in order to make Valvetronic suitable for future application. The main areas of this work are concerned with combining Valvetronic with the technologies of „homogenous direct injection“ and „supercharging“, achieving the best possible package optimisation and integrating all necessary components as well as complying with future emissions legislation, **Figure 2**.

The development of Valvetronic from the first to the second generation is the subject of this paper, which also includes an outlook into the future and detailed information about the following topics:

- design and mechanical system
- electrics and electronics
- thermodynamics and functional properties
- production.

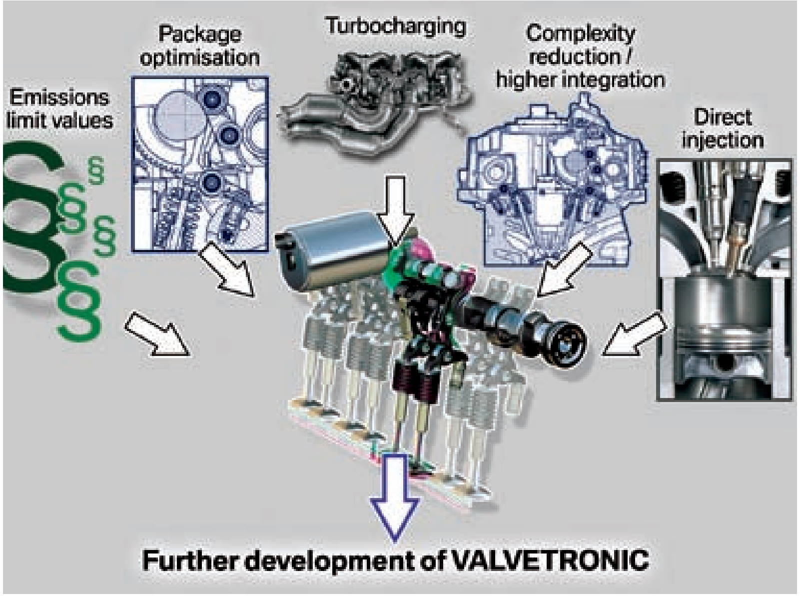

Figure 2: Future requirements on Valvetronic technology

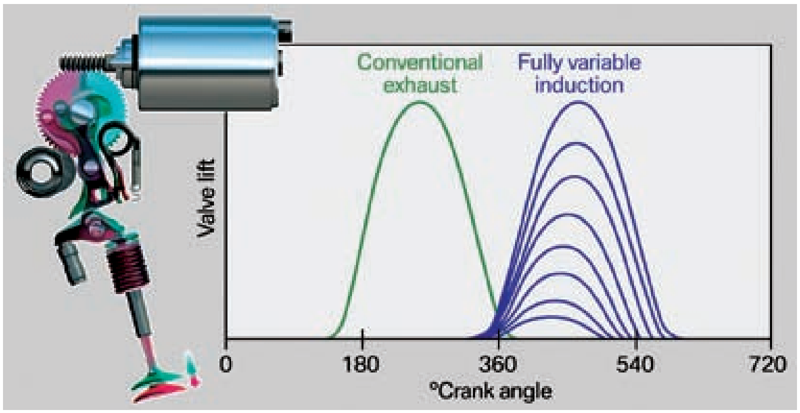

Figure 3: Design and valve lifts of Valvetronic generation 1

2 Design and Mechanical System

2.1 First Generation

The specifications for developing the first generation of Valvetronic can be relatively straightforwardly summarised as firstly implementing an infinitely variable reduction in the valve lift and control time within limits that were broad enough to permit load control and secondly no impairment compared to conventional valve train in all customer-relevant criteria.

The design implementation of Valvetronic generation 1 and the valve lift profiles that were made possible are shown in **Figure 3**. The valve train is based on a roller finger follower drive as well as the additional elements of an intermediate lever, eccentric shaft and return spring [1]. The valve lift is adjusted by turning the eccentric shaft which is engaged with an electric servomotor by means of a worm gear.

2.2 Second Generation

The requirements placed on the second generation of Valvetronic were significantly greater. The objectives were increased consumption reduction and increased power potential. Three approaches were employed in order to reduce consumption further:

1. Further reduction in pumping losses by means of more compact lift profiles at part load
2. further reduction in friction by completely dispensing with sliding friction
3. optimisation of combustion.

