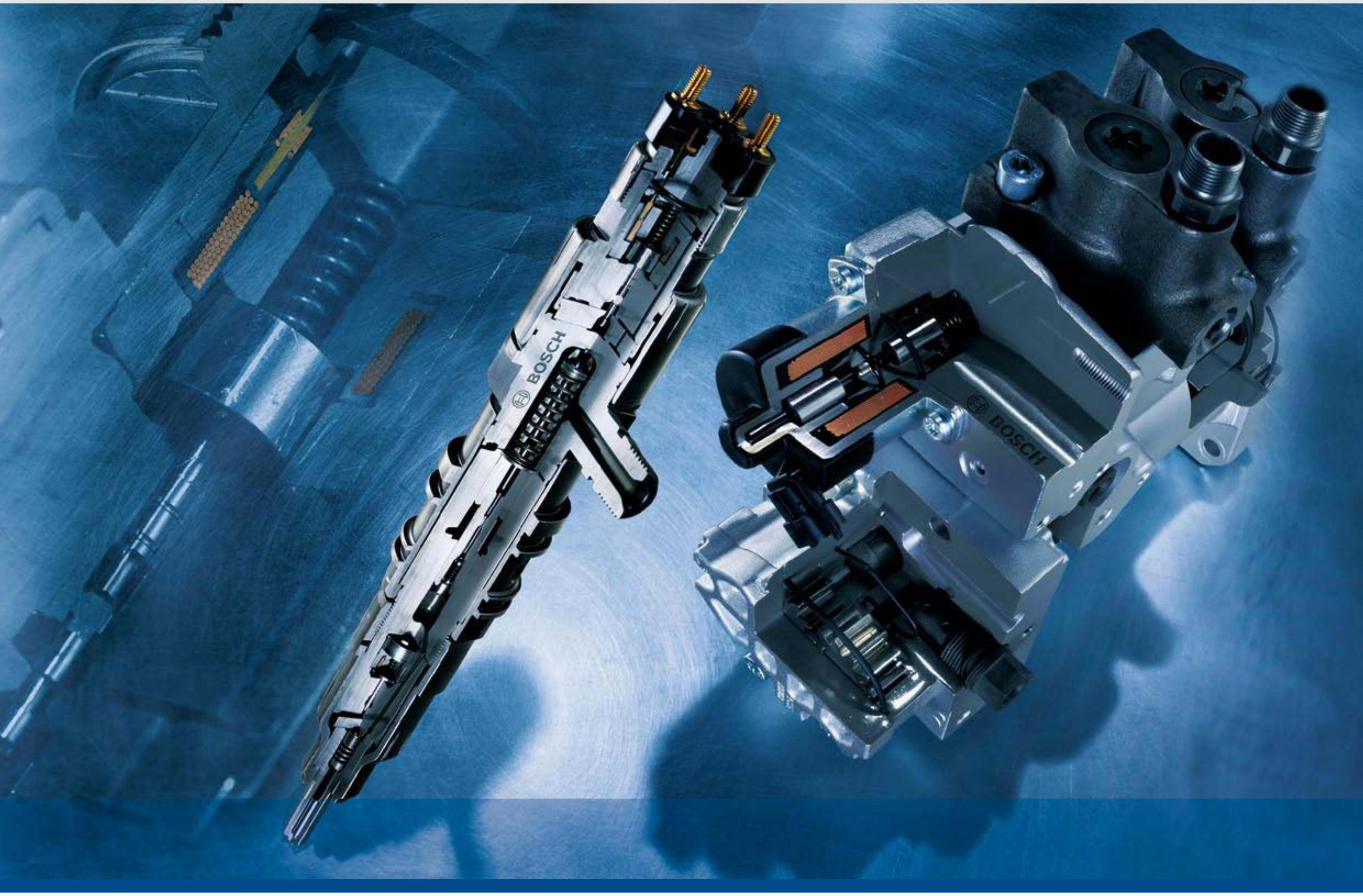

Pressure-amplified Common Rail System for Commercial Vehicles

The key to a successful layout of a combustion system for commercial vehicles is in the management of peak torque operation points. For this purpose, Bosch has enhanced its Common Rail System with increasing degrees of freedom – i.e. with flexible rate shaping. A second solenoid valve activates a pressure-amplifier inside the injector, an optimized offset of nozzle needle timing reduces the injection rate by half right at the start of injection, and the formation of nitrogen oxide is reduced considerably. This enables the engine manufacturer to adhere to the emission limits while further reducing fuel consumption and the engine-related effort for the air sytem.

