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Just air?

UniAir – The first fully-variable, electro-hydraulic valve control system

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Figure 1 Megatrends in the automotive industry

Despite the increasing trend towards the hybridization and electrification of automotive powertrains the internal combustion engine will continue to play a decisive role in the next few decades. The increasingly strict limits for CO_2 emissions and thus fuel consumption define the optimization of the internal combustion engine as the automotive industry's main task. Along with electrification, hybridization and the development of low cost vehicles, the optimization of fuel consumption has become a megatrend (Figure 1). One possible method of meeting ambitious fuel consumption and emissions targets is the use of variable valve trains.

The Schaeffler Group has been working on the different types of variable valve trains for a long time. A distinction is made between valve train systems with variable phases and valve trains systems with variable lift. Variable camshaft phasing units that adjust the phases can influence exhaust gas recirculation and the effective compression ratio. Systems with variable lift can have a discrete two- or three-step lift actuation or be fully-variable. This article focuses on fully-variable valve train systems (Figure 2). The Schaeffler Group soon recognized that fully-variable mechanical valve trains such as Valvetronic cannot optimally meet all challenges in terms of flexibility. The Schaeffler Group therefore secured the license rights to "UniAir", potentially today's most flexible valve train system, as early as in 2001.

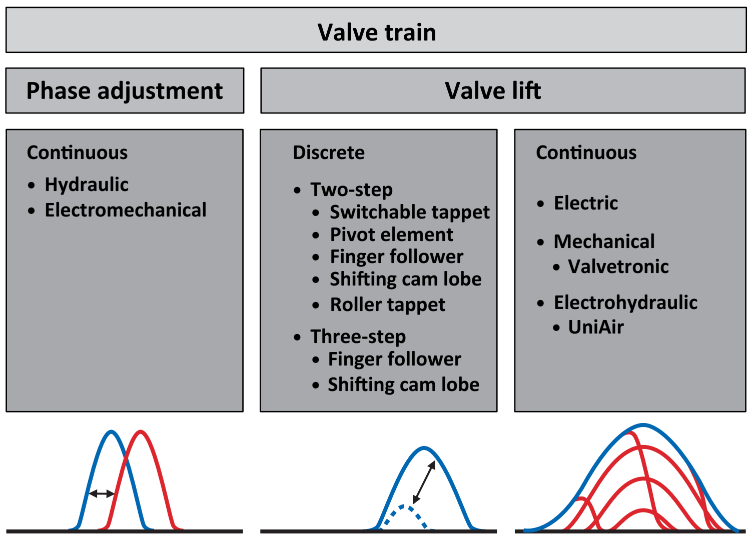

Figure 2 Variability of the valve train

Introduction

The variable valve train is one of the key technologies for implementing strategies for low CO_2 emissions. In conventional gasoline engines with throttle valve control, up to 10 % of the provided fuel is consumed as energy for pulling air into the cylinder against the throttling resistance when the suitable air volume is metered. If a variable valve train is used, the throttle valve can remain completely open (or even be omitted), and air can be drawn in by the piston without resistance. The correct air volume for each operating point is then controlled directly in the intake ports of the relevant cylinders by means of a timing and geometric control of the valve opening operation.

Figure 3 shows that variable valve trains continuously adjust the valve lift (see B). If variable camshaft phasing units are used in addition, the valve lift curves can be moved towards earlier closing of the intake valve during phasing. This reduces the pumping work and increases the effective work of the engine. The engine then operates in the so-called Miller cycle in partial load ranges (Figure 4). The Miller process describes the movement towards early closing of the intake valve. A comparison of the PV diagrams of the standard engine and the variable engine shows that the area indicating the pumping work is significantly smaller due to reduced throttling losses. In addition, less air is

