LITERATURE REVIEW ON STABILIZING HIGH SPEED VALVE- AND DRIVETRAIN CONCEPTS FOR RACING APPLICATIONS

Internship at the engine development department of Audi Sport

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Introductory remarks

In the summer season of 2016 I was allowed to do a six month internship within the research department of Audi Sport in Neckarsulm Germany. A dream came true after Le Mans 2015 when I offered my curriculum vitae to Mr. Baretzky, head of the engine department of Audi Sport. I want to thank him deeply for giving me the opportunity to be part of his team.
Moreover, I want to thank Prof. Dr. Ir. A. de Boer of the University of Twente for the great support during the internship and for his flexibility before the start of the internship.
A very special thanks goes to Dipl. -Ing. S. Wohlgemuth of the engine research department of Audi Sport for sharing his great knowledge, passion and support.

“There is no such thing as cam design, there is only valve lift profile design which requires the creation of a cam and follower mechanism to reliably provide this designed valve lift profile.”

G. Blair, 2006

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1. Introduction

It is expected that the cumulative energy consumption for global transport sector increases by 0.2% each year to reach an approximated total of 15.2 trillion kWh (Bin Mamat, 2015). Considering the declining fossil fuel reserve and the climate change that currently is taking place there is a need of finding more sustainable automotive solutions.

Automotive manufactures are therefore mainly focusing on downsizing and down speeding engines. Besides the fuel efficiency and therefore the CO_2 emission also the greenhouse gas emissions of street legal vehicles on mandated test cycles have been improved largely in the last decade (Taylor, 2016). Downsizing engines can effectively being done by compressing intake-air, e.g. by using turbochargers or superchargers. Combined with direct injection strategies many manufactures successfully replace their engines by smaller ones, while maintaining the same or even better performance.

Even in motorsports the fuel economy and the produced emissions are of large importance. This can for example being witnessed in the Le Mans Prototype series (LMP) for some time. However, also the Formula 1 (F1) series also entered a new era focusing on the fuel economy back in 2014 (Bengolea, 2016). Moreover, the governing body “Federation Internationale de l’Automobile” (FIA) encourages using hybrid powertrain technologies in both series.

Therefore it is no surprise that the Deutsche Tourenwagen-Masters (DTM) will be moving towards more fuel economic and CO_2-friendly concepts as well. The auto sport organizations “ITR” (Germany), “GTA” (Japan) and the “IMSA” (USA) are developing new common regulations. Stefan Ziegler mentioned in 2015 that smaller two liter turbocharged engines with 600 horsepower will become the new standard in 2018, compared to the naturally aspired V8 engines used nowadays. This racing-concept will be called “Class 1”.

The aim of the following paper is to evaluate available high-speed valve train concepts for the new Class 1 motorsport engines. Concept wise the engines in this class will be running up to 9000 or eventually even 9500 rpm, which is rather high compared to street legal vehicles. Only high end super cars reach similar values (e.g. Audi R8 V10 with 8,700 rpm, Ferrari 458 Speciale with 9,200 rpm). Therefore engineers have the task to cope with mechanical problems like excessive deformation of engine components due to the high engine speeds and accelerations.

The focus in the following text lies on valve train concepts, including the cylinder head, camshafts, valves plus attachments, gears and their bearings. The pistons, crankshaft, conrods and their bearings are critical components in the mentioned motor concept as well, however they will not be evaluated here. Moreover, only non-variable valve train systems are reviewed.
This document refers to multiple Cosworth and Honda Formula 1 sources. The reason being the extreme high revving engines back in the V8-era, also known as ‘The Era of Speed’.

2. Spring actuated valve train concepts

It can be said that the cylinder head is the connecting element of an internal combustion engine. Here the charge cycle of the engine is controlled up to a large extend by opening and closing the intake- and exhaust valves. As the name states it forms the upper part of the cylinder. Moreover, it houses multiple oil- and water channels and in motorsport it often is part of the carrying structure of the vehicle (Trzesniowski, 2014).

The main focus of this literature review will be on technologies that reduce mechanical losses and deal with oscillating accelerations. Both the friction as the vibrations increase quadratically while increasing the engine speed (Kondo, 2009).

This report will start with listing the general valve train principles, as mentioned in the introduction only non-variable valve train concepts are reviewed. The following text will be divided into two parts, namely the overhead valve (OHV) and the overhead camshaft (OHC).

One may notice that flathead engines (Turner, 1984) also known as L block or side valve engines are not listed. Even though this engine has its advantages, like being simple, reliable, insensitive to low octane fuel, cheap and compact it shows that it is not a compatible engine in race series nowadays. Some reasons for the weak performance of this engine type are: very poor gas flow, deficient combustion chamber shape and a mediocre compression ratio (Ballard, 2002).

2.1 Overhead valve (OHV)

Most overhead valve engines do have one camshaft actuating both the intake as well as the exhaust valves, since the packaging simply does not allow for a second one. Generally spoken two concepts are being used. On the left in **Fig. 2-1** a pushrod is being used to mechanically link the lifter at the camshaft to the pivoting body. These bodies, called fingers or rocker arms, act on the stem of each valve. This traditional set up is still being used for the 5,86 liter Nascar race engines (Trzesniowski, 2014). Where they reach up to 645 kW at 7200 rpm. However, the reliability is rather poor since a new engine is needed every race. On the right of **Fig. 2-1** the lobe of the camshaft directly actuates the rocker arm. It holds for both principles that the potential energy stored in the valve springs is used to provide the return force once the lobe rotates away.

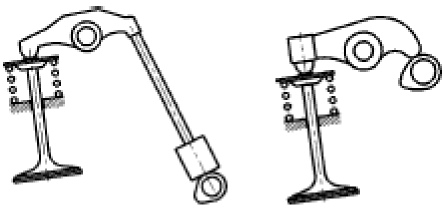


Fig. 2-1 Overhead valve concepts (Trzesniowski, 2014)

2.2 Overhead camshaft (OHC)

The overhead camshaft principle makes use of either one (SOHC) or else two camshafts on top of the valves (DOHC). This can be done by directly locating the camshaft on top of the valve using bucket tappets/lifters (**Fig. 2-2** left) or by using additional pivoting bodies (**Fig. 2-2** right).

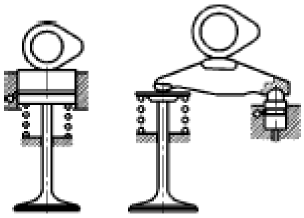


Fig. 2-2 Overhead camshaft concepts (Trzesniowski, 2014)

2.3 Comparison

When comparing both concept and focusing on high engine speeds it can be said that the OHC concepts are preferred. The rotating and translating masses are significantly larger for the OHV engines. In case of the pushrod concept also buckling, large deformations and low end Eigen frequencies can occur in the long and slender body, especially in the higher engine speeds.

Another advantage of OHC engines is that the number- and the area of the valves is not being limited by the pushrods. This allows for increasing the engine's volumetric efficiency or for enhancing the gas-air mixture by fine-tuning swirl and tumble parameters. Even though this document does not consider variable valve train concepts it can be said that they can be incorporated in OHC engines more easily.

A downside of the OHC cylinder heads is its packaging, placing the cams above the valves increases the height significantly. Besides enlarging the packaging it will also lift the center of mass (CoM) of the engine, which is undesired considering the handling of the vehicle.

Even though the OHC engine generally has fewer parts it tends to be more expensive. Mounting the cam(s) in top of the valves also complicates the lubrication system of the engine. A lower placement as in the OHV allows for lower oil pressure and a less complex cylinder head. Moreover, the distance between the crankshaft and the camshaft(s) is rather short for an OHV engine. The OHC engines require longer belts/chains or more gears to overcome this distance, which can possibly lead to increased unreliability and to a higher maintenance need.

Conclusively, it can be said that the OHV needs less components that are related to overcoming the distance between the crank- and the camshaft(s). On the other hand it increases the number of components considering the valve train itself. The additional flexibility inside the components and rotating/translating mass that come with the OHV principle make it an unsuitable concept for high speed (race) engines. The LS7 engine of General Motors sets the benchmark for high end OHV serial production street engines with having its red line at 7,000 rpm using hollow chrome moly pushrods (Chevrolet LS7, 2016). The target for class 1 vehicles is set at 9,000 up to 9,500 rpm, considering the top end tuning and maximizing engine power, therefore only OHC engines are considered in the following text.

3. Valves, fingers, rockers, valve springs

Sakurahara (2009) mentions that Honda in their Third-Era Formula 1 activities mainly focused on stabilizing the valve train by reducing its weight to obtain a reliable high speed engine. Moreover, they give much importance to increasing the durability and reliability of the reciprocating system. The following chapter focuses on reciprocating systems, including the intake- and exhaust valves, fingers, valve stems and tappets.

Honda did change its F1 engine designs from a conventional direct-driven system using tappets towards a rocker arm driven system. Besides stabilizing the valve train Honda did choose for this concept to be able to increase the valve lift, since that was limited by the lifter bore in the direct system (Kondo, 2009). The diameter of the valve stem is decreased and simultaneously the material of the valves has been changed from titanium into a titanium-aluminum alloy to reduce the weight even more.

Beside the mechanical strength- and stiffness parameters also the tribological behavior is important, especially for sliding contacts under high contact pressures.

3.1 Fingers or rocker arms

Fingers or rockerarms are, as mentioned previously, commonly seen in racing engines. Mainly, since the reciprocating weight is decreased and it allows for higher valve lifts with the same or even smaller camshaft lobes, due to the lever arm. Regarding friction this system has an advantage over direct-driven systems. The frictional behavior can be further enhanced by adding roller bearings at the cam-finger or finger-valve stem contact (**Fig. 3-1**). However, these parts come at extra weight and are not reliable when considering high engine speeds. Hence, set ups with rollers are mainly found in production engines instead of racing engines.

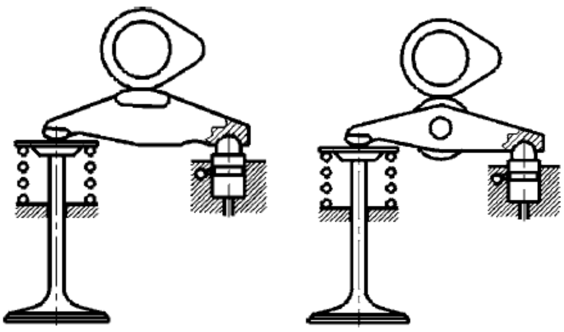


Fig. 3-1 Valve actuation using rocker arms (Trzesniowski, 2014)

Having a high ratio rocker arm does not only require less cam lobe height but also leads to a more linear behavior at the tip of the rocker arm, since the radius is larger. This directly results in reduced side loading. Moreover, the wear and friction on the valve stem are being decreased. Therefore, Nascar engines are having rocker arm ratios of 2:1 or higher. Bearings are needed on shaft mounted valve fingers, this can either be done by sliding contacts and a lubrication film (hydrostatic bearings) or with rotating bodies e.g. needle bearings.