1 Introduction

With the introduction of the future emission levels US10/Euro6 for heavy duty engines, the Unit Pump/Unit Injector Systems today still used in many applications will increasingly be replaced by Common Rail Systems.

The main driver for this is the use of exhaust gas recirculation with all relevant combustion systems. Engines using this system have to be able to handle injection pressure peaks at part load, and this can only be implemented in a hydraulically efficient way by using a rail as pressure accumulator.

The product portfolio of Bosch offers two variants of Common Rail Systems to facilitate combustion at operating points with high load. The system „CRSN3.3“ offers the freedom of fully flexible multiple injections.

It is used for combustion systems with high boost in combination with high exhaust gas recirculation rates. At present, for adaptation to the specific engine requirements, the injection pressure can be configured at a range of 2200 to 2500 bar, **Figure 1**.

The pressure-amplified system „CRSN4.2“ offers the possibility to select the injection rate in a flexible way at start of injection, thereby reducing the formation of nitrogen oxide in the area of the NO_x-sensitive engine map. **Figure 2** below shows an example for this application. At the same peak pressure of a conventional CRS, the pressure-amplified system utilizes the advantage of a lower NO_x emission for a reduction of the fuel consumption during pressure peaks. Additionally, the effort for the air system and for the cooling system can be limited.

While optimizing an engine with the pressure-amplified system, fuel consumption is reduced up to 3.5 % under real load conditions. Projected onto an operating life of four years in European long haul traffic, up to 200 t of CO_2 or 10.000 € of fuel costs, respectively, can be saved [1].