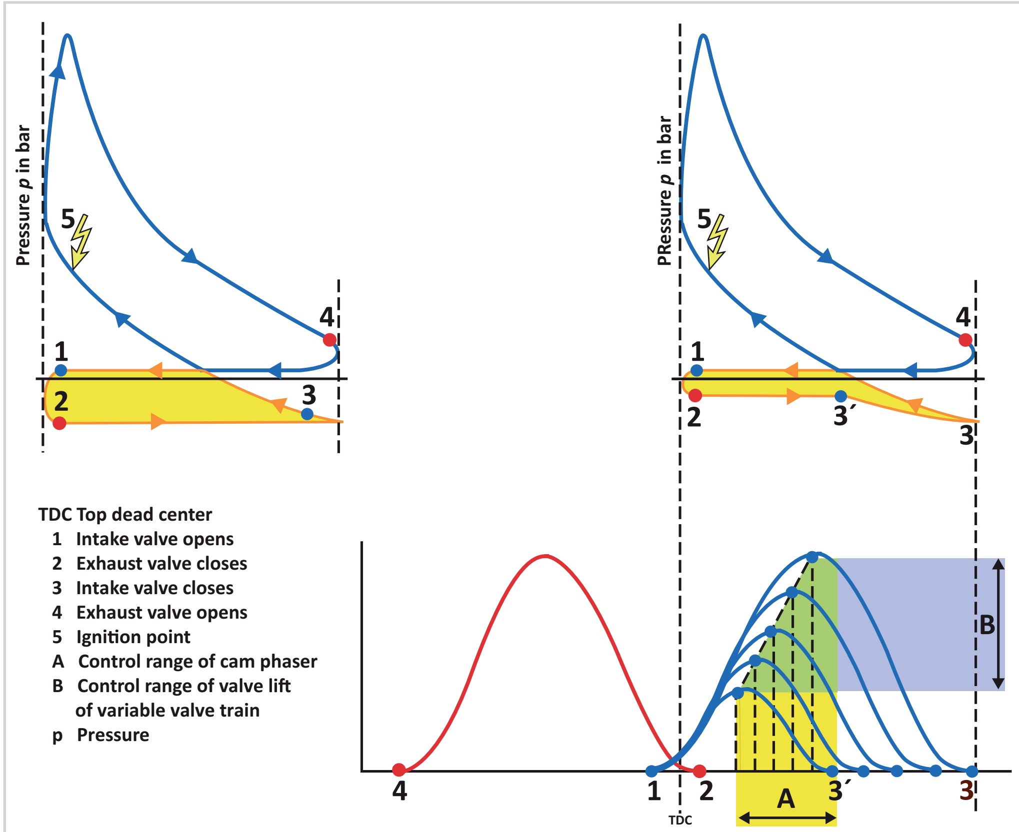

Figure 3 Process of continuous, variable, mechanical valve trains

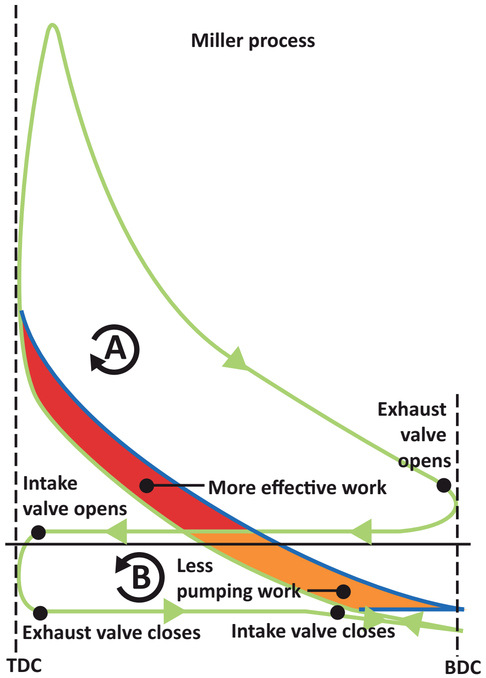

Figure 4 Miller process

drawn into the cylinder due to early closing of the intake valve. As a result, less work is required for compression and the temperature remains at a lower level so that the engine can provide more energy.

Comparison of systems

Figure 5 shows a selection of systems that have been developed by automotive manufacturers, suppliers or engineering service providers. Although efforts have been made for decades, the automotive industry has not succeeded in developing camless, electromagnetic or electro-hydraulic systems to a level ready for volume production that offer the highest degree of freedom in the valve lift. The main problems continue to be energy consumption, noise emissions, costs, and ultimately the safety aspect of incorrect control that can damage the engine. This is why only electromechanical systems have been used in volume production. Compared to camless valve train systems, they have a simpler and more robust structure but comprise relatively complex mechanisms and transmissions that are often combined with variable camshaft phasing units. The main disadvantages of such systems are the low level of variability, slower response times and the circumstance that individual control of the cylinders is not possible or highly complicated. With the UniAir technology, the best compromise between camless systems and electromechanical systems has been ready for volume production since September 2009. It has been introduced to the market in the Fiat FIRE MultiAir engine of the Alpha Romeo MITO. In contrast to other systems on the market, the UniAir technology offers the highest level of variability combined with low energy requirements, a high level of safety against malfunctions, and low system costs.

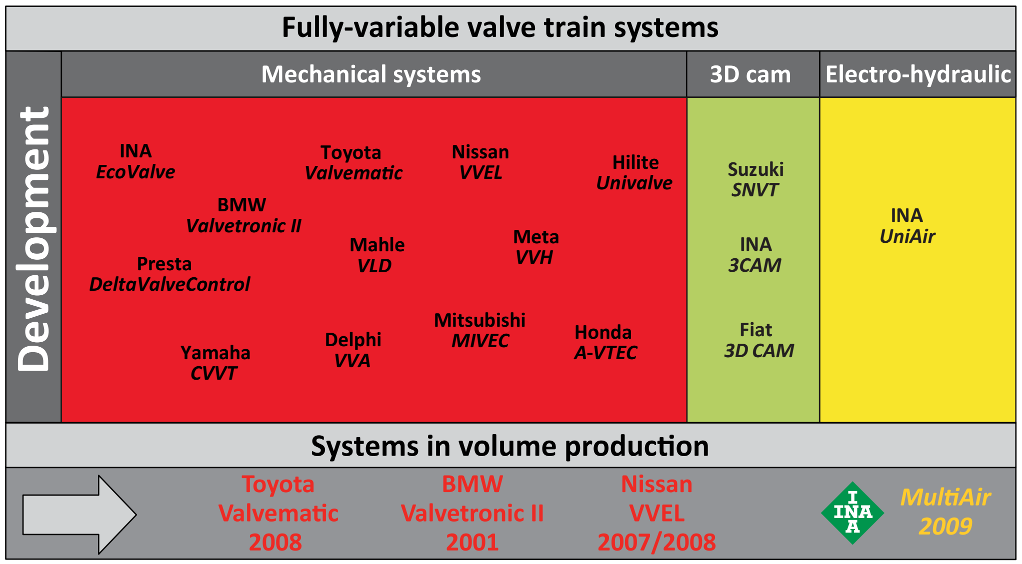

Figure 5 Comparison of variable valve train systems

Functional principle of the UniAir system

The system comprises an actuator activated by a camshaft with an integrated fast-acting solenoid valve and valve control software.