In **Fig. 3-1** the classical stud mounted rocker arms. However, combined with higher engines speeds the stability of this valve finger mechanism is rather poor. Nowadays, race engine developers tend to use shaft mounted setups. Besides stiffening the valve train it is also possible to use the shaft as a lubrication transport towards the contact surface. Shaft mounted rocker arms allow for easier adjustment and increased reliability since it is not side loaded as much as the stud mounted ones.

Considering fatigue strength and stiffness properties it can be said that steel rocker arms are preferable over aluminum ones. However, building the valve fingers as light as possible is an advantage in terms of valve train dynamics and friction, especially at high engine speeds.

Cody Mayer at CompCams states that stamped steel rocker arms are suitable for street use. Cast aluminum ones as a low cost upgrade and extruded rockers eventually with rolls are an option for racing engines. Aluminum has a dampening effect. However, the downside of aluminum is its mortality rate. Cast steel valve fingers do represent a durable solution for racing engines, since they exceed the stiffness and moment of inertia characteristics of other rocker arms (Carley, 2011).

According to Trzesniowski (2014) Diamond Like Carbon (DLC) coatings applied on the valve fingers of many racing engines. This thin layer minimizes both wear and friction at the sliding surface. A DLC coating is about five micrometers thick and has a Vickers-hardness of about 3000 HV. The surface to be coated has to be polished to prevent extreme abrasion on the counter surface. A DLC coated steel part in a sliding contact with an uncoated steel part does have a friction coefficient of around 0.1. This value can be bisected when coating both surfaces.

Bamsez (2013) from Cosworth also claims that finger followers contain a friction and stiffness advantage over bucket tappets. Moreover, they allow more aggressive cam lobes with higher lift values. Bamsez remarks that even with a DLC coating and an oiled surfaced some signs of wear are present after an engine-lifetime on their CA F1 engines. Wood states that it would be possible to run the engine with a DLC coating on the fingers only. However, they also coated the surface of the cam lobe to gain power by reducing friction. Cosworth uses the same coating on both surfaces, whereas others use differing materials in terms of hardness.
Honda started using the so called DLC coating for its camshafts and rocker arms back in 2002. The DLC coating effectively reduced wear and friction (Hoshi, 2009).

3.2 Valves

In general poppet valves are used to control the gas exchange cycle in an internal combustion engine. This implies that the timing, the quantity and for some cases also the turbulence of the gas or vapour flow are regulated by the intake- and exhaust valves. This literature review only considers poppet valves. These valves are usually applied in the automotive industries, mainly since they do not slide over the seat as slide- and oscillating-valves and therefore do not require seat-lubrication.

Poppet valves are usually a disk of metal with a slender shaft, also known as stem. An overview of a poppet valve can be found in **Fig. 3-2**, in this figure a free body diagram of the valve is given as well. The stem is pushed down by the camshaft to open either the intake or exhaust port.

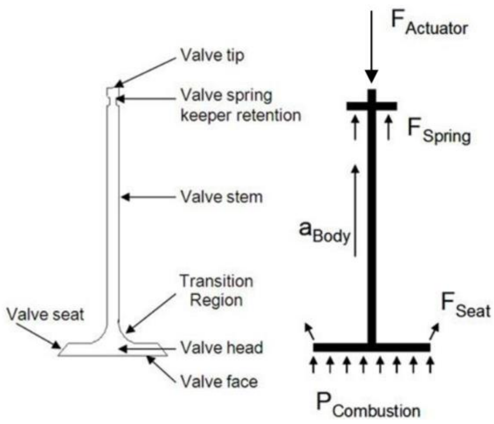


Fig. 3-2 Poppet valve and its free body diagram (Black, 2009)

Honda mentioned in 2009 that optimizing the valves diameter size for the given cylinder bore diameter had priority, however they also took the piston speed and the gas flow into account.

The intake valves do have a larger diameter compared to the exhaust valves, since the exhaust gas is forced out of the cylinder by the movement of the piston. Especially the thermal load on the exhaust valves is significant. On the intake side of the engine the colder intake air cools the temperature of the intake valves. Whereas the combustion gasses heat the exhaust valves. In most engines it can be seen that the material choice for exhaust valves (e.g. Chrome-silicon steel) is superior to that of the intake valves (e.g. Chrome-nickel steel).
The heat produced by the combustion with oxygen is transferred from the head of the valve to the through the stem up to the tip by conduction. To enhance the heat transfer sodium or natrium filled valves are used on production cars as well, since this material melts within the stem and therefore allows for heat convection besides the regular conduction.

Valves in racing engines are exposed to even higher temperatures, reciprocating accelerations and cylinder pressures. Moreover, there is a substantial risk of having so called floating valves when operating engines at higher speeds. Generally, it can be said that if the direct contact between the cam and the valve is lost, either via a tappet or else via a rockerarm, then one could speak of a "floating valve". This phenomenon can be seen when the inertia force including oscillations exceeds the available spring force (Ajay, 2014). In this case the valve does not obey the targeted timing and lift, since it does not follow the profile of the lobe of the camshaft. This valve behavior may lead to piston-valve collisions, decreased volumetric efficiency since the valves are not closed at the combustion start. Moreover, valves can be overheated and the camshaft can be damaged severely when the valve bounces back with excessive speed.

Multiple solutions to the floating valve problem are mentioned in literature (Trzesniowski, 2014) (Bamsez, 2013) (Ballard, 2002). The most obvious method is using stiffer spring(s). However, this has major drawbacks since it will increase the contact pressure at the surfaces the cam lobes, valve stems and rockerarms/tappets. Due to this increased contact pressure also the friction, wear and hence the temperature incline, leading to reliability problems and reduced engine power.

As in a regular mass spring system one has also the option to vary the mass of the valvetrain components. Hollow valve stems allow for mass reducing (Dark, 2004). Besides weight advantages also the thermal behavior can be optimized by modifying the medium inside hollow valve stems. Cosworth used exhaust valves with 60% sodium fill on their 20,000 rpm F1 engines (Bamsez, 2013), whereas other manufactures use natrium filled valve shafts. Drilling a 3mm hole in the 6mm stem from the top of the valve makes it possible to fill the valve. An intermediate plug is press fitted inside the valve and a second plug is welded on top to seal the valve. The sodium conducts heat more effectively than the surrounding material. Care must be taken when using filled stems, since the transferred heat can cause problems elsewhere. Cosworth for example reports that the heat transferred to the valve stem caused a seal failure in the PVRS system (see chapter **'Pneumatic valve return system'**).

Decreasing the valve's weight will improve the inertia of the system and may prevent floating valves. This is more advantageous than increasing the spring constant regarding friction and inertia properties. Considering durability as well one could say that the development focuses on materials with a high specific stiffness and high-temperature fatigue strength (Kondo, 2009). For an example see **Appendix A**. Trzesniowski states that a lot of valves for production cars are made of Chrome Mangan Nickel steel. In the following text more advanced valve materials are being considered. However, one has to keep in mind that not only the material but also the design and the production process are of great importance, according to the DPM-Triangle (Design-Production process-Material).

Light weight metals

Inconel, a brand name for a high-strength austenitic nickel-chromium-iron and is sometimes being used for exhaust valves. The high temperature behavior of Inconel is advantageous over plain steels, especially in terms of deformation resistance and surface stability. Inconel 751 exhaust valves can be found in some racing trucks, however 21-4N is more common.
Multiple race engines are equipped with titanium valves since a mass reduction of 40 percent compared to steel valves can be achieved. However, the main application of titanium valves is on the intake side of the engine, since titanium can cause problems in combination with high temperatures. According to Black and Radford (2009) exhaust valves reach temperatures over 900°C, whereas the intake valve sees approximately 400 °C. Titanium does have inferior high-cycle fatigue performance and therefore needs hardening treatments.

Ceramics

Ceramic (silicon nitride) and ceramic-head valves can be used for exhaust valves in terms of temperature, while reducing the weight compared to their steel counterparts with up to 60 percent. A major drawback of ceramic valves is however its brittleness in combination with the abrupt valve movement in race engines (Trzesniowski, 2014).

Metal Matrix Composites (MMC)

Focusing on decreasing the weight of the engine, and therefore of the vehicle, enhances the research on high performance materials, maximizing stiffness and minimizing weight. I.e. the specific stiffness is an important parameter.

MMCs can also be used to optimize the heat conduction in parts, like in the valves. Other parts where these materials are applied are pistons and connection rods for example, however these are out of the scope of this report.

This search for superior material was the main performance parameter in the F1 around 2000. Multiple teams used titanium aluminide intermetallic as a base material for the valves in their engines, reducing the mass by approximately 50 percent.
For example Honda managed to reduce the reciprocating mass of the valve train from 71.4 g in 2000 to 47.2 g (Kondo, 2009).

The FIA banned MMCs besides intermetallic compounds and magnesium alloys in 2001. Mainly because the cost of these materials and the research on it where extremely high. Therefore, the maximal specific stiffness was set to 40 $\frac{\mathrm{GPa}}{\mathrm{g/cm^3}}$. For the same reason a further restriction in the material choice took place in 2006 (the green area in **Fig. 3-3**) (Kondo, 2009).

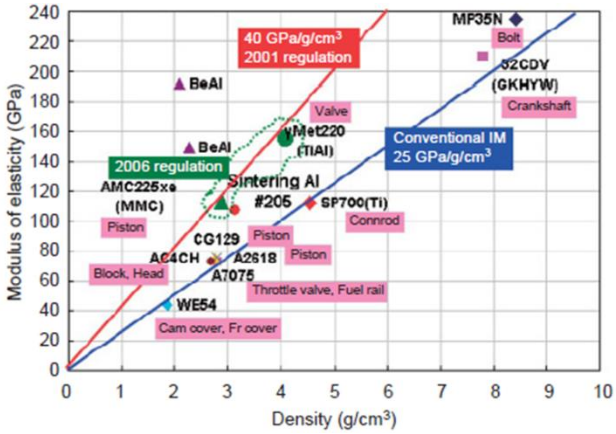


Fig. 3-3 Comparison of multiple materials used in the F1 (Kondo, 2009)

However, since CAE became more involved it was possible for Honda to maintain the same reciprocating mass of the valve train after the change of the regulations. With other words switching back from titanium-aluminum to titanium could be compensated by optimizing the shape in terms of weight (Kondo, 2009).