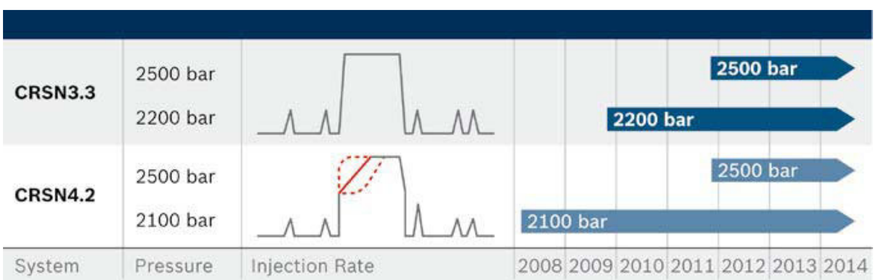

Figure 1: Roadmap Common Rail Systems for commercial vehicles

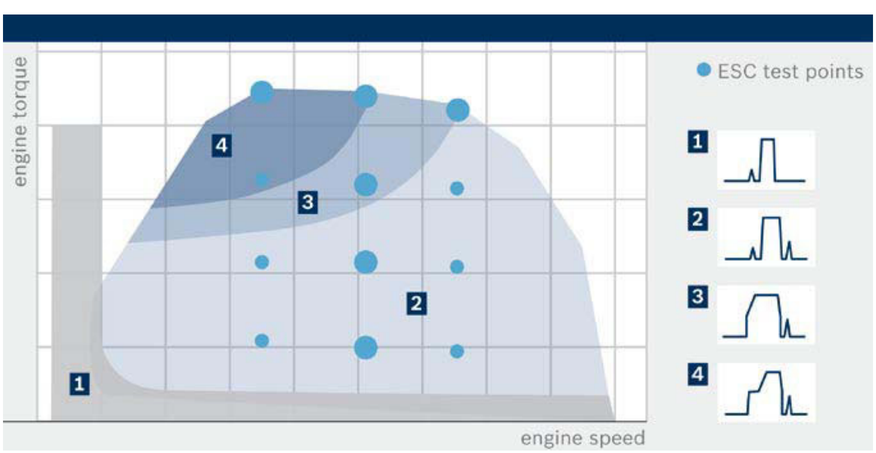

Figure 2: Optimum rate shaping in engine map

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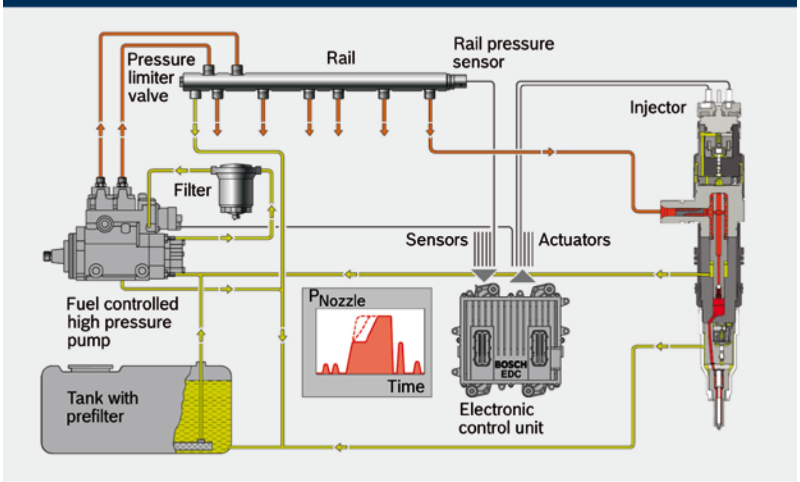

Figure 3: Injection system „CRSN4.2“ with pressure-amplified injector

2 System Design

The basic design of a pressure-amplified system, **Figure 3**, consists of the known components/functions of a CRS, like:

- fuel delivery by high pressure pump
- pressure accumulation and dispersion onto cylinders in rail
- fuel injection in injectors.

When compared with conventional CRS, a major distinguishing feature is the way the function "pressure generation" is divided into two stages in the system. During the first stage of pressure generation, the high-pressure pump compresses fuel to 250 to 900 bar. In the second stage, fuel is compressed up to 2100 bar by a pressure-amplyfier integrated in the injector. The pressure amplification is controlled by a separate solenoid valve.

When a system configuration with pressure amplifier ist chosen, it offers the following advantages for the development of modern engine concepts:

- flexible and hydraulically efficient rate shaping for optimized fuel consumption during pressure peaks
- pre-injection/post-injection with a rail pressure of ≤ 900 bar reduces the spray momentum, the wetting of the cylinder liner walls with fuel and the subsequent dilution of engine oil with fuel
- reduction of number of injector parts affected by peak pressure; Pump and rail as well as high-pressure lines only have to be designed for a pressure of up to 900 bar.

An important driver for the maximization of lifetime of an exhaust gas recirculation system is that any contact between engine oil and fuel is avoided. For the pressure-amplified system, the drivetrain of the pump, usually lubricated with engine oil for commercial vehicle appications, is lubricated with fuel instead.

A rail in the length of a heavy-duty engine is designed with the following advantages:

- reduction of variants of high-pressure lines to one third
- compact packaging of lines
- reduction of pressure oscilliations in the rail injector lines
- reduction of vibrations in rail and lines through a ridgid connection.

3 The Injector of the Pressure-amplified System

As a result of the tasks and requirements they have to cope with, 4th generation injectors for commercial vehicles are substantially different from their predecessors regarding functionality and design. The concept of a pressure-amplified injector was implemented by a reduction of the original injector to a fraction of the size know for heavy duty CRS. More precisely, that part of the injector was minimized, which is responsible for the injection function and for the control thereof by means of an electronic actuator. This was necessary in order to make room for an extended range of functions.

The miniaturization was accomplished with a newly developed pressure-balanced 2/2-way solenoid valve, which is directly connected hydraulically to the nozzle needle. In combination with the nozzle module (already used in Bosch 3rd generation passenger car injectors), one gets a compact and highly dynamic "injection module" with the complete functionality of a classical injector, **Figure 4**.

The concept of a modular structure with numerous advantages resulting from it has altogether shaped the design of the 4th generation, **Figure 5**. The now increased functionality of the separately selectable pressure amplification has also been depicted in modules: one "pressure amplifier" and one related „control module".