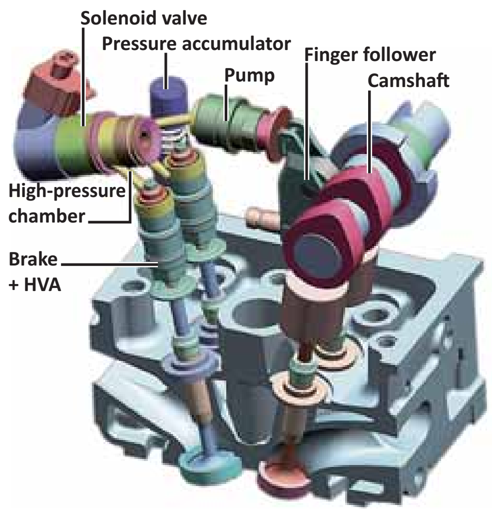

Figure 6 UniAir system - main components

In contrast to conventional electromechanical valve trains where the cam contour is transferred to the engine valve via a rigid element (such as a tappet or finger follower), UniAir uses a defined volume of oil that is confined in the so-called high-pressure chamber. This oil volume can be varied using a 2/2-way solenoid valve. When the solenoid valve is closed, the oil acts as a hydraulically rigid pushrod. When the solenoid valve is open, the cam and the valve are disconnected. This allows cyclical and individual setting of the valve lift curves for the relevant cylinders and intake valves by controlling the solenoid valves. For example, if the solenoid valve is opened before the cam has returned to the base circle, this is called early intake valve closing (EIVC). Here, the engine valve spring forces the valve towards "closing". The oil is forced out of the high-pressure chamber to the so-called intermediate pressure chamber that is connected with a pressure accumulator. To enable late opening of the intake valve (LIVO), the solenoid valve is not fed with current and remains open. The cam forces oil into the pressure accumulator via the pump piston. The solenoid valve is closed in good time before the engine valve opens. This mode and multi-lift operations (engine valve is opened twice in the same cycle) are permitted only at crankshaft speeds of up to 3000 1/min. Multi-lift is a combination of early intake valve closing with another late intake valve opening. When the solenoid valve is open, the pressure accumulator feeds the retained oil volume back to the high-pressure chamber to refill the chamber and minimize energy losses. During early intake valve closing, the intake valve always performs a ballistic flight phase. This ballistic flight phase is forced by the engine valve spring. Shortly before the valve reaches the seat, a hydraulic brake engages and ensures normal, gentle closing of the valve. Hydraulic valve lash adjustment (HLA) is also implemented in the system.

Valve lift modes

The UniAir technology enables an extremely high variability of the valve lift. The different modes assist in meeting the engine's requirements in all operating conditions. Full valve lift is mainly used at maximum engine power. In this mode, the solenoid valve remains closed during the entire cam lift phase. The EIVC mode is used in partial load of the engine. This means that the solenoid valve is opened early so that only partial valve lifts are performed and the air volume fed to the cylinder is adjusted to the torque curve. If high torques are required, the intake valve is closed only shortly before the cam end so as to prevent the drawn air from