Composites

In the 1980s carbon composite valves where introduced by NASA's research center in Virginia. The tested valves composed out of a carbon fiber reinforced stem and a ceramic valve head. However, it showed that the bond between both materials led to structural failure.
Researchers are investigating the use of one-piece moulded composite valves to increase the stability of the valve train. Resin Transfer Molded (RTM in the following text) fiber reinforced valves are being used (Black, 2009). A high temperature resistant matrix material called "PETI-RFI", that is developed by NASA and Naval Air Warfare Center will be used for this purpose.
The valves stem is build using a two-layered braided carbon filler tube of 6.4mm in diameter with 60 percent axial unidirectional tow for axial bending resistance. The valve face composes out of two plain-weave fabric disks that are designed such that they can withstand the bending loads. The total mass reduction compared to a steel counterpart as large as 80%. The matrix does not exceed a thermal degradation of 5% over a century at 250°C. Moreover, it can withstand peak temperatures of 425°C, however there are no manufacturers racing these valves yet.

3.3 Valve springs

The main function of the conventional valve spring is to ensure a continuous contact between the camshaft contour and the valve. I.e. a controlled opening and closing of the valves should be guaranteed, this may be indirect over valve fingers. The spring's design is influenced by the maximal engine speed, durability, the cam lobe contour, the available installation space and the dynamic properties of the reciprocating- and rotating system. According to Trzesniowski (2014) maximally 16,000 rpm are achievable using conventional valve springs regarding 'floating valves', however this requires a complex valve train concept. Moreover the Eigen frequency of the entire valve train should at least be higher than the highest camshaft speed, which is half the engine speed.
As mentioned previously, the characteristic curve of the valve spring should be as low as possible to reduce contact pressure. This will lead to minimized power loss and enhanced engine reliability. However, it still has to fulfill its main function, namely preventing 'floating valves'.
Shape optimizations are needed to diminish the spring's weight. Varying the spring's inclination or wire- and coil diameter over the length are commonly used solutions in motorsport engines (Ballard, 2002).
Bamsez (2013) states that back in 2002 Cosworth's XF IndyCar V8 ran 16,000 rpm using wire coil springs, since valve springs where obligated by the regulations.

Increasing the seat pressure, for example adding by a shim, is being done to suppress or shift certain resonances. However, caution must be taken when reducing the fitted length of a valve spring, since the risk of inter-coil clash rises (Dark, 2004).

Youd (2011) states that higher internal stresses typically equals better dynamic performance, on the other hand it also reduces life time.

A higher tensile strength can be obtained by selecting a specific alloy or heat treatment. To enhance the compressive strength shot peening, stress relieving and polishing (removes stress risers) can be applied.
Besides these static conditions also dynamic phenomena are of importance, like surge or impact forces, load loss impact, thermal influences (E-modulus/spring rate and strength properties), interference and damping either designed by the characteristic curve or external

in terms of Coulomb friction. Youd (2011) showed that in Drag Race engines the dynamic stress range is up to 65 % larger than the static stress range. Moreover, it is stated that most heat and friction implications at the valve springs are lubrication related. Whereas oiling does not only fulfill its function as frictional modifier but also as a coolant.

Valve float problems in rocker arm and in tappet driven systems where mainly caused by resonances in the valve springs according to high speed videos and simulations carried out by Buckley (2006). To reduce oscillations in the main spring up to two additional springs are nested inside of one other. These springs are only there to suppress resonances, since they nearly do not affect the stiffness of the main spring.

Alternatively, spring dynamics can be controlled by dampers (Youd, 2011). The frequently most used damper is the so called ‘Ribbon Damper’. Where a flat wire spirals inside the spring, or in case of a dual spring set up it is located between the inner and outer spring. At the contacting surface Rayleigh damping will occur, which is an effective damping mechanism. However, it generates heat and has a higher power consumption.
When having a dual or triple valve spring system it is possible to incorporate an interference fit and leave out the flat wire.

In the NASCAR series conventional single and even dual or triple valve set ups are changed for so called Beehive ones. The weight advantage especially of the retainer but also of the valve spring itself over the cylindrical system is significant. This results in a better revving and more durable valve train. On the other hand it also allows for higher valve lift and more aggressive camshaft contours (Trudeau, 2005).
A teardrop-shaped wire called ovate wire is being used to replace a dual spring set up for a single spring one, while retaining the same performance. The stress concentration at the inside of a valve spring is higher than on the outside. Therefore, the ovate wired springs have more material at smaller diameters (Labore, 2016). Trudenau (2005) tested both a dual spring and a single ovate wired spring set up. Summarized it can be said that a weight saving of 25% is accomplished, the sound production is equal and the Beehive spring is more stable. Moreover, no additional part changes are required to install the beehive springs except for the retainers.
Nowadays one can find conical springs as well, these springs are cone-shaped (Labore, 2016). Where the progressive reduction in spring diameter starts directly at the spring seat and ends at the retainer. Like the Beehive springs lightweight springs and retainers are obtained. However, a conical spring has a much higher natural frequency in contrast to other spring designs. The pitch differs from coil to coil resulting in a progressive characteristic curve. Hence a natural damping effect without heat development, wear and virtual play is integrated.

Obviously, not only the design but also material developments allowed for more durable valve springs with a higher performance. Iron spring wire is being used in multiple alloys, with chromium and silicon being the main elements. Nickel and vanadium are commonly used as well. Blair (2006) states that besides the Cr-Si and Cr-Va steels also stainless steel and titanium springs are being produced.

The production technique is of huge importance as stated in the DPM-Triangle (Design-Product-Material), this holds especially for the ovate wired springs. Labore (2016) quotes Godbold, where it is stated that the cleanliness is a larger variant in the ultimate tensile strength than the chemical makeup. Where the cleanliness of the spring wire refers to eliminating flaws in them.
Concerning the production technique it can be said that reducing surface stresses, increasing fatigue life and minimizing load losses are the main requirements to be fulfilled. Inducing compressive stresses by using multiple shot peening processes releases the stress of the applied tensile load during operation. Eliminating stress risers will enhance the fatigue resistance, which can effectively being done by polishing the wire. Heat treatment processes

minimize, amongst others, the load loss over the spring's lifetime. Valve springs of for example Top fuel and Pro Mod drag race engines do have a nitride coating. Leading to more durability regarding wear and fatigue. Moreover, higher compressive stresses are allowed. Nitriding can also be applied to existing valve springs to increase the spring rate (Labore, 2016).

3.4 Tappets

M. Dark from Cosworth showed in a GT-Vtrain analysis that the stiffness of a tappet in a direct-acting system (DA) is correlated to the valve velocity for a large extend. The valve velocity is sensitive to the damping ratio and the stiffness of the tappet.
In comparison to roller finger followed systems (RFF) it shows that direct acting systems do come with higher friction values (**Fig. 3-4**). Moreover, it can be seen that the friction for the RFF system increases once the surfaces beds in, since the asperities are smoothened and more real contact area is present.

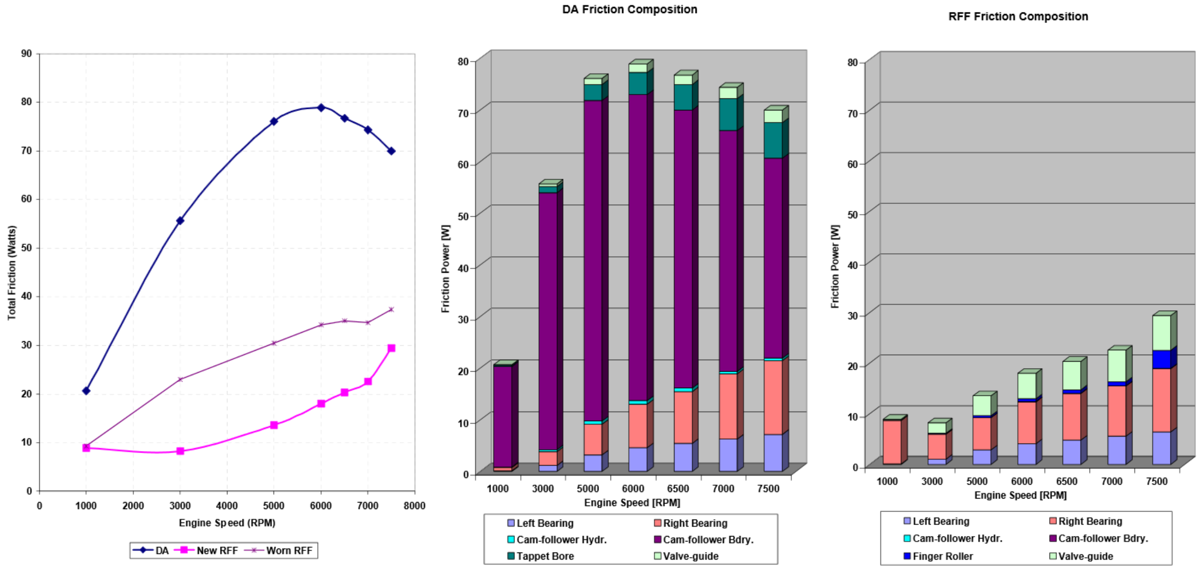


Fig. 3-4 Friction comparison between RFF (worn/new) and DA Valvetrain at Cosworth's (Dark, 2004)

3.5 Valve seats

The valve seats do seal the intake and exhaust channels when the valve is closed. Another essential function of the valve seat is conducting heat from the valves to the cylinder head. Most critical are the exhaust valves as they see extreme high temperatures when the exhaust gas is driven out of the cylinder. A lot of material development has been done to cope with these high temperatures and the abrupt landing of the valve when closing it. According to Trzesniowski most F1 engine manufactures use copper-beryllium alloys, whereas the valve stem guides are manufactured using bronze or copper-beryllium alloys.

Ferrari did use oil to cool its intake and exhaust valve seats in the V6-1,5L F1 engines, whereas multiple other manufactures like Porsche use engine coolant (Trzesniowski, 2014). Laser-cladded intake and exhaust valve seats were developed by Honda to enhance the durability of the F1-engines (Kondo, 2009). Compared to the press fit seats not only the wear resistance increases but also the ability to transfer heat towards the cylinder head.

4. Camshafts

Especially for naturally aspired engines, like in the V10- and V8-era of the Formula 1 high engine speeds and high valve lifts were sought to increase the engine's performance. However, this leads simultaneously to reliability and friction concerns. This also holds for the camshafts, to overcome these problems new materials, surface treatments and alternative actuating concepts are being developed. Moreover, the (rotating and translating) weight is minimized.
The camshafts are driven by gears, a chain or belt. These driving mechanisms can lead to fluctuations in the angular velocity of the camshaft, caused by vibrations (see chapter "**7. Driving mechanism"**).

For combustion reasons engineers want to open and close the engine valves rapidly, which can be done by so called aggressive cam lobes. However, this reduces durability and reliability due to valve bounce at higher engine speeds. Especially the seating load increases drastically when valve bounce is present. Hayakawa from Honda F1 states in 2009: "The maximum allowable engine speed for valvetrain performance can be defined as the limit speed up to which valve bounce would not occur, taking the over revving projected to occur in the circuit driving environment into consideration."