The pressure-amplifier module is used for the actual generation of high pressure inside the injector. The principle of

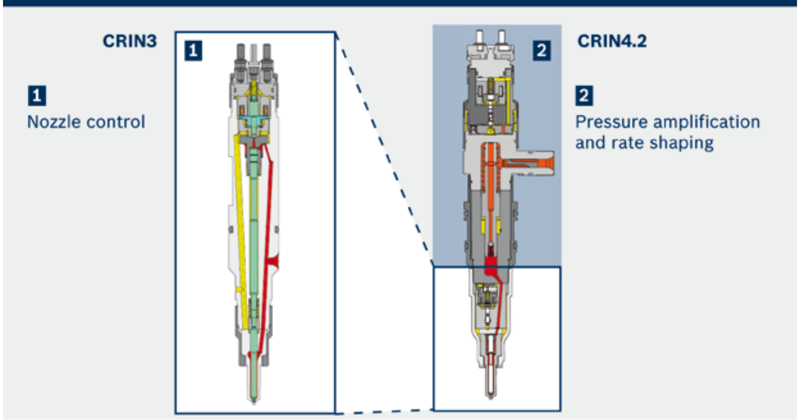

Figure 4: Transformation of the conventional nozzle management in the injection module of CRIN4.2

function is that of a hydraulic piston: Via a surface ratio a lower fluid pressure, in this case the system pressure in of rail, is amplified to a higher pressure beneath a smaller surface. This means the ratio of these two surfaces to each other determines the factor of pressure amplification. This static (i.e. geometrically defined) pressure-amplification rate in connection with a system pressure that can theoretically be scaled freely within a CRS, makes it possible that all ranges from minimum to maximum pressure within the engine map can be realized.

This means, depending on the relevant goal, the ratio of the pressure-amplifier can be adjusted to achieve the optimum result between injection pressure and hydraulic efficiency. The functionality "pressure amplification" is designed as a separately selectable option so that the injector can be used both in the pressure-amplified and in the unamplified mode. This distinctly sets itself apart from alternative solutions, which directly connect the activation of the injector with the pressure-amplification. This freedom (of using the injector in both modes) was achieved with the development and integration of another module for the 4th generation injector: the so-called "control module".

The movement of the pressure-amplifying piston is prevented or activated, respectively, depending on whether the relevant point in the engine map requires "only" rail pressure or pressure-amplified fuel injection instead.

The control function is implemented by means of a specifically for this application newly developed directly controlled 3/2-way solenoid valve. If the valve is triggered, the control chamber of the pressure-amplifier is decoupled from the rail pressure and is short-circuited to the fuel return line. Once the hydraulic pressure on the control chamber has been released, this leads to excess force on the surface affected by the rail pressure.

The pressure-amplifier piston now starts moving, and the "high-pressure chamber", now exclusively feeding the injection, is closed via a check valve integrated into the piston. This way, the "locked up" fluid is compressed to a higher pressure level. If the fuel is injected without pressure-amplification, due to a balance of forces and supported by spring force, the pressure-amplifying piston remains in its position at the upper end. This means, the spring is not only responsible for supporting the reset but also for ensuring that the piston is always in the same initial position when the system is started. The fuel then flows with unamplified injection pressure through the pressure-amplifier piston and through the open check valve to the nozzle. The real strength of the 4th generation injectors can be explained when combining the aforementioned function options, supported by the modular design: the decoupling of the function blocks "injection control" and "pressure-amplification control". This facilitates flexible rate shaping. Not only can the customer select between unamplified and pressure-amplified injection – also the point in time when the pressure-amplification is to start can be selected independently of the beginning of the injection. The rate shapes named "Boot", "Ramp" and "Square", **Figure 6**, in connection with the feature "multiple injections" offer engine developers further possibilities from the optimization of combustion to a reduced fuel consumption, improved emission rates and an increased specific efficiency. At the same time, the adaptation of different applications e.g. to regional legislation based on different emission laws can be accomplished more easily due to this system freedom.

