
Development of Valvetrain for Formula One Engine

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ABSTRACT

From 2000, the development teams involved in Honda's Formula One engine development program worked as one in development efforts focused on the achievement of increased power through increased engine speed. As part of these efforts, the configuration of the valvetrain was reexamined from the bottom up, and new mechanisms were developed.

To enable the realization of high speed and high lift in the valvetrain, a finger follower system was employed as the valve drive method in place of a bucket tappet system. In addition, the application of a measurement method applying Bezier curves to the acceleration of the valve lift curves and the optimization of the gear train reduced fluctuations in the angular velocity of the camshafts and enhanced valve motion.

Furthermore, it was necessary to reduce the excessive friction due to increased engine speed. In response to this, the pneumatic valve return system was advanced by reexamining the configuration of the cylinder heads. The development of electronically-controlled regulator system also contributed to reducing friction.

1. Introduction

Competition in technological development is particularly intense in Formula One, the pinnacle of the world's auto races. Merely maintaining competitiveness represents technological stagnation or regression – constant advances are demanded.

In the development of valvetrains for Formula One engines to respond to these demands, increased speed and higher lift are sought in order to increase power, but this generates the issue of controlling increases in friction.

With increased power and higher lift as the targets, the valve drive mechanism was redesigned, new materials were employed, and surface treatments such as diamond-like carbon (DLC) were applied, in addition to the achievement of maximal weight savings in the moving parts. Moreover, efforts including reexamination of the valve lift characteristic and the gear train layout reduced lift load at the same time as enhancing the motion of the valves in the high-speed range, thus increasing the allowable speed for the valvetrain.

Changes in Formula One regulations placed restrictions on the materials able to be used, set limits on engine speed, and stipulated that components must be capable of long mileage. This made the reduction of frictional losses in the engines an important issue, and resulted in a significant change in the direction of development efforts.

In response to this trend, a jet-type air control system (J-valve mechanism) was newly developed to modify the pneumatic valve return system (PVRS). This system enabled oil agitation resistance in the PVRS cylinder to be reduced, resulting in reduced motored friction of the valvetrain.

Looking back on development efforts from 2000 onwards, this paper will provide an overview of technologies developed to increase engine speed and reduce friction in Formula One valvetrains with the aim of achieving increased power, and will discuss the performance of these technologies.

2. Overview of Valvetrain

Table 1 shows the main specifications of the valvetrain used in Honda's 2008 Formula One engine, and Fig. 1 shows an external view of the components of the valvetrain.

A variety of studies were conducted of the valve, including those on the angle of the intake and exhaust valves from the perspectives of increased volumetric efficiency and enhanced combustion. For the intake side, a compound valve layout that also displays an angle of inclination in the longitudinal direction of the engine was adopted. The intake and exhaust valves were the components in which the maximum weight savings were sought, and development proceeded on materials for valves so that weight could be minimized within the ratio

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Table 1 Valvetrain main specifications

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
	EX	SCM435 nitriding
		Surface treatment
		DLC
Valve	IN	Lift, valve timing
		13.0 mm 19/64
		Material
	EX	SCM435 nitriding
		Surface treatment
		DLC
Finger follower	IN/EX	Stem diameter
		ϕ 5.8 (hollow stem ϕ 3.5)
		Valve diameter
		ϕ 41.6
Air spring seal	IN/EX	Material
		Ti6246
		Surface treatment
		DLC
Reciprocating mass (g)	IN/EX	Material
		SNCM815 carburizing
Maximum engine speed for valvetrain (rpm)	IN/EX	Surface treatment
		DLC
Upshift engine speed (rpm)	IN/EX	Material
		SNCM815 carburizing
Air spring seal	IN/EX	Surface treatment
		DLC
Reciprocating mass (g)	IN/EX	Material
		SNCM815 carburizing
Maximum engine speed for valvetrain (rpm)	IN/EX	Surface treatment
		DLC
Upshift engine speed (rpm)	IN/EX	Material
		SNCM815 carburizing

range of specific weight to stiffness as stipulated in the Formula One regulations.