It was only possible to achieve the first point by optimising the design of the basic kinematics which now have one fixed centre of rotation about which the inter-

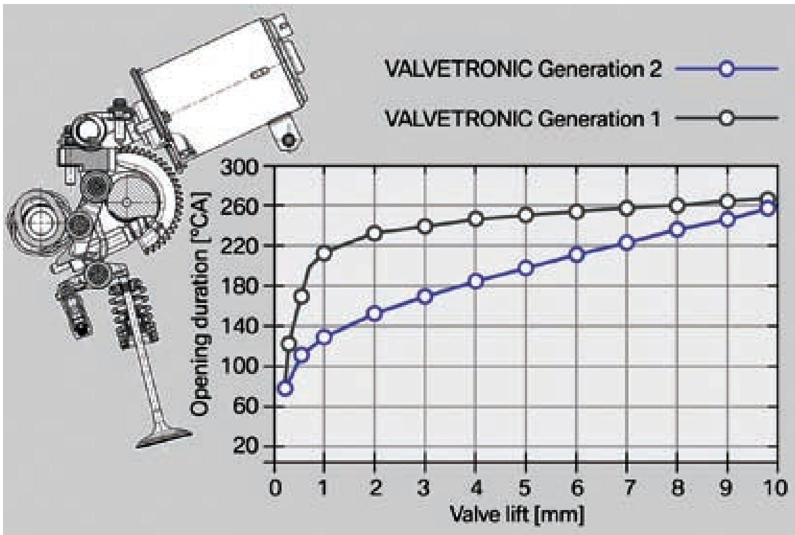

Figure 4: Design of Valvetronic generation 2 and comparison of opening durations

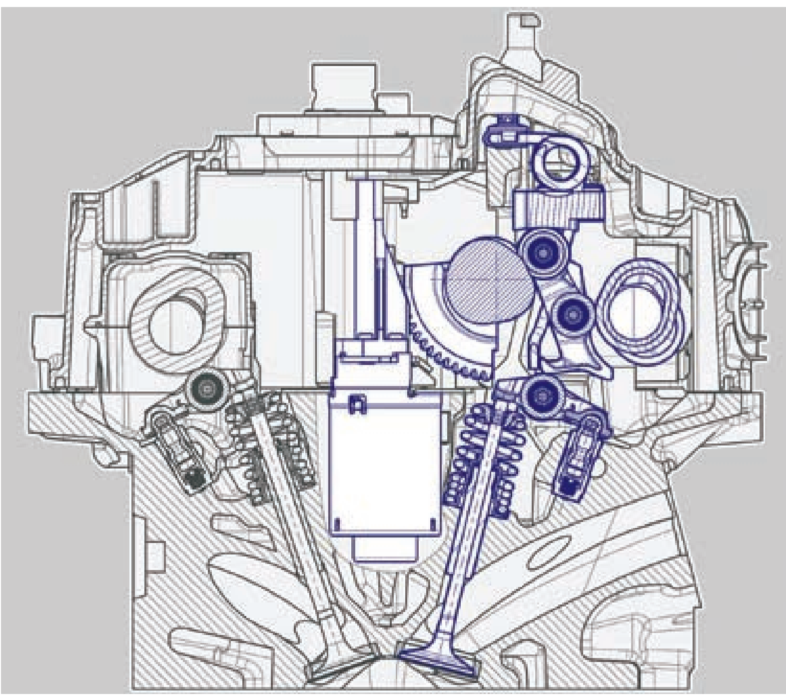

Figure 5: Concept for a Valvetronic engine of the future

mediate lever describes a purely rotational movement in each combustion cycle [2]. This design made it possible to shorten the control times in the configuration with the same valve lift, resulting in the desired reduction in pumping losses, **Figure 4**.

To reduce friction further, all points of contact on the intermediate lever were changed over to roller contact, thereby both reducing the adjustment forces and increasing the adjustment dynamics.

The optimisation of combustion was achieved by phasing and masking, the function and effect of which will be described in more detail in the subsequent chapter on thermodynamics.

In order to increase the power potential, it was necessary to ensure that the valve train would not become the limiting factor on engine power. It was necessary to achieve complete valve lift profiles with high valve accelerations in conjunction with an adequate engine speed capacity. The main key to achieving this was to reduce the moved masses at the same time as increasing the rigidity of the valve train.

2.3 Outlook into the Future

The main design emphasis in further development of Valvetronic in the future will be directed towards broadening and increasing integration of Valvetronic components on the one hand, and on the other hand achieving a package combining Valvetronic with direct injection in a central position.