Cosworth uses steel camshafts with a fluid damper on the rear to obstruct vibrations caused by the camshaft's length and the various inputs to it from the interface between the cam lobe and the finger follower. The camshafts are front-driven, where the driving system is friction dampened. A quill drive is used to dampen a potential torsional resonance. The quill shaft is driven by the gears, that projects into the internally splined camshaft. The quill drive can twist relative to the camshaft. This is realized by milling slots in the ends of the camshafts that engage with disk springs which gives the quill drive its dampening properties. Hayakawa states that in 2009 they used a similar system for their F1 Engines, also with a viscous damper at the end (**Fig. 4.1**)

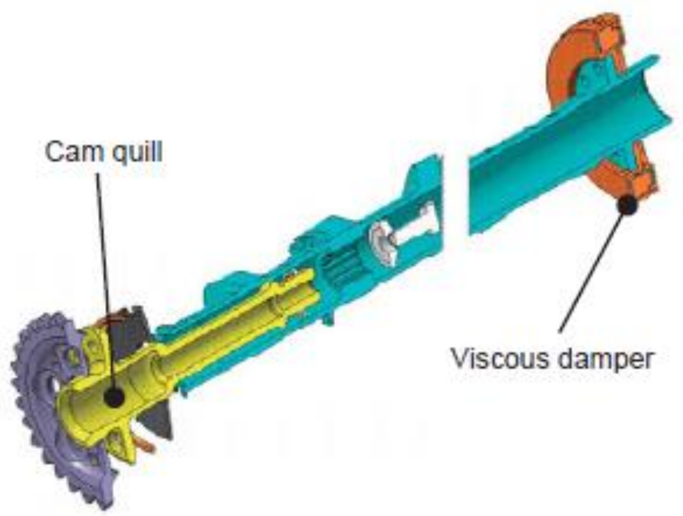


Fig. 4.1 Cam Quill on a Honda (Hayakawa, 2009)

To enhance the sliding performance it is common to use surface treatments. In the F1 a DLC-coating is being used on the cam lobes. Both Honda and Cosworth run DLC coatings on the cam lobes and on the finger followers (Bamsez, 2013). Honda reports that the development of the coating on the lobe was the major parameter to reduce the Herzian stress level and friction. Optimizing the balance between the film hardness of both sliding surfaces and the formation of the film has being a research subject for many years. They claim to have reduced friction between 2002 and 2008 by 2kW per year and enlarged the allowable surface pressure by 17%, allowing for more aggressive lobes (Hayakawa, 2009).

In combination with finger followers one can modify the lever ratio between the follower-cam lobe contact and the follower-valve stem contact. Honda did choose to position its cam such that a ratio close to 1:1 is obtained, for increasing stiffness and reducing surface pressure.

Valve-piston contact should be prevented at all times. However, when increasing the compression ratio of the engine while maintaining the same lobe profiles contact may occur, especially at higher engine speeds. To be able to raise the compression ratio Hayakawa mentioned that a so called Bezier curve was applied. This type of curve enables to freely set valve lift acceleration and simultaneously vary the lift curve in real time. The negative acceleration of the valve was enhanced by optimizing the pressure in the PVRS. This led to a balance between the valve lift load and the inertial forces, which resulted in a 1000 rpm higher maximal allowable valve train speed.
The positive acceleration of the valve was designed to have two stages using the Bezier curve (**Fig. 4.2**). This to balance the high lift with a high compression ratio. Actually, the level of lift was being reduced only when the clearance between the pistons and the valves was small. This resulted in a 0.3 higher compression ratio.

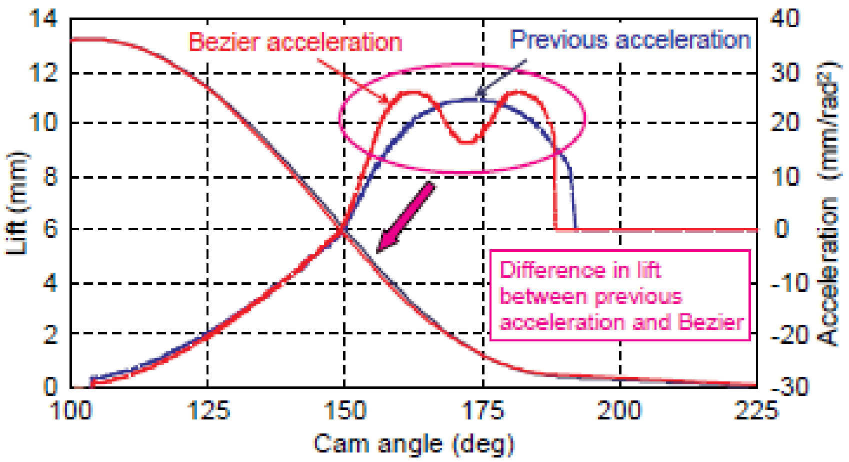


Fig. 4.2 Bezier lift curve of the 2008 Honda F1 engine (Hayakawa, 2009)

The reaction forces of the valve lift cause the previously mentioned twisting of the camshafts between the lobes. The fluctuating angular velocity of the cam may lead to uncontrolled valve behavior and therefore needs to be reduced. According to Hayakawa this can be done by optimizing the following parameters:

- Drivetrain moment of inertia
- Spring constant of the drivetrain
- Gear backlash
- Cam drive torque
- Damping coefficients of the dampers and friction

A side note can be placed by the cam drive torque, since this parameter is prioritizing the dynamical vehicle performance and can therefore generally not be changed. It is also stated that changes to the valve- and drive train should not rise the weight and the center of mass of the vehicle. Moreover, the packaging is of importance when considering the aerodynamics of the vehicle.

Honda developed an “Angular Velocity Reduction System” (AVRS), which reduced angular cam fluctuations. In the following text only measures taken at the camshaft are considered, measures at the driving system can be found in the chapter “**Driving mechanism**”.
Even though reducing weight in the valvetrain is of great importance Honda did add two weights at the rear ends of the camshaft. By increasing the moment of inertia they managed to shift Eigen frequencies towards the low speed range (**Fig. 4.3**). Moreover, they did reduce the back lash of the gears, resulting in a 1500 rpm higher valve motion speed and a 6kW friction reduction.

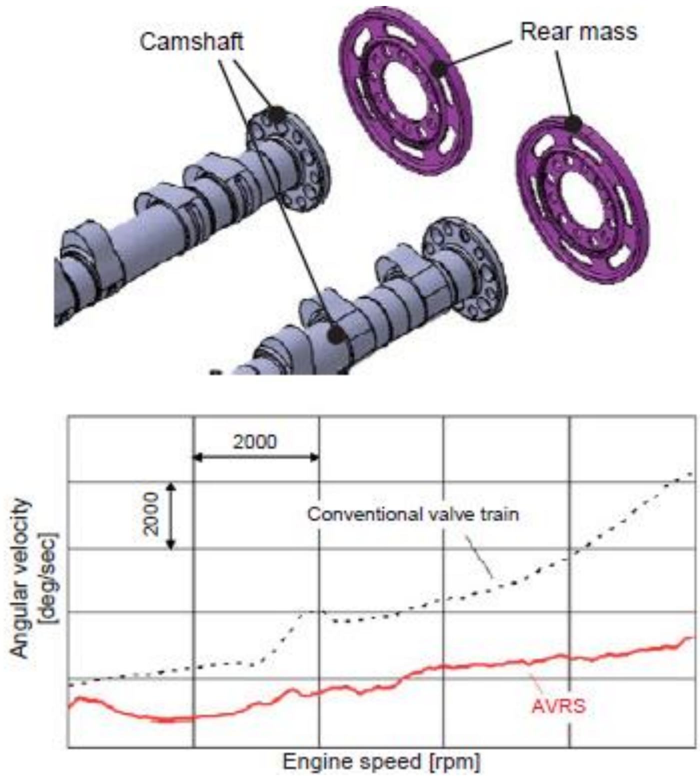


Fig. 4.3 Reduction of the fluctuation of the angular velocity using AVRS (Hayakawa, 2009)

During racing it showed that the fluctuation in angular velocity of the rear ends of the camshafts became higher than they are at the front, because of the free ends. The AVRS-G was developed, where G stands for gear. Two gears connect the shafts at the ends and therefore increase the spring constant of the entire shaft assembly. Besides reducing fluctuations it also reduced twist in the individual shafts (**Fig. 4.4**). This enabled the high specific gravity tungsten alloy weights from the AVRS system to be replaced by steel gears. Moreover, the hole inside the camshaft could be increased in diameter, obtaining a 2 kg weight saving over the AVRS system, while maintaining identical valve motion.

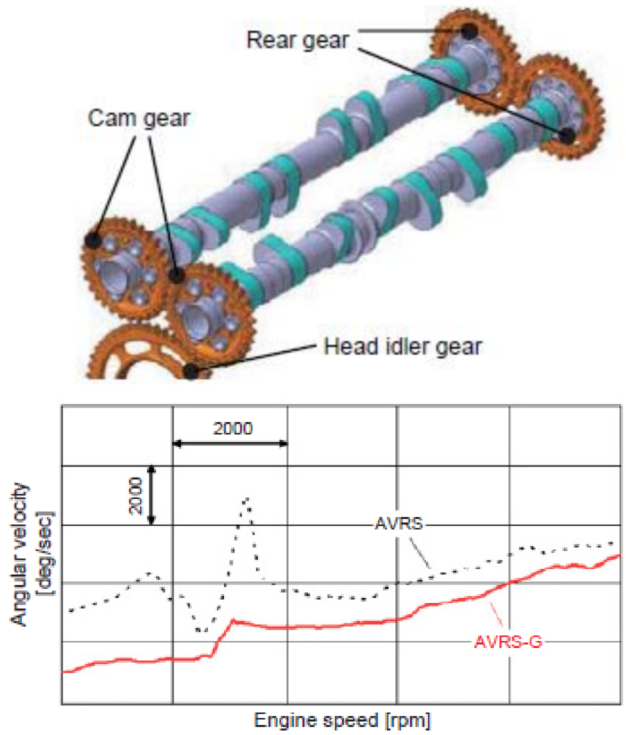


Fig. 4.4 Honda's AVRS-G system (Hayakawa, 2009)

The last camshaft evolution is displayed in **Fig. 4.1**, where a viscous damper and a quill drive are being used. Honda did increase the power of the engine by even higher lift, making it unavoidable to correct a resulting deterioration in valve motion. The dampening effect can be regulated by the silicon housed in the viscous damper and the stiffness of the quill shaft. An increased valve motion speed by 1100 rpm in comparison to the AVRS-G system was obtained. Moreover, the valve motion (**Fig. 4.5**) and lift load where reduced.