A camshaft and finger followers was used for the opening and closure of the valves, and a DLC coating was applied to the sliding components. In addition, the application of a PVRs using compressed air in place of normal metal springs reduced reciprocating mass, and prevented the surging at high speeds that originated in the metal springs. Figure 2 shows a view of the PVRs as fitted in the vehicle. The system incorporated an air bottle filled with high-pressure air and two regulators,

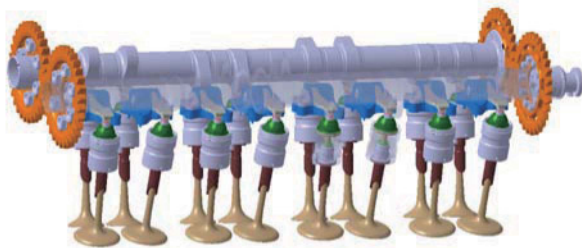


Fig. 1 View of valvetrain

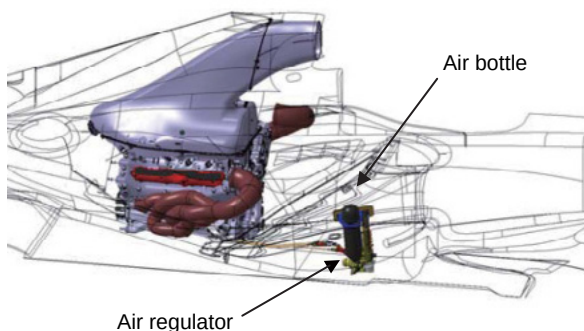


Fig. 2 View of air spring system

for supply pressure and discharge pressure.

Torque was transmitted by the gears from the crank to the camshaft. This helped prevent delay in the valve timing due to high drive torque and resonance generated in the chain or the belt. The gear train was designed to reduce fluctuations in the angular velocity of the camshaft caused by vibration, thus enhancing valve motion and reducing friction.

3. Technologies for Increased Engine Speed

3.1. Changes in Speed Targets

Figure 3 shows changes in the maximum allowable engine speed for valvetrain performance in the Honda Formula One engine development process from 1990 to 2008. In the valvetrain, the seating load increases rapidly due to valve bounce at a higher engine speed. This might reduce durability and reliability of each component of the valvetrain, resulting in a failure. In response to this, valve motion should be enhanced so that valve bounce would not occur even at the maximum engine speed. 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. At the commencement of development efforts, increases of approximately 400 rpm per year were achieved, and this contributed to increased power. From 2004, regulations specified long mileage, and the mileage for each engine consequently increased. From 2007, maximum engine speed was limited to 19000 rpm, increasing the frequency of wide open operation of the throttle valves. These changes made increased valvetrain durability and reliability necessary, and development therefore proceeded in order to achieve a maximum engine speed for valvetrain performance of 20000 rpm or more.

3.2. Reduction of Reciprocating Mass

Figure 4 shows a cutaway view of the valvetrain and the reciprocating mass of each component of the valvetrain. Weight savings were achieved by the application of methods including the use of a finger

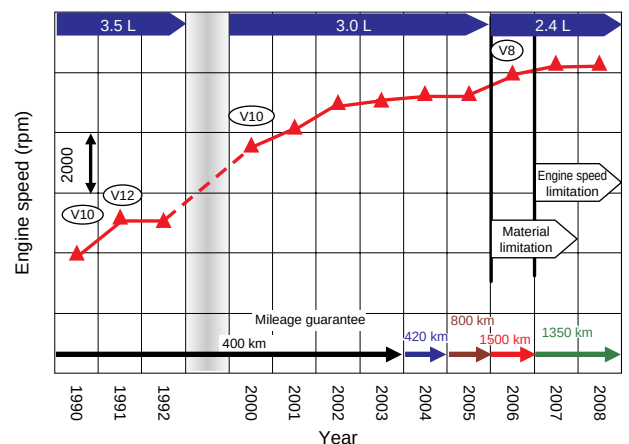


Fig. 3 Changes in maximum allowable engine speed for valvetrain

follower mechanism to drive the valves, instead of a bucket tappet system, and the reduction of the diameter of the PVRs cylinder. In addition, efforts in materials development and the use of CAE enabled the durability and reliability of the valves to be ensured with the minimum weight increase, despite restrictions on the materials that could be employed and the requirement for long mileage. These efforts reduced the reciprocating mass of the intake-side valvetrain by 21.7 g (30%) between 2000 and 2008.