The objective with the first requirement is to integrate the electric motor required for control entirely within the oil space of the cylinder head. This will significantly simplify initial assembly in the engine plant as well as various jobs in the service area, **Figure 5**.

In terms of the second point, namely combining it with direct injection in a central position, it will be necessary to undertake consistently detailed work on arranging all components so that the requirements of the kinematic systems, mechanical strength, cooling and the combustion process will be met.

3 Electrics and Electronics

3.1 First Generation

Based on the concept of the valve train, it was necessary to achieve the requirement of load control by means of the angle position of the eccentric shaft. Following intensive investigations, a system was selected comprising an electric control motor, a valve lift control unit and a redundant angle position sensor.

The driver‘s request is sent from the accelerator pedal to the digital engine electronics (DEE) where it is interpreted as the desired torque and converted into a nominal cylinder charge. This results firstly in optimum spreading of the valves and secondly in the corresponding opening lift of the inlet valves. This opening stroke is converted into an eccentric angle in the DEE, and sent to the valve lift control unit as a nominal value.

The valve lift control unit was configured as a conventional single PCB unit and is suitable for direct installation in the engine compartment. The control unit is configured as a classic microcontroller unit with a flash memory and its own microprocessor.

The actual adjustment of the stroke adjustment system is performed using a DC motor with cross collector, representing the optimum compromise between package restrictions and dynamic requirements in terms of the power density that can be achieved.

The eccentric shaft sensor operates according to the magnetoresistive principle in which a change in resistance caused by variations in a magnetic field is converted into a voltage value that is proportionate to the angle. Using high-temperature electronics together with the latest construction and connection technology such as flexible PCBs or high-temperature solder, it is possible to achieve an operating temperature of up to 160 °C for the eccentric shaft sensor.

3.2 Second Generation

The major challenge in terms of the electronics of the second generation was to reduce the number of control units used. The objective was to integrate the contents of the Valvetronic control unit into the DEE. This step was made possible by using a microprocessor from the Tricore range from Infineon which offered significantly more power compared to the predecessor.

The DC motor was adopted from the previous system largely unmodified, although a way was found to optimise the even mixture distribution further and to control the valve lift for selected cylinders in some cases.

As part of a further development of the angle position sensor, using a new ASIC module made it possible to improve the measuring accuracy to values less than 0.1° of eccentric shaft angle.

3.3 Outlook into the Future

The requirements on further development of Valvetronic from the perspective of the electronics are as follows:

- increasing the adjustment dynamics to achieve a highly dynamic adjustment with cylinder selectivity and to implement load control only by means of the air mass without intervention in the ignition angle
- reducing the space required to integrate the servomotor into the cylinder head
- reduction in individual components to implement cost and package advantages by means of registering the eccentric shaft position by sensors integrated in the servomotor.

Development progress in the electrics and electronics of Valvetronic is shown in **Figure 6** which illustrates the ever increasing quality of integration of functions and the associated dispensation with individual components that this made possible. Only an electronically commutated, brushless DC motor can be used if the electric motor is going to be completely integrated into the cylinder head. In spite of integrating the sensor assembly including the magnetic wheel, the volume can be reduced by about 60 % and the mass by about 40 % compared to the current servomotor. The servomotor can be cooled by the oil circuit of the combustion engine through being integrated in the cylinder head. The kinematic design prevents a flank change in the worm gear, therefore it is possible to determine the eccentric shaft position by means of sensors integrated in the servomotor. Three Hall elements are required for this, which provide the signals necessary for commutation.