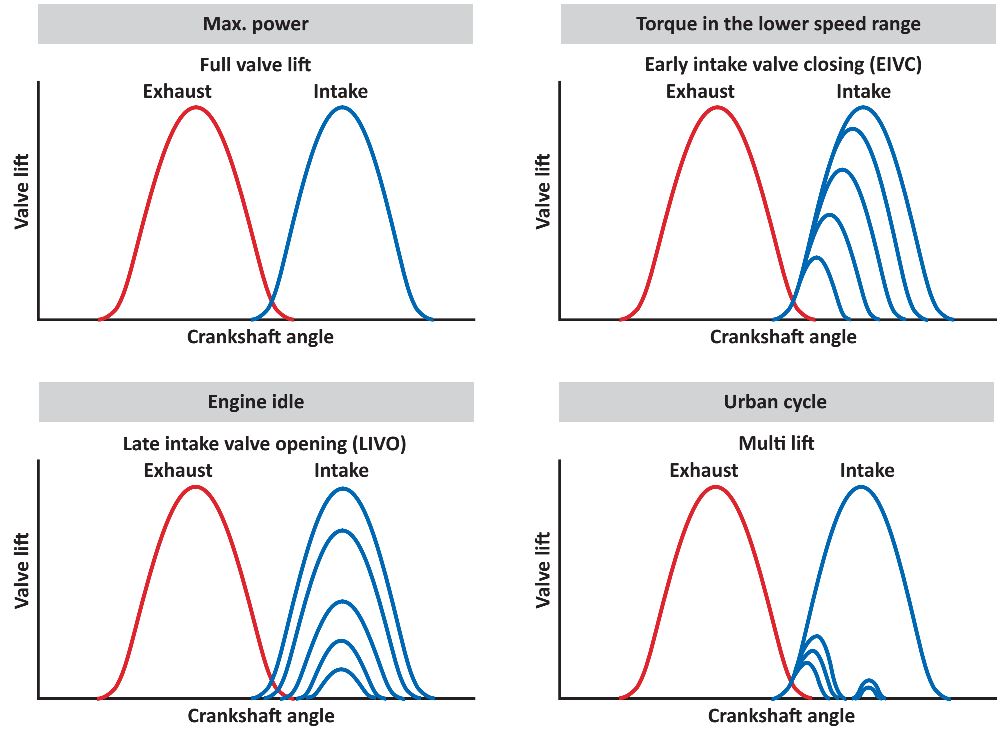

Figure 7 Valve lift modes for the intake side

being forced out and to increase the effectiveness at lower speeds.

In ranges close to idling, the intake valve remains closed at the beginning of the cam lift to set the air quantity in the cylinder and at the same time generate high air intake speeds and therefore sufficient turbulence for the mixture preparation. The intake valve is opened later (LIVO) by closing the switching valve. At very low speeds and loads, the two modes are combined, i.e. EIVC in the first lift and LIVO in the second lift. This leads to stable combustion and prevents problems with overexpansion of the air volume that is limited by closing the intake valve early.

Design requirements

To ensure the correct mixture in each operating condition, the UniAir system must be designed based on the following requirements:

- Oil temperature (min. -30 °C, max. 150 °C)
- Full function in the entire speed range (700 to 7000 1/min)
- High level of accuracy of the air quantity set in the cylinder
- High precision and repeatability of the valve lifts of each individual valve of the entire engine
- Ability to respond as fast as possible (during a camshaft rotation) to be equipped for transient operation
- Compensation function for specific component tolerances and changes in environmental conditions such as temperature or aging of components

The UniAir system was designed with a special focus on achieving the functional requirements at the lowest possible costs. The design also took into account that customers are not willing to make considerable concessions with regard to design envelope, additional weight and friction, despite the system's numerous advantages. The

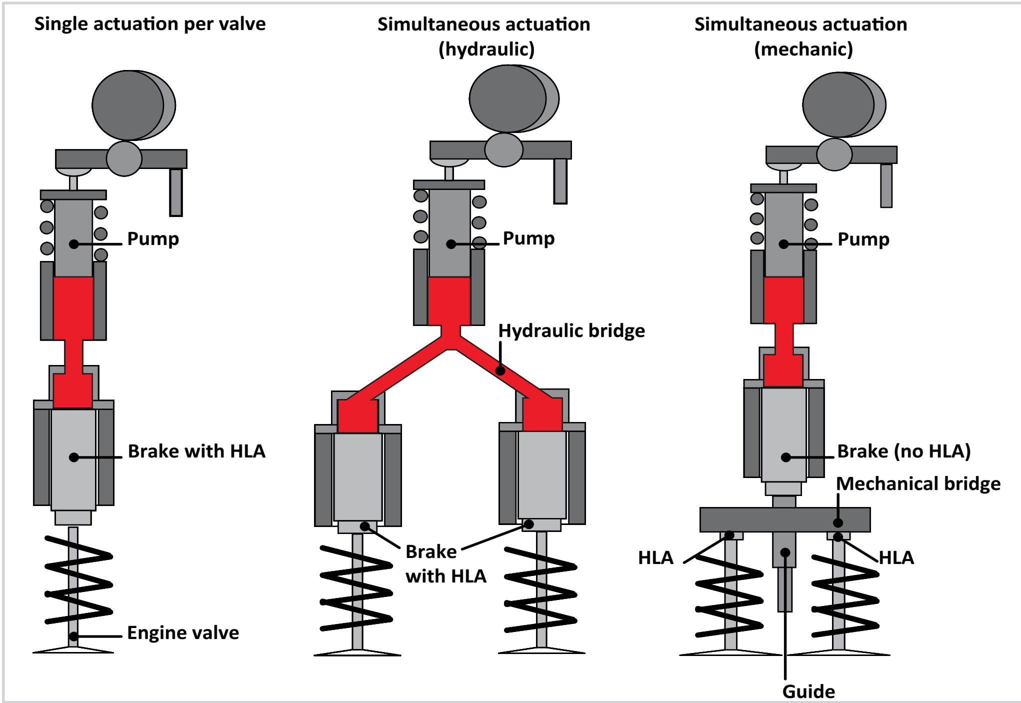

Figure 8 Possible principle system architectures

need for an engine oil supply for the system was also known from the beginning.

Requirements

Various designs have been developed to cover all types of applications in gasoline/diesel engines on the intake and exhaust side (Figure 8).