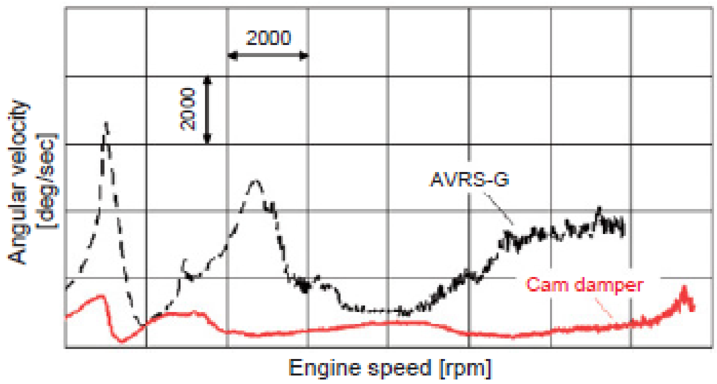


Fig. 4.5 Honda's Cam-Damper system (Hayakawa, 2009)

5. Alternative valvetrain concepts

Spring based valvetrain concepts as treated in the previous text may restrain engines to turn even higher, since they reach their dynamical limits. To maintain control over the valvetrain even in these harsh conditions engine engineers were forced to develop different concepts. The some well-known alternative valvetrain systems are being listed and explained in the following chapter.

5.1 Pneumatic valve return system

In some race series, like the Formula 1 and in the MotoGP, a so called “Pneumatic Valve Return System” (PVRS) is being applied. This started in the mid-1980s in Renault’s RVS-9 1.5L F1 engine. Whereas the 2002 Aprilia RS3 Cube was the first PVRS bike in the MotoGP. Instead of using a conventional spring compressed gas is being used to generate the required valve closing force. Having both a low own weight and a highly progressive characteristic spring curve suites the demands of a motorsport engine perfectly. In serial production cars these systems cannot be found, mainly due to the high production- and development costs that come along with it.
For safety reasons the medium in the cylinder typically is an inert gas, for example nitrogen. In **Fig. 5-1** one could see the entire PVRS set up, whereas 1. Represents the pressure reservoir; 2. Tappet; 3. One-way valve; 4. Inlet regulator; 5. Camshaft; 6.Finger follower; 7. PVRS Piston; 8. Piston seal; 9. Cylinder; 10.Valve stem seal; 11. Outlet valve.

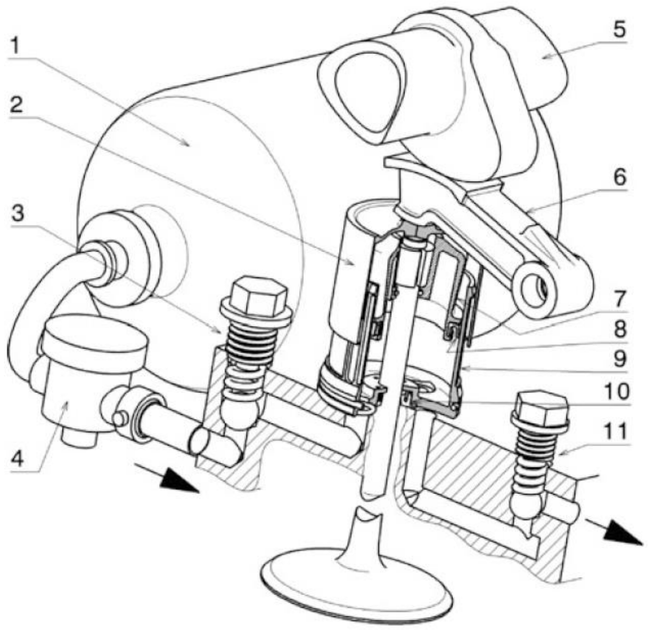


Fig. 5-1 Pneumatic valve return system (Trzesniowski, 2014)

Honda managed to produce a single piece PVRS cylinder head using head shell cores in a sand casting production technique, back in 2003. Even though the casting moulds are complicated, the head structure itself is more facile than the cam case-head assembly (**Fig. 5-2**). Moreover, a weight saving of 6.2 kg is realized.

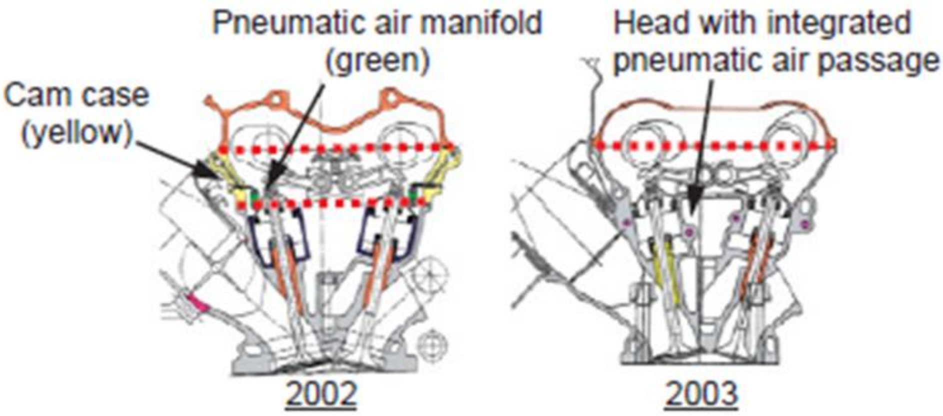
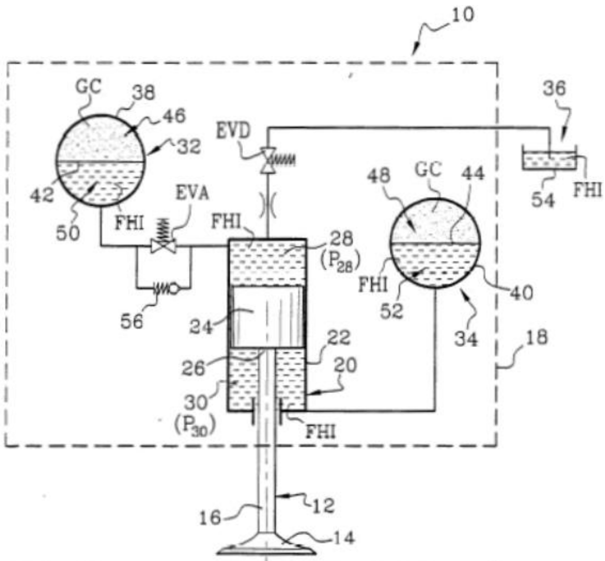


Fig. 5-2 Honda's two and one piece cylinder heads

5.2 Hydraulic valve system

Renault did develop a controlled electro hydraulic valve system without conventional camshafts. Not only does this concept reduce moving parts in the engine and therefore oscillations but it also allows for more advanced valve timing. The valve (part 12 in **Fig. 5-3**) is actuated by the fluid above and underneath the piston (nr. 24). An electro actuated solenoid valve (EVA) is used to control the pressure in the upper chamber. The oil is contained in a depressurized tank (nr. 32).
The lower chamber (nr. 20) is connected to a pressurized vessel (nr. 40) to ensure a high closing force once releasing the pressure in the upper chamber. However, this system has never been employed in the F1-series, since the technical regulations prohibit variable valve timing. Moreover, the electrical performance of the solenoids in combination with the hydraulic pressure build up made this system unsuitable for the extremely high engine speeds of the F1.



5-3 Renault's hydraulic valve system (Scarborough, 2016)

5.3 Desmotromic valve actuating system

Another solution would be using a desmodromic valve actuating system, which does not require springs. Two rocker arms are being used to open and close the valve. Extra lobes or even extra camshafts are needed to actuate the second rockerarm. Even though this design does not incorporate a spring there is no significant weight and inertia advantage since it needs an additional lobe and rocker arm per valve. Another disadvantage is that two rollers are needed to prevent excessive surface pressures at the cam/rockerarm contact, resulting in an increased reciprocating mass. In general curved lever tappets of desmodromic valve lift systems do tend to develop a higher contact stress than flat tappet- or rocker arm driven systems do.

Porsche and Inventus Engineering have developed another desmotromic valve actuating system called VarioDesmo. It is a mechanism also allowing for variable valve timing, as the name states. Moreover, the valve is actuated by one camshaft lobe only, hence it is advantageous over alternative valve train systems in terms of weight.

Back in 1954 and 1955 Mercedes Benz incorporated the desmodromic valve system in its F1 (W196 F1) and its 300SLR engines. Ducati's desmodromic valve system (**Error! Reference ource not found.**4) is based on hard-chromed rocker arms to overcome wear problems and is currently still being produced.

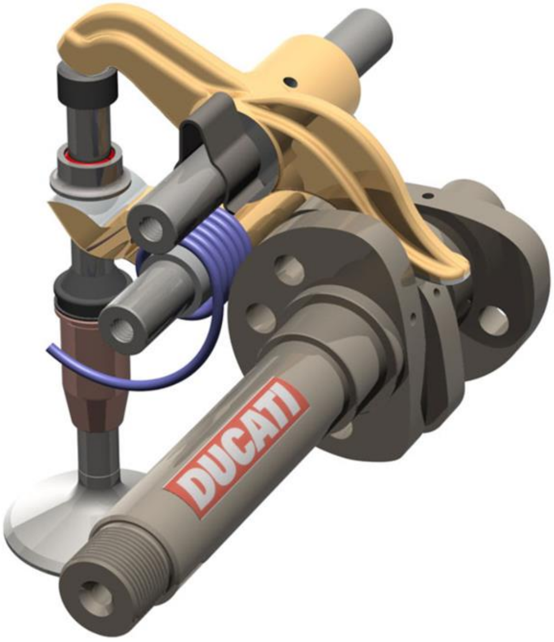


Fig. 5-4 Ducati Desmodromic valve system (Ducati, BLUmING mechanical engineering, 2014)

Traditionally Desmodromic valve systems where being used when increasing the engine speed. Nowadays, testing benches and simulation models are getting more involved and therefore do have a larger correlation with the real engine circumstances. In general it can be said that rocker armed and tappet driven engines can be optimized such that they do not suffer from valve float.

6. Lubricant development

Obviously a lubricant like oil has a large influence on the performance and the reliability of engines, especially on race engines with extreme small tolerances. The following chapter is limited to the lubrication development itself. Therefore, sump systems, the oil conditioning like heat exchangers, crankshaft- and auxiliary unit lubrication and are excluded.

In general it can be said that less viscous oil reduces friction loss but on the other hand increases reliability concerns. The main objective of oil is to separate sliding surfaces and therefore reduce friction and wear. The oil serves, besides as a lubrication medium, also as a coolant (Trzesniowski, 2014).

As Kondo (2009) mentions, oil deterioration is less of an issue for race engines. Mainly, since the replacement intervals are short and the engine is conditioned before starting. However, during the shorter lifespan the operation conditions are much harsher.