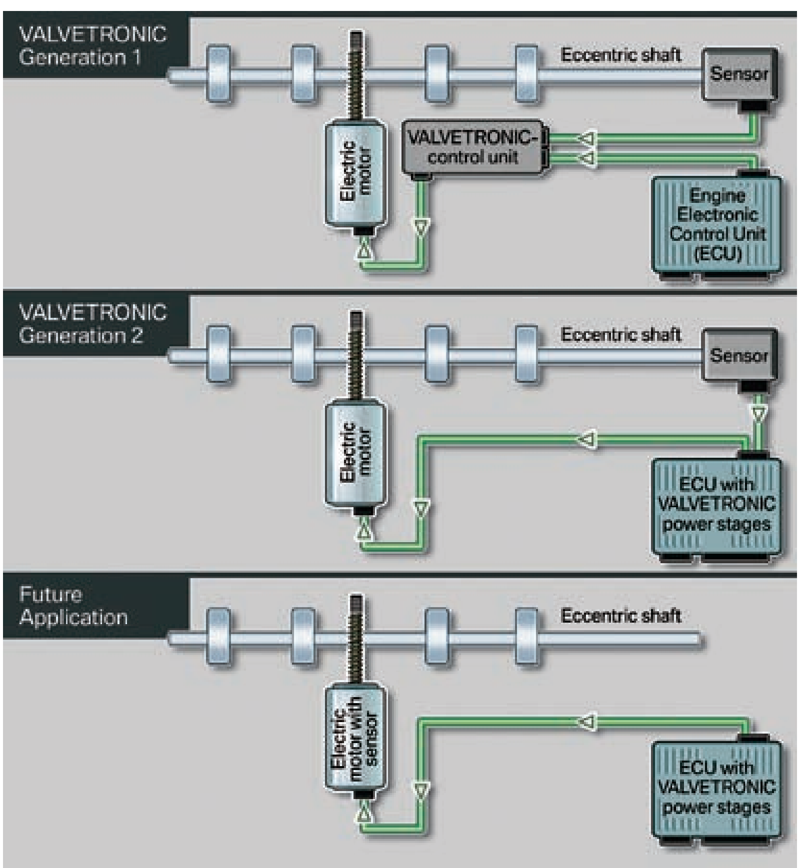

Figure 6: Development in electrics and electronics for Valvetronic

4 Thermodynamics and Functional Properties

4.1 First Generation

On the inlet side, BMW Valvetronic achieved infinitely variable variability of the valve lift and opening duration as well as infinitely variable adjustment of the phase position of the inlet and outlet control time. This made it possible for the first time for the valve train to control the load of the combustion engine. The process of „early inlet closing“ was selected [3]. In the first Valvetronic application of the four-cylinder engine, consumption was improved by 12 % in the test cycle and 25 % at idling speed compared to the previous engine. At the same time, specific power values of 56 kW/l, specific torques of 102 Nm/l as well as EU4 and ULEV 2 exhaust emissions regulations were achieved.

4.2 Second Generation

The second generation of Valvetronic further shortened the valve opening duration in the part stroke, which is associated with a further reduction in pumping work at part load of 7 %. To increase the level of turbulence at the end of compression, phasing and masking, **Figure 7**, generate charge movement in the shape of swirl and tumble, thereby significantly improving the stability and residual exhaust gas compatibility of the combustion process at part load and when heating up the catalytic converter.

Phasing in the lower part-load range results in a valve lift difference of up to 1.8 mm between the two inlet valves, and therefore an asymmetrical distribution of the sucked-in mass flow. The mass flowing in through inlet valve 1 is orientated by means of masking in the valve seat area at partial lift, with the effect that the required charge motion is achieved.

Simulation and testing confirm the positive effects of the charge motion measures, **Figure 8**. The level of turbulence is significantly higher, the combustion delay is shortened by approximately 10° CA and combustion is significantly faster overall. The associated improvement in combustion stability allows greater valve overlaps, and therefore increased residual exhaust gas contents, and also reduces pumping losses whilst maintaining the high efficiency of the high-pressure process. Compared to the basic four-valve engine without variabilities, there is a purely thermodynamic consumption advantage of about 9 % in the part-load operating point being considered, n=2000 rpm; wi = 0.27 kJ/l.

There are also advantages in catalytic converter heating operation due to the increased level of charge motion. The increased internal EGR rate implemented in this way and the fuel vaporisation significantly reduce untreated NO_x emissions. In this way, good combustion stability could be combined with low untreated emissions and high exhaust temperatures at the same time as achieving favourable fuel consumption values. The combustion process therefore forms a robust basis for achieving the lowest possible exhaust emissions.