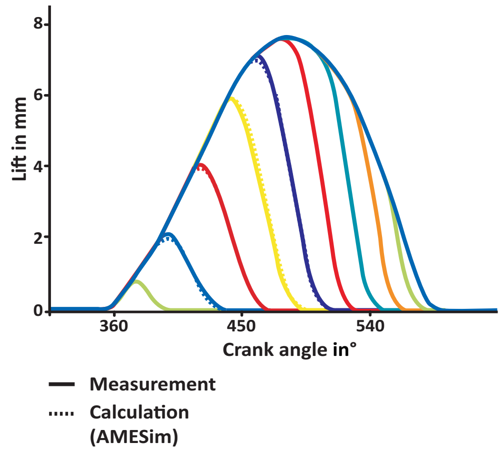

Figure 9 Simulated and measured valve lift curves

The individual control of valves offers the highest level of flexibility. If the valve of a cylinder is actuated by means of a hydraulic or mechanical bridge, this slightly restricts the flexibility but makes the system significantly more cost-effective. The decision for the best configuration in terms of the cost-benefit ratio depends on the specific application and objective.

System development and design

During the development phase, the system was preliminarily designed using state-of-the-art design, calculation and simulation tools. By linking powerful programs such as Matlab/Simulink and AMESim, a comprehensive tool for numerical simulation was generated that facilitates systematic analysis. This tool was used to design the cam contours and to simulate the valve lift curves of the intake valves. Figure 9 shows a comparison of the simulated group of curves with the group of curves actually measured.

UniAir components

The solenoid valve as a high-precision component

Extremely high requirements in terms of accuracy are placed on the UniAir system to ensure constantly identical valve lifts of the same valve and for each actuator over the entire cylinder head. It is crucial that all components ranging from pump to brake conform to the tolerances. The solenoid valves as the control elements for every required lift curve are of central importance for the overall system. During the design phase of this new solenoid valve, the developers were faced with special challenges such as the required on and off times, the switching time precision and durability.

System architecture with a “normally open” solenoid valve requires the solenoid valve to switch once per rotation of the camshaft and even several times during multi-lift operation. To ensure that the high-pressure chamber is full and therefore to ensure full lift during the next cycle, the solenoid valve is opened for a short time after each cycle to ensure refilling of the chamber. In the case of multi-lift operation, it must be ensured that the armature has reached its resting position again after opening for the first time before the solenoid valve is activated a second time. The current for the second lift can only be fed after the armature has been in the resting position for approx. 2 milliseconds.

Figure 10 shows the activation curve of the current for a solenoid valve and the corresponding engine valve lift curve. The diagram compares early intake valve closing with the full lift curve.

A special activation strategy was developed for the solenoid valve current in order to produce a fast-acting solenoid valve with the lowest possible current requirements. The current profile comprises several sections. The non activated solenoid valve is first fed with the so called bias current, which pre-magnetizes the solenoid valve but does not switch it. In order to ensure a rapid and precise energizing procedure, increased peak current is applied at the time of switching. The switching point is determined by the software depending on the operating condition. After the solenoid valve has been actuated completely, the current is reduced to holding current, which keeps the solenoid valve closed. In turn, the software determines the point in time at which the current is completely switched off, thereby opening the solenoid valve again.

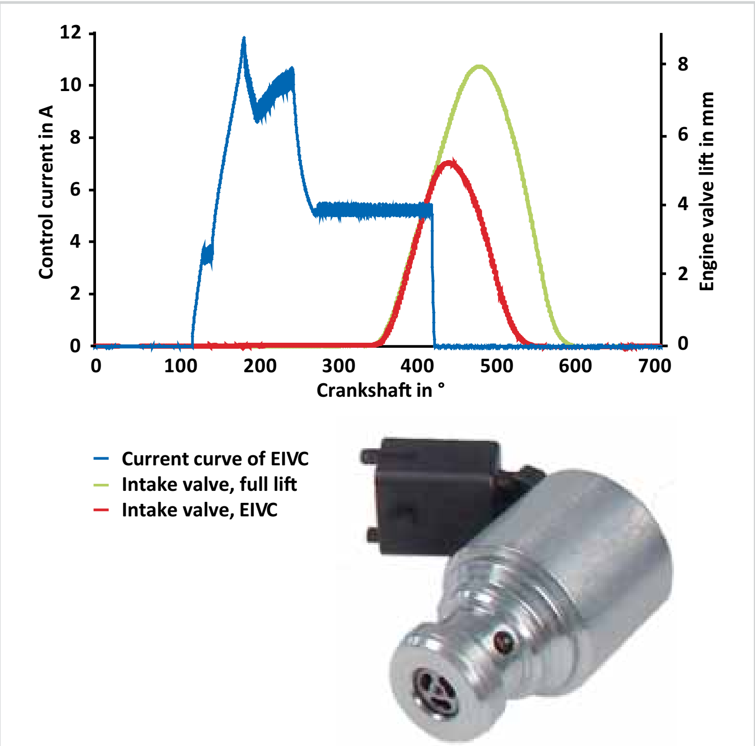

Figure 10 Solenoid valve and current curve of the solenoid valve

The precision of the opening and closing angles of the engine valves is essential for system function. The switching time precision of the solenoid valve makes a considerable contribution in this regard. During the assembly of the solenoid valve and their subassemblies, various function values such as flow and switching times are measured on the assembly line and the assemblies are adjusted in such a way that the function values are within the required range. This means that the manufacturing tolerances of the individual parts can be compensated by sorting them accordingly. Despite compensating the tolerances of the individual components, it is still necessary to optimize the precision of the switching times by means of an appropriate compensation function. This compensation is active during the entire lifecycle of the product and therefore also counteracts changes in switching times caused by aging. This ensures optimum balancing of the cylinder charge of one engine during the entire lifecycle.