Honda's F1 engine developers reduced the oil agitation resistance and the shear resistance, mainly for the PVRS system. This combined with minimizing the reciprocating mass and the angular velocity fluctuations a tremendous reduction of friction losses from 35 kW to 12.8 kW was realized for their V10 engine in 2005 (Kondo, 2009).
Nowadays multiple additives suitable to the coating materials used in that specific engine are mixed to improve the base oil. The main focus thereby is on wear reduction, heat transfer and on reducing friction.

Nanolubricants are being researched at the moment, where geometrical features of diminutive particles serve as a lubricant. The Weizmann Institute of Science in Israel is for example working on 'NanoLub', a multilayered hollow structure of nested spheres. They claim to be able to replace normal lubricants by those structures. Moreover ApNano (a New York based company in applied nanomaterials) state that it is proven that nano powder structures are six to ten times more effective than regular lubricants. The material used in the research is tungsten disulfide (WS2).
Besides reducing friction by acting like miniature ball bearings also the contacting surfaces are smoothened. The nanostructures bond to the metal surface and filling the gaps between asperities. The particles can withstand higher pressures and last longer than regular lubricants, some manufactures even claim that those structures hold over a lifetime.
Carbon nested nanotube structures are being researched as well, however they disintegrate under friction of the contacting surfaces. The British company Nanovit uses besides Carbon also Aluminum Oxide and Silicon Dioxide particles. Moreover, they investigate the self-healing-surface potential of a hybrid form between those structures and regular lubricants.

7. Driving mechanism

The camshaft(s) have to be rotationally synchronized with the crankshaft to allow for the gas exchange, since the valves have to be opened and closed. Auxiliary units like pumps and balance shafts have to be actuated as well, therefore a coupling or driving mechanism is required. A ratio of 2:1 has to be realized between the crankshaft and the camshaft. The driving system is a crucial component, especially in an interference engine, what most race engines are. In an interference engine the travel path of the valve extends into the area where the piston or an opposing valve may run into. The principal differences between the driving mechanism of a production car and that of a race car are found in the amount of torque and rotational speed to be transferred. Moreover, noise production is of less importance for a race car and the service intervals are shorter.
In the following text multiple concepts are being evaluated, with the focus on race engines.

7.1 Belt driven

The use of a timing belt to transfer the rotational motion of the crankshaft towards the camshafts and eventually ancillary units is commonly seen on production cars. The elastomeric composite belt has curved teeth to prevent slip between the pulleys and the belt. Timing belts are acting like a vibration dampening element in the drivetrain. Moreover, they are quiet, lightweight, require no lubrication and are cheap. Belts are often being used to cover large shaft distances. However, the belts are relatively wide and therefore negatively influencing the engine's packaging, have shorter life spans and are not capable to transfer extreme loads e.g. high pressure fuel pumps. The efficiency of a belt driven system is rather good compared to other systems. Commonly used materials are natural rubber reinforced with glass- or Twaron/Kevlar fibers to cope with the tensile forces in the length direction. Other elastomers, plastics or urethanes are used as well.
In 1989 Yamaha and Renault did produce the RS01 V10 Formula 1 engine and equipped them with two belts.

High temperatures lead to degradation of the rubber, the same holds for engine oil. To overcome this problem and to replace metal chains multiple belt manufactures, amongst them Mitsuboshi, are investigating the possibility to use so called 'wet belts' (Nishikawa, 2016). These belts are engine integrated and run in oil. Mitsuboshi claims to have a large weight advantage over chains while no guides are required. Moreover, a more quiet system is obtained, energy loss is decreased and therefore the fuel efficiency is enhanced. Cam- and crankshafts do not have to be sealed as in conventional belt driven systems, the same holds for auxiliary units. Therefore, the disadvantage of the belt driven system, namely having multiple vulnerable seals vanishes.
Temperature resistant materials like highly saturated nitrile (HSN) are being implemented in newer belts. Nevertheless, these advanced materials come with other problems, e.g. HSN is affected by water and antifreeze.

7.2 Roller chains

Mainly because its mechanical properties multiple production cars are equipped with roller chains. Besides being strong, durable, less noisy as spur gears and relatively efficient they also do have some measure of vibration dampening. When comparing belts with roller chains it can be said that chains do come with less frictional losses. On the other hand the drive train inertia is increased. To ensure a correct timing the chain has to be preloaded on the unloaded side by some sort of tensioner, like with belts. Additionally longer or multiple-curved chains require guides that may be pretensioned as well.

Timing drives with more demanding requirements are often equipped with chains to transfer the desired torque. An example can be found in the current common rail diesel engines with high fuel pressures, where the high pressure pump is being driven by the chain (e.g. BMW's M57 diesel engines). A lot of acoustic development is being carried out for production cars, but as mentioned this is of less importance for a racing car. Besides the simlex, duplex and triplex chains many different concepts are invented. An example that is being used for high rotation speeds is the inverted tooth chain, where Cross Morse states that speeds up to 12,000 rpm with two shafts can be realized.

When the chain is not properly lubricated it will wear out rapidly. Another problem with roller chains is the variation in speed. This is known as ‘surging’, caused by a constant acceleration and deceleration of the links around the sprocket(s). The chain is pulled towards the pitch circle of the sprocket at the tooth contact. The opposite holds at the last tooth contact. Since the pitch line of the links is fixed it cuts the virtual radius of the sprocket, between the two pitch points. The rising and falling of the links pitch line is what leads to the chordal effect of speed variation. Speed variations may lead to vibrations inside the drivetrain as the effective radius of the chain continuously changes during revolution (Mulik, 2015). A higher amount of teeth on equal chain length will minimize this problem, since the radius can be described more accurate.
The tensile and fatigue strength are the most important measures for the roller chain. Chains are mostly built from heat treated steel and have surface coatings. Reinforced plastics, like glass fiber reinforced nylons, are often used to manufacture lightweight levers and guides.

7.3 Spur gears

Spur gears are even more durable, accurate and efficient than roller chain mechanisms. Moreover, the width of the driving system can be reduced simultaneously. Therefore, almost all high revving engines developed especially for racing are equipped with gears (Trzesniowski, 2014). Nonetheless, gears are sensitive to torsional vibrations. The reason being is that gears suffer from frequent torque reversal as the valve spring energy is released when the lobe turns away. This is causing a motion at the camshaft’s gear against the drive of the crankshaft that may lead to excessive noise and wear (Scott, 2012).

Another disadvantage of having gears is that it the relative location of the gears and mainly the shafts is constrained. A belt or a roller chain driving system offers more design freedom.

In some production cars one could find a direct drive (gear driven) system, however these are often nylon or carbon fiber coated to minimize drivetrain vibrations and noise production. Senthilvelan’s research in 2005 showed that ‘tan delta’ damping factors of about 0.030 for carbon fiber reinforced nylon 6/6 gears and up to 0.120 can be reached for non-reinforced ones. However, noise production can be neglected regarding race engines, therefore mainly steel spur gears are being installed. The downside of (reinforced) polymer related gears is that, in combination with high engine speeds surface temperatures may rise above the glass temperature. Moreover, the mechanical properties are rather poor, they do have a deflection hysteresis and there are multiple failure mechanisms possible in composite materials (Senthilvelan, 2005).
The potential weight savings makes such composites attractive on the other hand. Reducing the rotating mass and dampening vibrations do augment the engine’s performance, especially when considering high revving engines. Therefore, a lot of research is being performed to enhance the material and design properties to overcome the mentioned drawbacks of the (semi) composite gear.

Sakurahara (2009) states that an improvement of the gear material and the reduction of gear vibrations will make it possible to reduce power loss by decrease the thickness of the gears and therefore friction. One important parameter is the backlash between the gears. Trzesniowski (2014) states that a precise valve actuation at large engine speeds can be realized when reducing the backlash in the hundredths of millimeters. The spur gears can run on roller bearings and on plain bearings that are mounted on quick release axles. An eccentric tappet at one of the gears can be implemented in the engine to adjust the backlash and find the optimum.
Besides driving the camshafts at either the mass-flywheel or on the end of the crankshaft, it is also possible to drive them in the middle of the engine. Locating the driving mechanism at the mass-flywheel is advantageous in terms of vibrations. Given that the torque is taken at a

torsion-node on the crankshaft. Moreover, the engine's stiffness is enhanced tremendously with a driving system at the fly-wheel, especially in combination with the engine being part of the vehicle's carrying chassis. The downside is, that this installation position complicates the assembling and maintenance.
The spring forces acting on the cam lobes and the drive at the gear on the other hand can lead to twist inside the camshaft. Torsional oscillations in the camshaft have to be suppressed to ensure precise valve actuation. Therefore damping elements are being added in the driving mechanism (Trzesniowski, 2014). These can, in its simplest design, be an elastomer vulcanized inside the idler gear.

Bamsez (2013) states that Cosworth uses multiple dampers in its F1 CA Engine timing drive. Wood remarks "In Formula One it is a case of using the best performing firing order and fixing the torsionals that is why we have lots of dampers on the CA!" A compliant gear train is chosen, including two dampened compound gears (**Fig. 7-1**). Compliant quill drives for both supplementary drives, a big viscous damper on the back of the crankshaft, viscous dampers on both camshaft ends and friction quill dampers in the front of each camshaft are implemented in the CA engine. This leads to a total of thirteen dampers per engine (fourteen when using a kinetic energy recovering system).
Other F1 engine developers chose to go for pendulum-type dampers back in the V8-era. Cosworth moved the mass-flywheel and the clutch towards the gearbox to keep the Eigen frequencies of the crankshaft as high as possible, by lowering the weight. By doing so, they created room for the viscous damper to be mounted on the end of the crankshaft.

Fig. 7-1 Dampened compound gears of Cosworth's CA engine (Bamsez, 2013)

Moreover, Bamsez states that various oil feeds from the from the front cover supply oil directly to the gears that are embraced by the cover.

7.4 Vertical Bevel-Drive

An alternative camshaft driving mechanism is the so called vertical or upright shaft (**Fig. 7-2**). This traditional mechanism mechanically connects the camshaft(s) to the crankshaft using a vertical shaft, as the name states. Bevel gears or worm wheels can be found on both sides of the vertical shaft to transfer the rotational motion. These gears should obviously be constructed such that they guarantee a 2:1 ratio between the crank- and camshaft. They tend to produce noise, which amongst others is a reason that this system is not used on production vehicles nowadays, excluding some exceptions.

The most recent applications of vertical cam drive systems can be found in the V2- and V4 Motorcycle engines, e.g. the Kawasaki W800 which is currently still being produced. Ducati did use the bevel-drive in combination with the Desmodronic valve actuation system (see **Chapter 5.3**) in its former single cylinder racing engines. Whereas BMW used this mechanism for the RS Boxer racing engines. An application of the worm wheel in combination with a helical gear can be found in the Ford GAA engine.