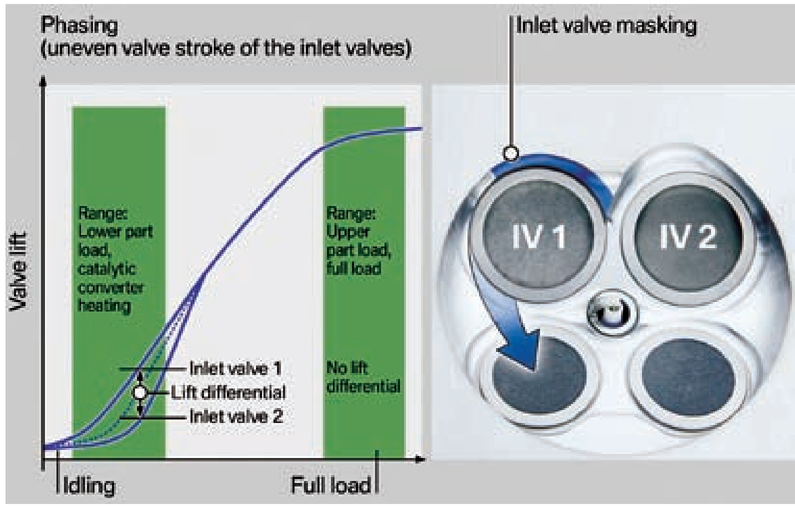

Figure 7: Phasing and masking in Valvetronic generation 2

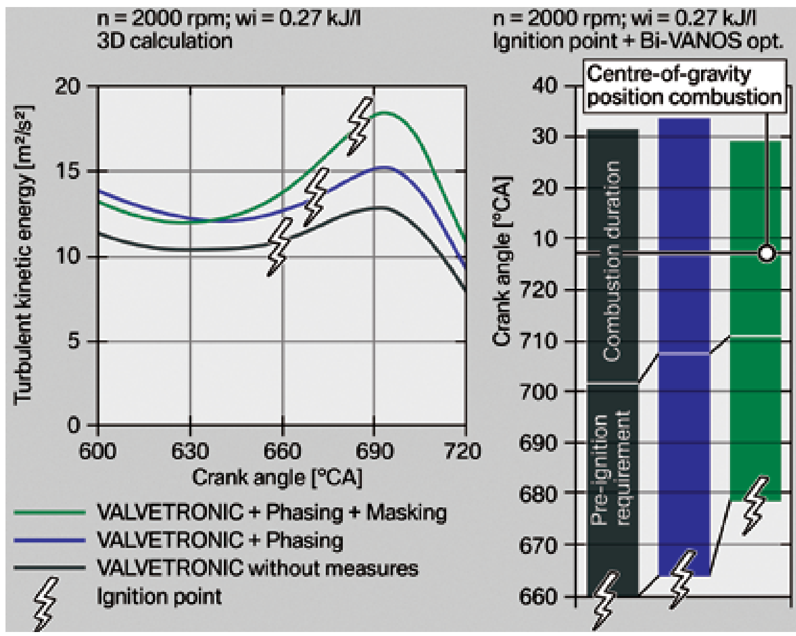

Figure 8: Charge motion and combustion delay (advanced ignition requirements) with phasing and masking

Naturally aspirated engines with the second generation Valvetronic achieve specific power values of about 67 kW/l, specific torques of 105 Nm/l as well as satisfying the strictest exhaust legislation including SULEV.

4.3 Outlook

Further potential for low fuel consumption in conjunction with high specific power values as well as synergy effects in terms of emissions can be achieved by combining Valvetronic with homogenous direct injection and turbocharging. The development of the combustion process is focusing on total implementation of the thermodynamic potential at the same time as making the configuration robust with regard to supercharging capacity and exploitation of the emissions control advantages. The reduction in compression ratio for the turbocharged engine can be largely compensated by optimised charge motion and internal mixture formation with direct injection.

A concept of this type also achieves significant advantages during catalytic converter heating through the possibility of setting a small valve lift and thereby generating an advantageous charge motion. This therefore results in an optimisation window in the application in which both HC emissions and smooth running can be improved. This potential is shown in **Figure 9**, in which the variation coefficient of the indicated work is a measuring parameter for smooth running.

The combination of Valvetronic and direct injection with turbocharging also holds the key to significant potential in terms of response behaviour. The load step up to naturally aspirated engine full load is reduced with Valvetronic as in the case of a naturally aspirated engine, because there is no manifold filling procedure. The subsequent torque build-up during acceleration of the turbocharger can be accelerated at low rpm values by setting a partial stroke. This promotes purging of residual exhaust gas and in turn leads to faster torque build-up.