There are further advantages that have not been described before: By integrating the pressure-amplification into the injector, only those components in the "bottom" half of the injector are affected by the amplified pressuer. The pump, the lines, the rail as well as the major part of the injector are only affected by the standard rail pressure. Since the requirements on the system components are determined by the pressure they have to handle, those parts not affected by higher pressure have to fit for rail pressure only. The implementation of subsequent pressure increases are sim-

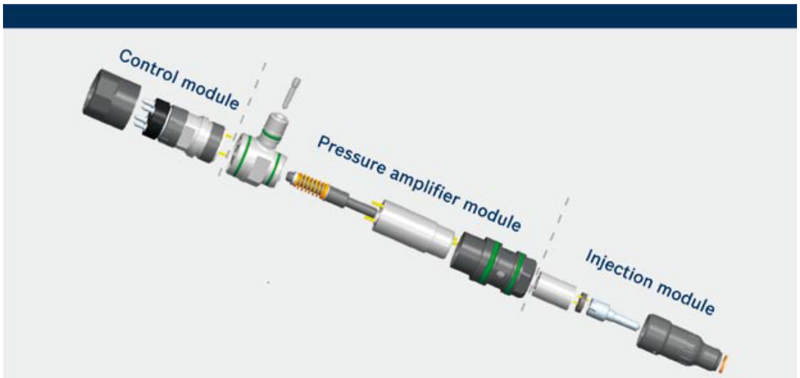

Figure 5: Modular structure of the pressure-amplified injector

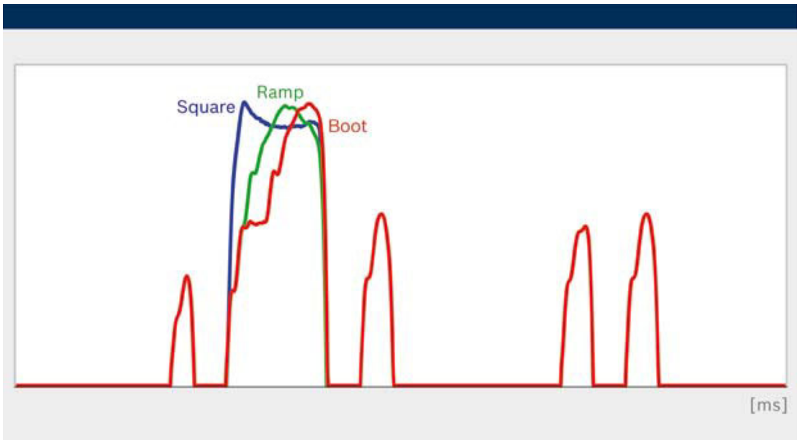

Figure 6: Variants of multiple injection and rate shaping

plified considerably. Production and series maintenance profit from the modular structure of the injectors, since function tests and debugging can be carried out on each module individually.

4 The High-pressure Pump Family

In the first stage of the two-stage high-pressure generation process, the „CPN5-9/2" (5. generation – 900 bar and two pistons) – a pump of the „CPN5" pump family – is used. By the evolutionary development of the basic design, this pump concept is capable to cover the increasing system requirements of future Common Rail Systems. With identical or even reduced pump weight, the hydraulic power can be increased distinctly, **Figure 7**.

The „CPN5" pump family is based on an inline pump concept. Compared to other pumps in this power segment, this type is lubricated with fuel instead of engine oil. The drivers behind this fundamental switch were the increasing demands of emission legislation, in particular regarding soot.

While oil-lubricated types require a considerable effort to minimize leakages along the pump piston, the fuel-lubrication facilitates a perfect separation between oil circuit and fuel circuit. With the implementation of constructive manufacturing measures, an impact on robustness caused by lower fuel lubricity is avoided. The buildup of the lubricating film between those parts moving relatively against each other is specifically supported by design features of those components and their environment. For the cam drive e.g. a roller shoe concept is used which has been derived from the „CP4" – the pump that has already proven itself successful in newer common rail pumps of passenger cars, light duty and heavy duty systems. Furthermore, friction-minimizing coatings as well as special bearing material are also used to meet the requrirements of variing fuel qualities.

The „CPN5" pump family is characterized through its modular design. Using adequate combinations of cam numbers, piston diameter and piston lift as well as a transmission ratio suitable for the engine speed, volume and pressure ranges from 250 l/h at 2500 bar up to 520 l/h at 900 bar can be covered.