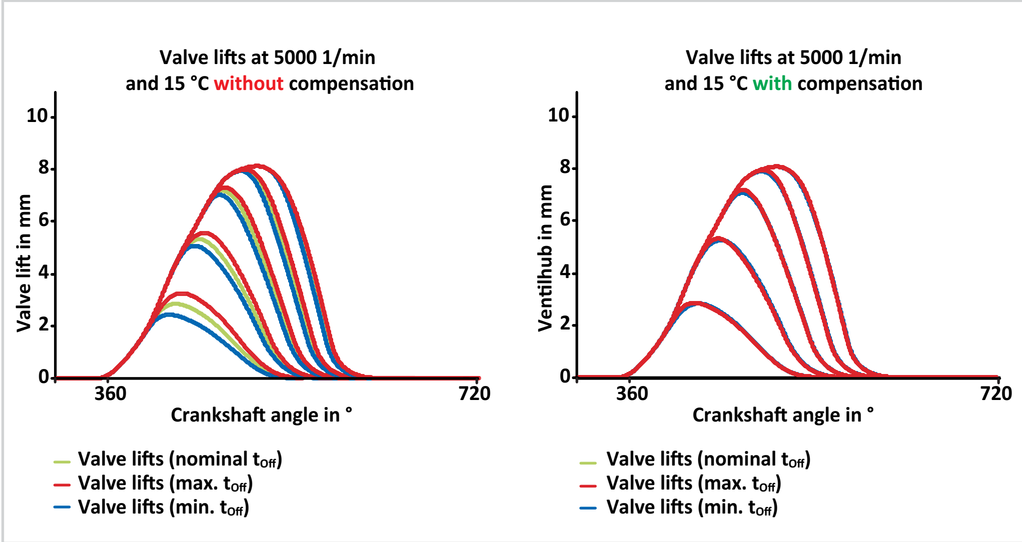

Figure 11 Compensation of off time t_{off} of the solenoid valve

The solenoid valve carries out around 330 million switching operations each during the operating life of the system. This number of switching cycles at the required precision poses a significant challenge for the development of the solenoid valve. This new solenoid valve was developed from the concept phase to volume production readiness using the most advanced design and simulation methods in cooperation with Continental Automotive Systems. The function was accurately validated and the solenoid valve was integrated in the overall system by means of several function and operating life tests on component test stands, system test stands and in vehicles.

The solenoid valves are individually controlled by the control software via corresponding power stages. The function of the control software is to implement the modes and opening and closing angles of the engine valves as defined by the engine control system. Here, the software considers various factors that influence the behavior of the system in order to find the correct actuation point of the solenoid valve in each case. It thereby determines the timing of the engine valves (Figure 12). The main influencing factors are covered in greater detail in the component descriptions and the following section.

First of all, the on and off times of each solenoid valve must be mentioned here. They are individually monitored using the current curve during each switching process for each cylinder and then readjusted depending on the operating condition using data maps in the engine control system. The special challenge in this case is the detectability of the current curve over the entire required temperature range and the oil viscosity associated with it. All solenoid valve components must be perfectly matched to each other to ensure this function.

The system architecture and the component geometry also determine the character of the valve

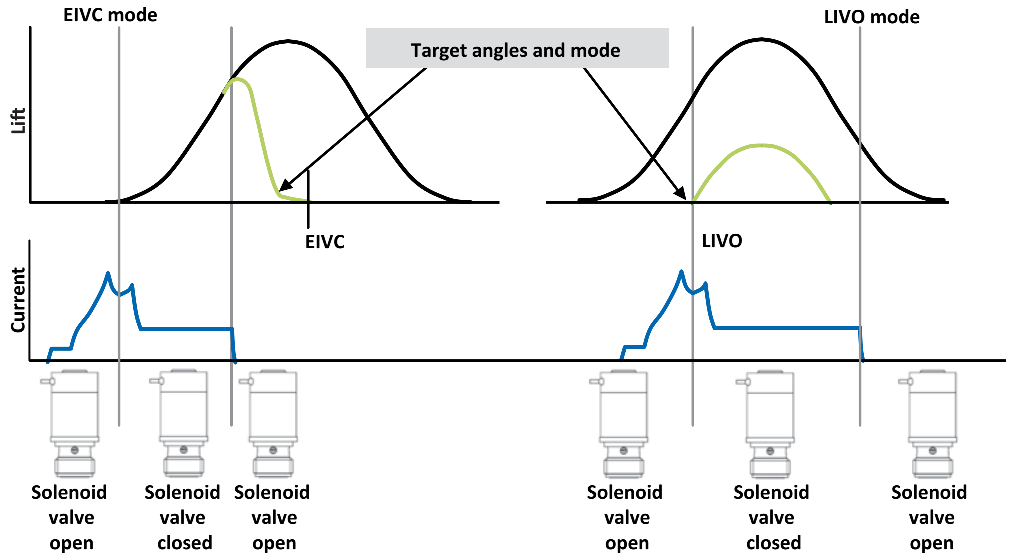

Figure 12 Target angle and modes

lift curve. This includes the brake unit. This unit is a slave cylinder that converts the hydraulic pressure into the movement of the engine valve via a hydraulic valve lash adjustment element. Since the engine valve is always closed independently of the cam contour, it is not braked mechanically before it lands. To prevent excessive closure speeds that can generate noise and damage the valve, the engine valve is braked at the end of its ballistic flight phase by means of hydraulic control geometries in the brake piston guidance. This in return enables fast opening speeds as the brake is short-circuited by means of a special check valve. Designing all these components in a specific manner ensures that the engine valve is closed in good time under cold conditions (-30 °C) and low closure speeds with hot engine oil.