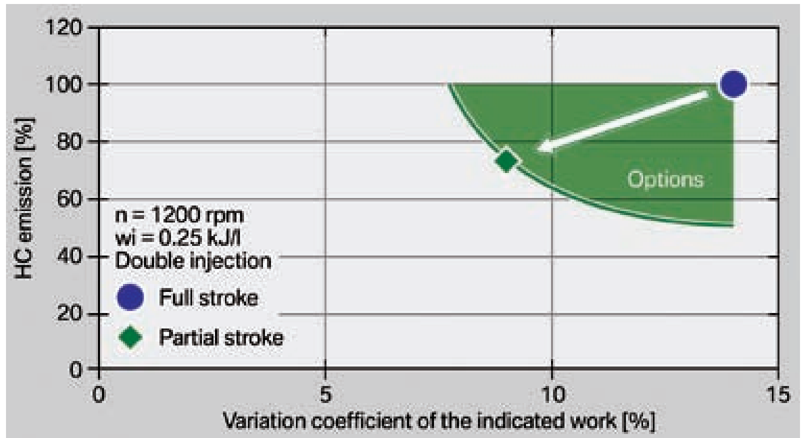

Figure 9: Advantages of the partial lift in catalytic converter heating in an engine with turbocharging and direct injection

5 Production

Mass production of Valvetronic started with the launch of the new generation of four and eight-cylinder engines in 2001. Two aspects revealed themselves as major challenges during the process development for industrialisation.

5.1 First Challenge: Process Security for Mass Production Assembly

The challenge was to integrate the Valvetronic function in the cylinder head system in a sufficiently modular and accessible way to guarantee the reliability of the assembly process and functional checking in mass production, with cycle times of < 1 minute. **Figure 10** shows a comparison between the assembly content of a Valvetronic valve train and a classic valve train. In some cases, the Valvetronic-specific content demanded entirely new assembly and testing techniques to be developed, involving a high level of engineering in terms of machinery, systems and special operating material.

5.2 Second Challenge: Tolerance Chain with Regard to even Mixture Distribution

The major challenge in introducing mechanical Valvetronic technology into mass production concerned achieving process reliability in maintaining the tolerance chain in order to guarantee a sufficiently accurate even mixture distribution of the volumetric air flows in all cylinders throughout the entire adjustment range of the valve lift. To guarantee engine function with a level of smooth running acceptable to BMW customers, the Valvetronic valve train requires tolerances of +/- 8 % (corresponding to +/- 0.024 mm) to be reliably maintained over all cylinders, even with a minimum valve lift of less than 0.3 mm. In combination with the more complicated mechanism of the Valvetronic entailing additional components that determine tolerance (eccentric shaft, intermediate lever and sliding-block guide), this demands in many cases that dimensional and shape/position tolerances