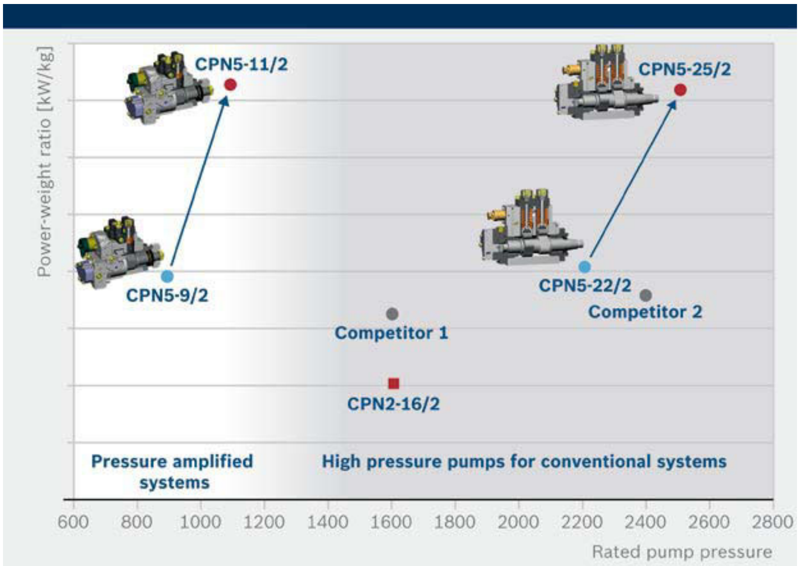

Figure 7: The „CPN5" pump family

In particular the selection of a suitable combination of speed ratio to the number of cams can support the adherence to narrow injection tolerance limits. By using adequate combinations, the delivery stroke of the pump elements is either synchronized to the fuel injections or each individual injector is always assigned to the same pump element. This so-called injection-synchronous or element-synchronous delivery ensures that the influence of a strewing rate shape on the injection quantity tolerance is minimized from injection to injection. The described modular structure of the „CPN5-9/2" pump generation can best be depicted by the example of **Figure 8**.

The fuel is pre-delivered by a gear pump, which is integrated into the pump housing. The fuel delivery is controlled by the solenoid valve of the measuring unit. Depending on the combination chosen and the drivetrain ratio, two or three loads per pump element are located on the camshaft. The barrels with its pistons consist of steel and are mounted as one unit into the aluminum pump housing.

Also in the commercial vehicle sector the demands on noise emissions are gaining importance. Corresponding demands on the injection system are derived of this. Apart from measures to optimize the combustion noise, there are growing demands regarding measures to reduce

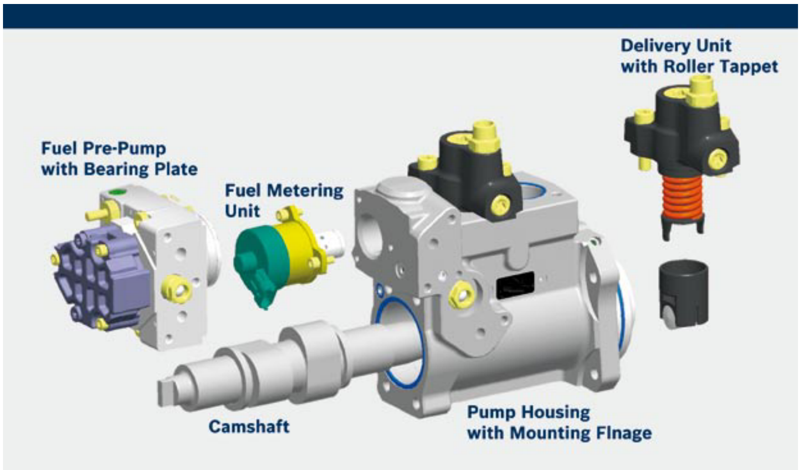

Figure 8: Assembly of a „CPN5-9/2"