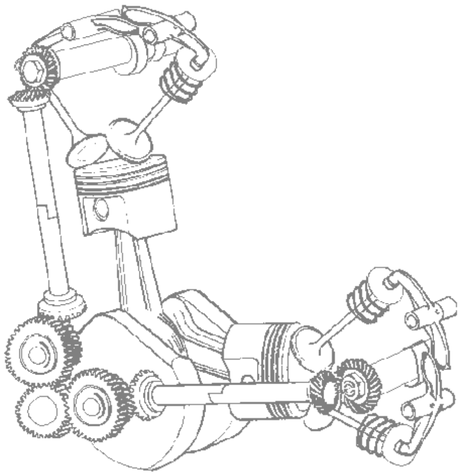


Fig. 7-2 Vertical Bevel-Drive (Filippa, 2015).

A precise valve control is obtained using the upright shaft mechanism. Moreover, re-adjusting the timing belt/chain is not required. Depending on the design and materials used a stiff coupling between the camshaft and crankshaft can be realized. Compared to a fully gear driven system the virtual play and friction are limited in this layout, since only two gear-pairs are needed. However, in most applications, as in **Fig. 7-2**, additional gears are being used, mainly since ancillary units have to be driven as well. This implies that the ancillary units, such as water- and oil pumps, have to be located such that they can be driven. Limiting both the ability to optimize the center of mass and the packaging of the engine.

The teeth of the bevel gears are shaped either straight, spiral or hypoid. The straight ones are mainly being used when the axes intersect at an angle. However, the spiral bevel gears tend to have a higher load carrying capacity and produce less noise. If both axes do not intersect hypoid bevel gears can be used, these gears are related to the spiral gears.

The thermal expansion of the engine-assembly and the shaft have to be known in detail when designing the upright shaft mechanism. Small deviations can cause additional friction, gear problems and even failure of the shaft or engine parts. Therefore some manufactures, like Kawasaki use spring loaded rings with splines to thermally decouple the shaft from the engine. Moreover, the dynamical behavior of the system has to be known in advance, since the gear contacts and the engine's vibrations could excite an Eigen frequency of the shaft. The shaft(s) should be optimized for torque-transferring. Hence, twist-resistant closed profiles are of great importance. So that at least a one cell shear-flow circuit can be established within the cross section (Filippa, 2015).

8. Cylinder head

The cylinder head houses a large part of the valvetrain and therefore predominantly influences the stability of it. Besides forming the upper part of the combustion chamber it also provides space for the fresh air feed, a part of the fuel and ignition system, exhaust gas escape and water cooling channels. The focus in the following chapter lies on stabilizing the valve train. Therefore all combustion relevant topics like the gas exchange and thermo management are not considered.

Many race engines are part of the carrying chassis, therefore one can find mounting holes in the cover of the cylinder head. Sakurahara (2009) states that a stiffer car has a better performance on the track. Being part of the carrying chassis means that the stiffness of the cylinder head and actually of the whole engine have to be as high as possible. Having a stiff cylinder head means that deformations are minimized. Therefore, camshaft bearings, rockerarm-, valve- and spur gear positions and –backlash should be in a close tolerance field around the designed value.

Even though, a lot of engine manufacturers in the F1 V8-era did use MMC's (see **Chapter 4.2**) Cosworth stayed at all aluminum cylinder heads (Bamsez, 2013). The camshafts are mounted inside a so called cam carrier (**Fig. 8.1**) and are not mounted using more compliant bearing bridges or caps as one could see on production cars. Besides being stiffer these cam journals also have a weight advantage over caps.

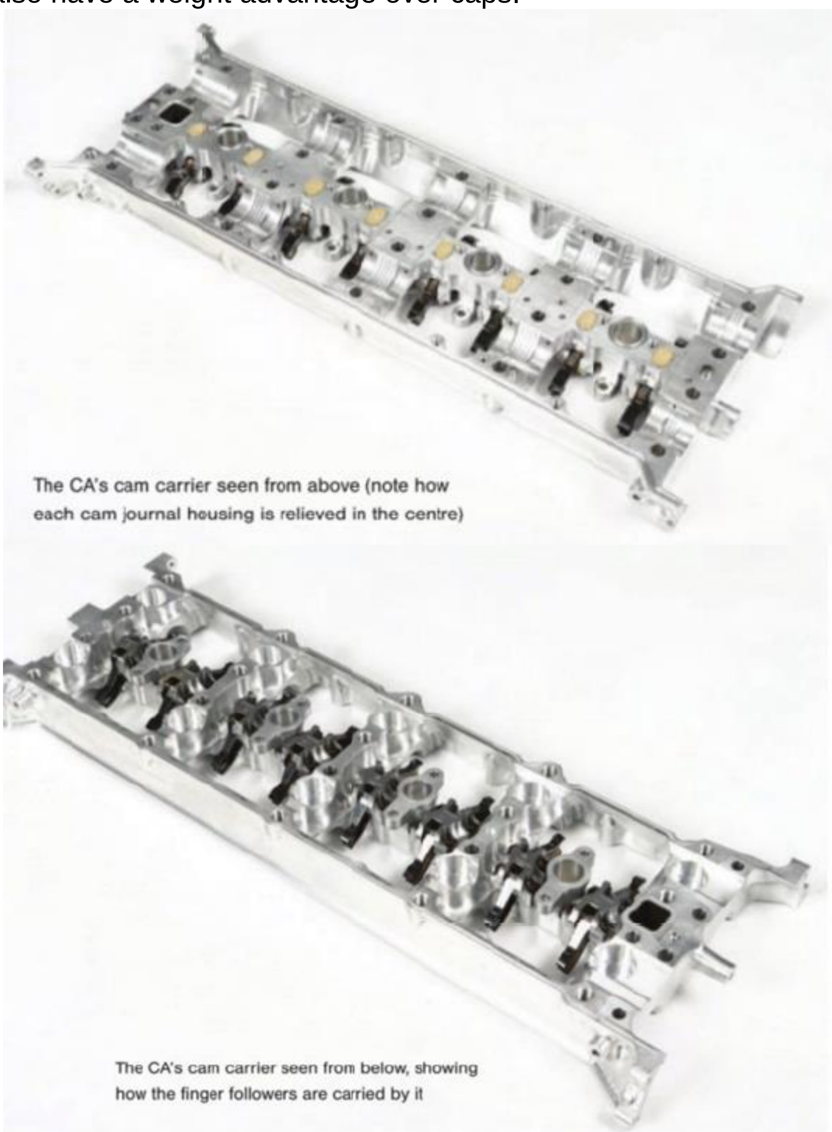


Fig.8-1 The CA's cam carrier (Bamsez, 2013)

Cosworth milled their covers from billet material to have the possibility to modify the design for individual chassis requirements. The covers and carriers are machined from 7075 Aluminum, where the covers form three of the five upper bearing housings for each camshaft. The other two are caps to enhance assembling. Cosworth's constructors used two bolts per housing, eight bolts to secure the individual caps and another twelve bolts to fixate the cover and the carrier. All twenty bolts that go into the cylinder head are Multiphase screws, to optimize their thermal behavior.
The followers pivot in brackets underneath the respective cam, where the intake and exhaust finger opposite it share one bracket. The brackets are made of powder metallurgical (spray-compacted) aluminum, do have an oil feed to the steel spindle and are mounted using four bolts.
The center section of the carrier is machined to minimize the contact area and therefore friction. So actually there are ten individual bearing supports per camshaft instead of five.

Bamsez also notices that when the minimal allowed engine weight was raised by the FIA they continued saving weight on individual parts. To reach the permitted 95kg they added more than 10kg to stiffen the engine. Wood states "Given our 20,000 rpm target, all the dynamic parts and the bearings needed to be as stiff as possible, otherwise when you are running really fast you end up with things flexing and moving unexpectedly. You cannot always predict that behavior, and that is when things break."

Aluminum alloys are mainly being used for racing engines, whereas standard casting materials are being used for serial production cars. Trzesniowski (2014) summarized common cylinder head alloys where the material with the highest mechanical strength at 250 ˚C is listed first: EN AC-ALSi6Cu4 (G-AlSi6Cu4), EN AC-AlSi8Cu3 (G-AlSi9Cu3), EN AC-AlSi7Mg0,3 (G-AlSi7Mg) and EN AC-AlSi10Mg (G-AlSi10Mg), all of these materials get a heat treatment, e.g. a T6-heattreatment.
High temperature resistant aluminum alloys are hard to process but do possess desired mechanical properties. Examples of these materials can be found in F1 and LMP1 engines (G-AlSiCu5Ni1, 5CoSbZr, G-AlCu4MgTi, G-Al2MgTi). The casting process of cylinder heads is tedious, without going into detail it is stated that close to the combustion area small dendrite distances are desired for stiffness and thermal properties. This is being realized by locally cooling the tools.

Sand molds are often being used to cast the cylinder heads. Honda did make a complex mold to integrate the PVRS system in the head without cam carrier to stiffen the head and reduce weight (**Chapter 5.1, Pneumatic valve return system**) (**Fig. 8.2**). (Kondo, 2009).

Fig. 8-2 Honda's cylinder head sand mold with PVRS (Kondo, 2009)

9. Validation methods

Predictive computer aided engineering (CAE) did not only help the F1-engineers of Honda optimizing their vehicles and engines but also their tests. The load on the engine is estimated for each circuit from the throttle opening angle and the duration of continuous wide open throttle (WOT). Driving modes are developed using CAE and then validated by endurance tests on a test bench (Kondo, 2009).

Kondo (2009) states that precaution must be taken when validating concepts. In the F1 engine development of Honda in 2006 ten different cylinder heads with dissimilar porting where tested. It showed that a high induction performance on a steady flow test did not mean enhanced engine performance by definition. In order to do improve the engine's performance also the combustion including the mixture forming must be evaluated for that specific cylinder head. Honda was able to predict and maximize these dynamic effects more accurately by coupling the steady state induction performance to a 3D-2D volumetric efficiency model.

Obviously progressive and localized structural damage can occur when considering cyclic loads. It is known that these loads can cause material failure even though the yield stress limit is not reached. This is referred to as fatigue. A list of currently used fatigue calculation methods in the motorsport can be found in the following text.

Honda used Miner's rule back in the third F1 era to guarantee durable reliability (Kondo, 2009). Miner's rule can be formulated as follows:

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C$$

Where the number of cycles to failure of a constant stress reversal ($N_i(S_i)$) is calculated by using an empirically determined C (normally between 0.7 and 2.2) and the stress magnitudes k in a spectrum $S_i(1 \leq i \leq k)$ that contribute $n_i(S_i)$ cycles.
The disadvantages of this method are that design curves are needed to account for scatter, since this method does not relate the probability distribution with the part's predicted life. A second drawback is that it does not account for history. Variation in high and low stress cycles may cause significantly more damage, which is not taken into account in this method. Also residual stresses after deforming plastically are not considered.