The valve movements and the brake function in particular are determined not only by geometric and architectural influences, but also environmental and operating parameters such as engine speed and oil viscosity. The control system also needs information about these factors in order to take them into consideration.

It is necessary to monitor the oil viscosity, particularly during cold starts and the subsequent rise in internal temperature of the system. In this context, and as the only additional sensor for this system, the temperature sensor (Figure 13) is an important component. The sensor measures the oil temperature in real time and supplies an important input for the control unit for determining the oil viscosity. The temperature measurement sen-

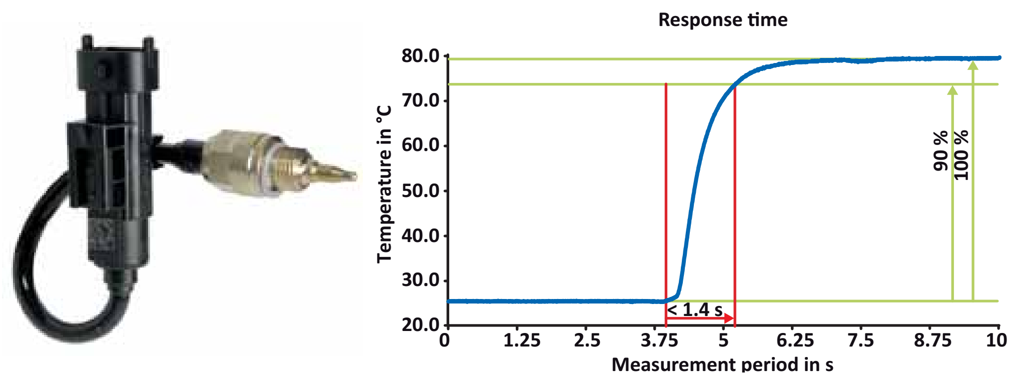

Figure 13 Temperature sensor

sor already present on the engine for measuring cooling water and engine oil is not fast enough.

The sensor with a NTC element (negative temperature coefficient) is specially calibrated for use at low temperatures (highest precision at 0 °C) and has a response time (τ_{90} in water) of a maximum of 1.4 seconds.

Ensuring function and quality

After the UniAir actuator has been manufactured and assembled, it has to pass quality tests to ensure that the system runs error-free in conjunction with the control software and fulfills the required function. An end-of-line (EOL) test stand (Figure 14) that conforms to development test stands was specially developed for this purpose. Essential functions such as full lift, late intake valve opening and early intake valve closing are tested for defined control angles and speeds using a special EOL test program. Switching times are tested especially in the late intake valve opening mode where precision is extremely important. The brake unit is also comprehensively tested. These tests are performed on the EOL test stand by means of an automated procedure. Each actuator is firmly located on the test cylinder head and checked with regard to the required precision of the opening and closing angles as well as the maximum lift height.

Summary

The variability of valve trains is an important aspect of internal combustion engine technology of the future and will assist us in fulfilling increasingly strict current and future legal requirements regarding emissions and fuel consumption as well as customer requirements. The fully-variable electro-hydraulic valve train system UniAir can expand the potential of current variable valve control mechanisms and makes a considerable contribution to optimizing combustion processes. The development of the UniAir system with Fiat means that the Schaeffler Group has succeeded in launching a new valve train system. This system provides numerous benefits compared with conventional valve trains not only for vehicle manufacturers, but also for end customers. The world's first fully-variable electro-hydraulic valve control system was launched on the market in September 2009 in the Alfa Romeo MITO (engine: Fire 1.4 l 4 V 135 HP Turbo variant) under the name MultiAir. The UniAir technology, which has been included on the intake side, is now also used in the Punto EVO. Figure 15 shows the measured advantages for the Alpha Romeo MITO.