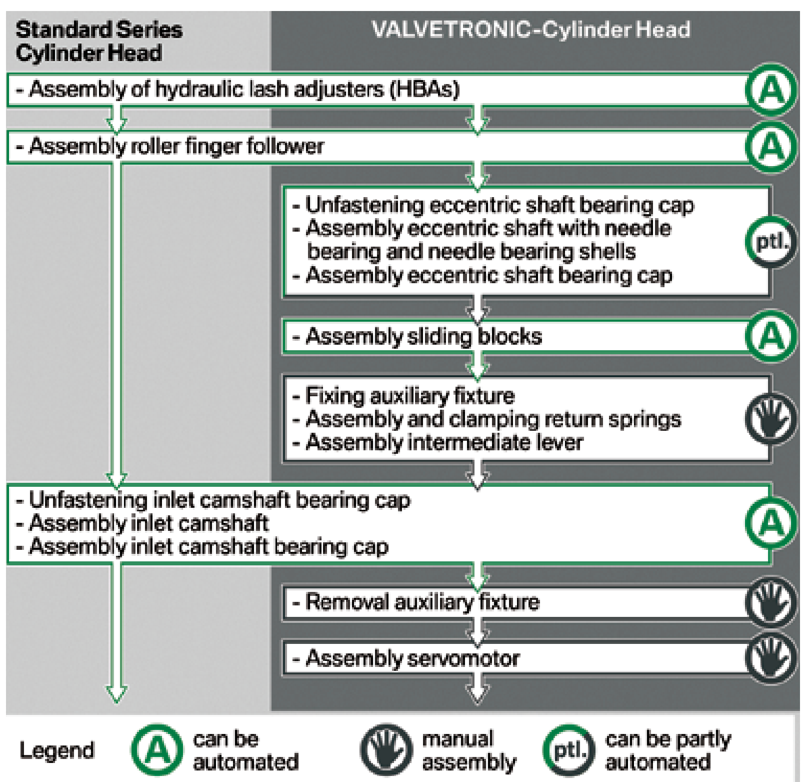

Figure 10: The Valvetronic assembly process

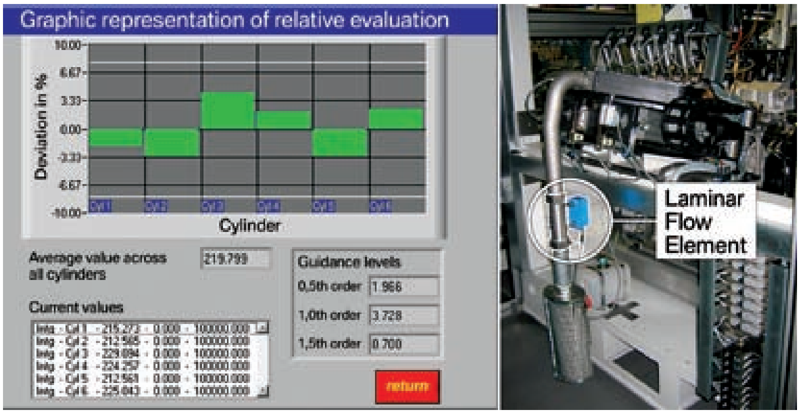

Figure 11: Even mixture distribution measurement in an inline six-cylinder engine

have to be reduced by more than a factor of 10 compared to a conventional cylinder head. Furthermore, the variability of the valve lift results in new, additional quality features such as maintaining dynamic even mixture distribution tolerances of the 0.5th, 1st and 1.5th order. In total, this resulted in requirements on the tolerance chain of the mechanical components within the functional group which still approach the limits of production technology today in terms of maintaining the process reliably as part of mass production. For instance, this demands absolute position tolerance of the camshaft and eccentric shaft bores throughout the entire length of the cylinder head at +/- 0.01 mm. This can only be achieved by specific, optimised clamping onto machining centres that have been converted into special machines with thrust bearing units.

Despite all efforts to increase the precision of individual components in the Valvetronic valve gear, the tolerances mentioned previously result in a statistical proportion of about 1 % no-go Valvetronic cylinder heads which then have to be readjusted accordingly in series production by means of classified roller finger followers. An additional mechanical test specific to Valvetronic is intended to measure the even mixture distribution in the cylinder head or engine. If the result indicates a problem, then it should also specify the cylinder(s) which require readjustment. This also includes determining which class of roller finger follower must be installed as an alternative.

Different measuring principles are used for measuring even mixture distribution. The principle of indirect measurement by valve lift measurement is used in V-engines. Whilst the eccentric shaft is stationary in its idling position, the camshaft is turned and the valve lift profile measured using a linear potentiometer.

Further developments of the test technology were intended to allow even mixture distribution to be measured and evaluated directly by measuring the air volume fill of the individual cylinders. In particular in BMW inline 6-cylinder engines, ensuring an acceptable level of smooth running means that it is necessary to maintain order criteria. **Figure 11** shows an example of the mechanical test that has been used since introduction of the second generation in the six-cylinder engine in 2004. This means the increased requirements of the six-cylinder engine could be ensured robustly and with process reliability in mass production by means of dynamic differential pressure measurement using a capillary system in laminar flow elements and evaluation of selected cylinders.

6 Summary

In Valvetronic, it has been possible to develop a technology that significantly reduces fuel consumption in SI engines and can be offered worldwide without restrictions in terms of fuel quality. At the same time, all applicable exhaust emissions legislation has been satisfied, including even Sulev in the USA. Valvetronic has undergone permanent and consistent technical further development since it was first launched in 2001 in order to keep pace with rising demands.

The greatest challenge for production is to control the tolerance chain in order to guarantee sufficiently accurate even mixture distribution of the volumetric air flows into the individual cylinders of an engine.

Further development of Valvetronic will require the cylinder head package to be optimised to enable it to be combined with direct injection, even in a central position. The electric motor must be entirely arranged within the cylinder head and must also integrate the function of the angle position sensor. In terms of thermodynamics, it is important to seize the advantages offered by Valvetronic, including in combination with homogenous direct injection and turbocharging.

For the foreseeable future, the lean-burn direct-injection SI engine will not be able to be offered worldwide to all markets. With Valvetronic, BMW is capable of offering an optimum solution for specific markets in terms of low-consumption engines and has therefore achieved a unique degree of freedom in the global competition.

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