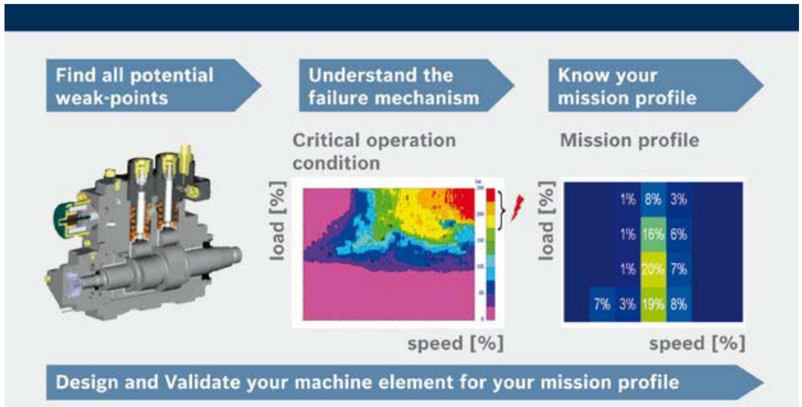

Figure 9: Quantitatively Accelerated Life Testing (QALT)

noise emission of the components of the fuel injection. One of the dominant noise sources is the pressure generation inside the pump. The growing demands for higher pressure levels and the increasing energy consumption resulting thereof ensure that these newer pump generations are more sophisticated.

The dynamic of the piston movement is a major influence factor on the noise emitted by the pump. One oft he dominant noise sources of the high-pressure pump itself is the moment when during delivery the piston comes into contact with the "locked up" and compressed fuel in the element room. Regarding the noise emission of the entire system, the effective torque in the drivetrain of the pump is a major factor. This torque puts the drivetrain under a pre-tension, and causes the characteristic "ratteling noise" when the tension is released and the metallic drivetrain components hit on each other. The same effect is caused by backing torques.

The transmission of these exitations to the gearbox of the engine and the resulting amplification of this noise due to the "loudspeaker effect" of the engine components elevate this parameter to the central factor of the hydraulic system that has to beoptimized to achieve optimum noise emissions.

The best results can be obtained by a suitable design of the camp loop geometry to reduce torque fluctuations. Combined with damping measures on the coupling elements between the drivetrain and the gearbox, the noise level can be reduced significantly.

5 Validation Strategy

Due to the high lifetime requirements of 1.2 million miles in combination with a very tight project schedule, the demands on the validation efficiency of components and of the entire system have become more and more important. In view of this background, a new and optimized validation strategy has been worked out and implemented.

The previous validation concept, with its runtime-intensive endurance tests, usually only detects the weakest part of each product. This results in a high number of necessary iterations. The new validation is focused on the lifetime-sensitive assemblies and machine elements of the products and their specific testing. The assemblies to be tested are determined making use of experience with similar assemblies or of theoretical considerations i.e. calculations. The so-called HALTs (Highly Accelerated Life Tests) play a major role in it. During these tests, critical factors, for example temperature and pressure, are gradually increased to detect machine elements "reacting" on these parameters.

In the next step, the load collectives are identified under real life conditions in close cooperation with the engine manufacturer. Based on these load collectives, so-called QALTs (Quantitative Accelerated Life Tests) are defined. This way, targeted, component-specific accelerated tests can be performed under critical conditions correlating with lifetimes in the field, **Figure 9**.

The modular structure of the products used supports this concept. It facilitates the accelerated optimization and validation of various assemblies and machine elements in parallel. Long lasting endurance tests are only performed with "mature" products to verify the trouble-free interaction at the different component interfaces. Particular importance is placed on the testing of the products under real life conditions. Therefore, the test benches have been modified in such a way that the use of cylinder heads and of the entire lower pressure circuit became possible.

The high quality standard of the recently started series production confirms impressively the effectiveness of this validation strategy.

6 Prospect

Preliminary investigations demonstrates, that further development of conventional combustion methods for commercial vehicles with the target to improve fuel consumption is possible. A major element of this measures package is a futher increase of the injection pressure.

Based on the features described before, the „CRSN4.2" with its pressure-amplified injector is ideally suited for another pressure increases. The evolutionary development of this platform for pressure levels up to 2500 bar as well as of for the platform for conventional fuel injection systems, with one-stage pressure generation, has already been started. This means all application-specific customer requirements can be fulfilled. In order to be able to respond to future requirements for even higher pressure levels, Bosch already conducts research for target pressure levels of up to 3000 bar.

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