9.1 Calculation of cam lift profiles and spring rates

Before numerical methods in engineering where fully developed the only option to calculate the dynamics of the valves was by differentiating the cam lift curve twice, resulting in an approximate acceleration. However, this method is extremely sensitive to noise.
Nowadays optimal cam profiles can be obtained by integrating the desired jerk curve three times. Moreover, temperature and flexibility parameters can be incorporated as well. The influence of this calculations can be seen in the cam profiles of high speed engines. Having an asymmetric profile, with a steep opening and shallow closing curve to reduce wear. The speed of opening and closing the valves is limited by the Hertzian contact stress between the rocker arm and the cam.

In the past valve spring calculations where performed using the cam lobe profile, mass properties of the components and the engine speed. If the control over the valve train was lost, i.e. floating valves occurred, then pressure was added. Obviously, this directly increases friction, stresses and possibly weight of the entire system as well.
However, like Labore states in 2016 this static representation does not display the reality since the dynamics of the system as a whole is not being considered. In general a valve train should be built as a system and not as individual component. Especially while the springs are responding more to frequency than load. Not only the seat- and open load of the spring do matter, even though that is commonly conceived. It is namely possible to fabricate multiple

springs that all obey those numbers however differing tremendously in their transient behavior and durability.

The Spintron test bench is used to validate whether the contact between the camshaft and the valve including the components in between them is present during operation. With this testing device racing conditions can be simulated and durability test can be performed. Moreover, it is possible to study failures and frictional horsepower loss. Using a Laser Valve Tracking System (LVTS) it is possible to identify valve behavior component deflection and spring harmonics.
The engine going on the Splintron test bench is cut open on the side, to make it possible for the laser beam to measure the valve movement. A calibration measurement at a low stable engine speed is being made for reference purposes.

The company COMP Cams uses a load cell or force ring mounted underneath the valve spring to monitor the dynamic forces acting upon the valve spring. Besides those cells they utilize proximity probes (either capacitive, photoelectric, electromagnetic or inductive) which are used as a supplement to the lasers. This is done to compensate for the engine vibrations on for example a Splintron test bench.

Strain gauges are frequently being applied to monitor the behavior of the valvetrain. During operation the engineer can see when the control over the valves is being lost, i.e. when floating valves occur compared to a stable reference situation at low engine speed. In **Fig. 9.1** multiple parts are being displayed. 1. Shows timing chain guides which Mulik (2005) uses to monitor the contact forces between the cam chain and the guide. The strain gauge in 2. monitors the force transmitted towards the hydraulic lash adjuster. 3. Can be used to monitor spring oscillations and also to check for floating valves, which will be distinguished by a (short) zero load situation. The strain gauge on the follower (4.) is also being used to track valve bounce.

Fig.9-1 Strain gauges 1. Timing chain guides, 2. Lash adjuster, 3. Valve spring, 4. Follower (Mulik, 2015)

A lot of Splintron testing is also being done using high speed cameras, where valvetrain oscillations can be visualized. However these kind of tests are expensive since engine blocks or/and cylinder heads have to be machined to be able to look inside.

A big part of the research capacity of the manufactures goes into developing valvetrain models (Hayakawa, 2009). Some software packages specialized on valvetrain and drivetrain calculations are listed below. **Fig. 9.2** shows how complex these calculations are, even just for one component of the valvetrain.

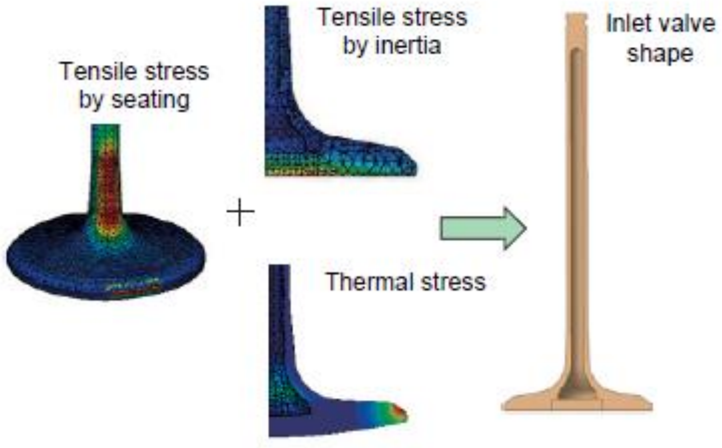


Fig.9-2 Computer aided design of a F1 racing valve (Mulik, 2015)

It is stated that Honda's F1 valves had to have bigger valve heads to increase the volumetric efficiency of the engine, while having to reduce the weight of the stem (**Fig. 9.2**). The valves simultaneously had to withstand inertial forces and seat loads generated by accelerations of more than 6000G, while operating at 700+˚C.

9.2 GT-Vtrain

Cosworth is using GT-Vtrain to optimize their valvetrains. The validation of fundamental valve train concepts in GT-Vtrain is the first step in their design process. Mainly, since large constructive changes can be implemented in a relative short amount of time. Further research done using GT-Vtrain:

- Loss of contact between the tip of the rockerarm and valve stem
- Friction related research
- Investigating dynamic lift profiles, that on their turn can be used for 1D motor simulations in GT-Power
- Wear and contact tribologal behavior
- Kinematic analysis including cam profile optimizing

Whereas Cosworth states that Gamma Technologies is their preferred supplier of valve train analysis software (Dark, 2004).

9.3 Valdyn

Ferrari, amongst others, uses Valdyn to optimize the valvetrain of their F1 engines for a long time (di Paola, 1996). Valdyn is also being used to model the valvetrains of production cars, one example of a high revving engine developed with help of Valdyn is the Lamborghini V12. Ricardo Software developed Valdyn and states that this multi-body dynamic and kinematic simulation package is specially developed for cam and spring pack design within a valvetrain. Valdyn bases on a building block architecture, which therefore can be used with more efficiency. However, the simulation engineer has to be aware of the formulas behind the building blocks, to avoid black boxes. It is possible to simulate at a component level and on an engine level when linking the program to other simulations, e.g. Engdyn, Fearce and Simulink. Besides being able to plot 3D frequency responses and taking variable valve timing into account it also plots several involved mathematical expressions. Moreover, tribological analysis can be performed with this software as well, including cam contact Herzian stress, friction, oil film thickness and cam wear.

10. Conclusion

This report gives an overview of the currently available valvetrain concepts of racing vehicles. The focus hereby lies on increasing the valvetrain's stability and reducing friction and wear.

It can be said that the Overhead valve concepts (OHV) needs less components to overcome the distance between the cam- and crankshaft. However, the additional flexibility inside the components and rotating/translating mass that come with the OHV principle make it an unsuitable concept for high speed (race) engines. Therefore only Overhead camshaft (OHC) engines are being considered (Ballard, 2002) (Trzesniowski, 2014).

Fingers or rockerarms are, commonly seen in racing engines. Mainly, since the reciprocating weight is reduced and it allows for higher valve lifts with equal or even smaller camshaft lobes, due to the lever arm. A valvetrain including rockerarms also has an advantage over direct-driven systems in terms of friction (Carley, 2011). According to Trzesniowski (2014) Diamond Like Carbon (DLC) coatings applied on the valve fingers of many racing engines. This thin layer minimizes both wear and friction at the sliding surface. Bamsez (2013) from Cosworth also claims that finger followers have a friction and stiffness advantage over bucket tappets.

Valves in racing engines are exposed to even higher temperatures, reciprocating accelerations and cylinder pressures than those in production cars. Moreover, there is a risk of having floating valves when operating engines at higher speeds (Ajay, 2014). Multiple solutions to the floating valve problem are mentioned in literature (Trzesniowski, 2014) (Bamsez, 2013) (Ballard, 2002).
Decreasing the valve's weight may prevent floating valves. This is more advantageous than increasing the spring constant regarding friction and inertia. This can be done by changing the design, the material and the production technique, since they all are strongly related.
Varying the valve spring's shape, surface treatment, inclination or wire- and coil diameter over the length are commonly used solutions to the floating valve problem in motorsport engines (Youd, 2011). Moreover, the number of springs is varied to cope with oscilations.

The camshafts are driven by gears, a chain or belt. These driving mechanisms can lead to fluctuations in the angular velocity of the camshaft, caused by vibrations. To minimize these viscous dampers, gears, masses and quill drives are being designed (Hayakawa, 2009).

To maintain control over the valvetrain even in harsh high speed conditions engine engineers were forced to develop different concepts, like the Pneumatic Valve Return System (PVRS), that can be found in the F1 and MotoGP series. Moreover, a hydraulic valve system and a Desmotromic valve actuation proved to be solutions as well.

Spur gears are more durable, accurate and efficient than roller chain and belt mechanisms. Therefore, almost all high revving engines developed especially for racing are equipped with gears (Trzesniowski, 2014). Nonetheless, gears are sensitive to torsional vibrations and produce sound.
Sakurahara (2009) states that a stiffer car has a better performance on the track. Being part of the carrying chassis means that the stiffness of the cylinder head and actually of the whole engine have to be as high as possible.

A major part of the research capacity of manufactures goes into developing valvetrain models (Hayakawa, 2009). Besides being cheaper than testing it is also faster, allowing for a shorter responding time on regulation changes.

Whereas G. Blair states in 2006: *"There is no such thing as cam design, there is only valve lift profile design which requires the creation of a cam and follower mechanism to reliably provide this designed valve lift profile."*

A. Valvetrain specifications Honda F1

Year			2008
Engine code			Honda RA808E
Head			J-Valve
PVRS		Control	P2/P3EAR control
		Air bottle	Carbon bottle 570 cm^3
Gear train			AVRS-G
Cam	IN	Lift , valve timing	13.5 mm 19/64
		Material	SCM435 nitriding
		Surface treatment	DLC
	EX	Lift , valve timing	13.0 mm 19/64
		Material	SCM435 nitriding
		Surface treatment	DLC
Valve	IN	Stem diameter	ϕ5.8 (hollow stem ϕ3.5)
		Valve diameter	ϕ41.6
		Material	Ti6246
		Surface treatment	DLC
	EX	Stem diameter	ϕ5.8
		Valve diameter	ϕ32.4
		Material	KS64411Ta
		Surface treatment	DLC
Finger follower	IN/EX	Material	SNCM815 carburizing
		Surface treatment	DLC
Air spring seal		IN/EX	PTFE
Reciprocating mass (g)		IN	50.0
		EX	45.6
Maximum engine speed for valvetrain (rpm)			20300
Upshift engine speed (rpm)			19000

Tab. A.1 Honda's valvetrain specifications (Hayakawa, 2009)

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