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Along with the contribution to increasing performance and reducing consumption, UniAir offers a wide range of additional benefits. Due to its highly flexible design, the system can meet diverse customer requirements and be adapted to nearly every type of engine. The UniAir engine is operated using conventional engine oil. The control software, which is

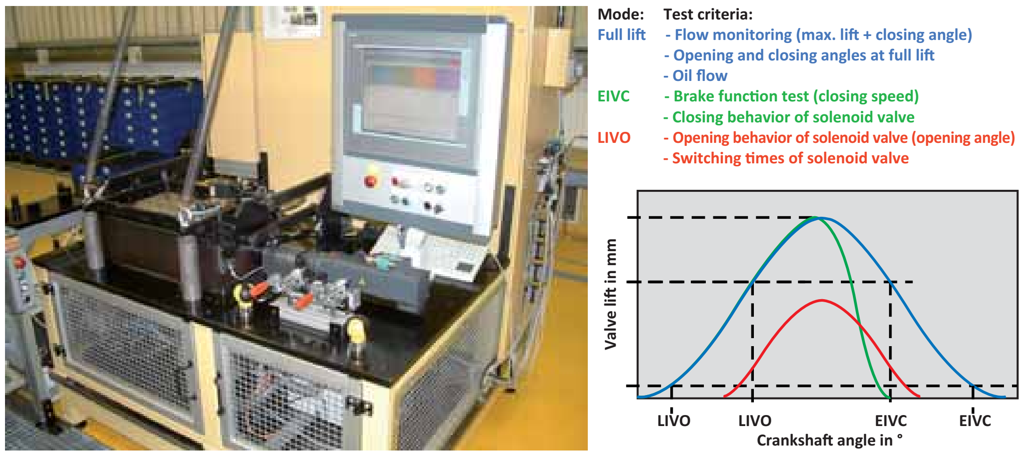
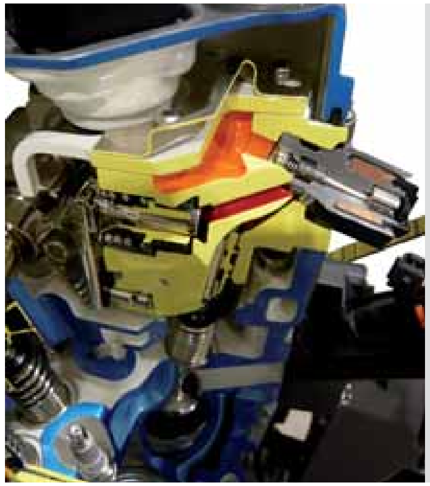


Figure 14 End-of-line test stand/test criteria

also supplied by Schaeffler, is integrated in the engine control unit. Schaeffler considers itself as a system partner of the automotive industry and supplies the complete UniAir system comprising hardware, software and calibration data set (Figure 16). The system offers a clear benefit to automotive manufacturers as they receive a tested module from one source that can be easily integrated in a cylinder head at the engine plant.



- Up to 10 % reduced CO_2 emissions/ fuel consumption
- Up to 10 % more power
- Up to 15 % higher torque in the lower speed range

(Compared to an engine with a conventional valve train without a camshaft phasing unit)

Figure 15 First volume production application of UniAir in the FIAT Fire 1.4 l MultiAir – advantages

The UniAir system has first been implemented specifically on the intake side of gasoline engines. However, the system is not solely restricted to the intake side.

UniAir is also interesting for applications in diesel engines of passenger cars. This extremely flexible system enables strategies such as internal exhaust gas recirculation, intake swirl generation and variability of the effective compression ratio. UniAir has already been implemented in prototypes of diesel engines for passenger cars.

First developments have been successfully used in commercial vehicles. Schaeffler and ABB have signed a cooperation agreement for using this valve train system in large off-highway engines (in ships, trains and power generation applications).

In order to meet the requirements of future combustion methods, for example CAI/HCCI, in terms of air and exhaust paths, Schaeffler and its partners are already working on the relevant systems in advance development.

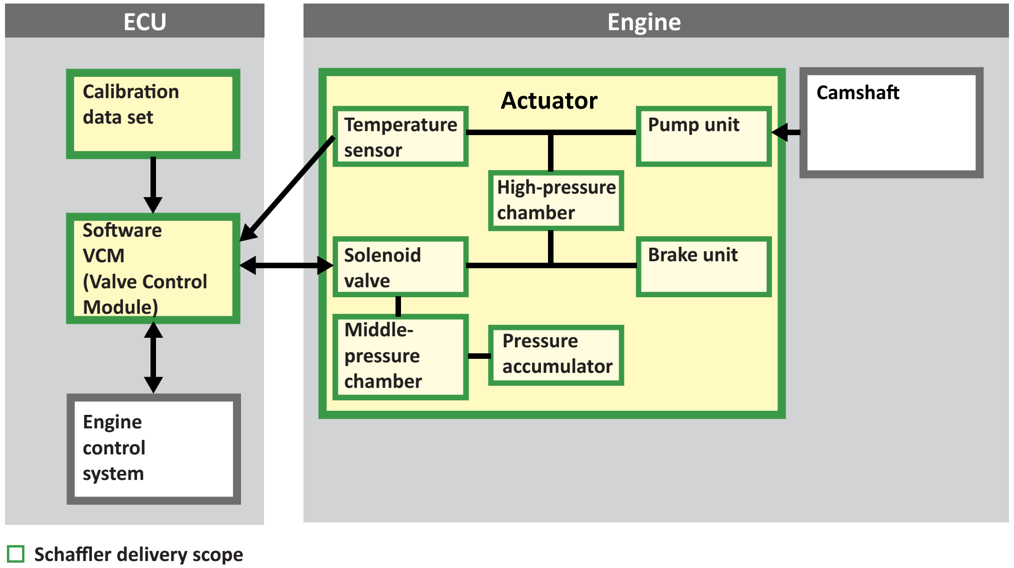


Figure 16 UniAir system operating sequence

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