3.2.1. Development of finger followers

The drive system for the valves in a Formula One engine must use lightweight parts in order to achieve increased power, and at the same time must enable increased valve lift in order to increase the volume of intake air. Using the previous bucket tappet system, it was necessary to increase the diameter of the bucket tappet to achieve higher lift, and it was challenging to balance this necessity with the achievement of weight savings. Because of this, finger followers were employed from 2002 onwards, enabling weight to be reduced by 13.5 g and valve lift to be increased by 1.0 mm or more. Figure 5 shows a comparison of the valve drive systems used in Honda Formula One cars.

The shape of the finger followers was determined through studies using 3D models and CAE based on a variety of considerations, including frictional losses at high speeds and high-hertz stress levels as well as the local stiffness and strength depending on inertial loads and the direction of rotation of the cam.

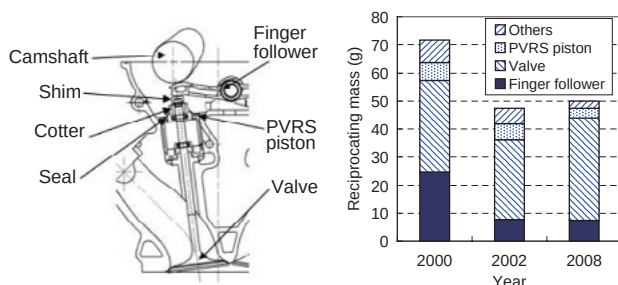


Fig. 4 Reciprocating mass of parts

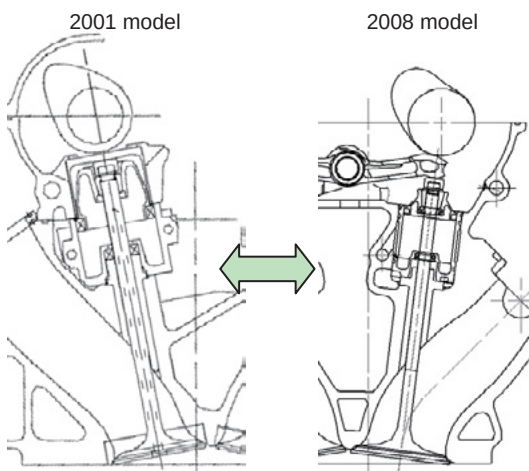


Fig. 5 Comparison of valvetrain layouts

From the perspective of sliding performance, a DLC coating was applied to the cam lobe and the finger follower top pads in order to help ensure durability and reliability at high speeds and high hertz stress levels, and to reduce friction. In the development of the DLC coating, factors, including the balance of film hardness between the parts and the formation of the films, were optimized. By comparison with the initial stage of DLC development, an increase in surface pressure limit of 17% in high-load operating environments was achieved, and friction was reduced by approximately 2.0 kW per year.

From the perspective of finger follower geometry, positioning the camshafts almost exactly on the stem of the intake and exhaust valves brought the lever ratio close to 1 and reduced surface pressure, in addition to enhancing valve motion by increasing stiffness. Furthermore, positioning the pivot of the finger follower on the same axis as that of the intake and exhaust valves enabled the finger followers to be lengthened and helped to ensure the formation of an oil film on the sliding surfaces.

The oscillation of the finger followers and the inertial load on the arms generated a large moment on the valve stems, raising concerns over bending of the valve stems or fracture of the valve heads. Minimization of the bending moment on the valve stems was an effective means of responding to these concerns. The curved shape for the bottom pads was therefore designed to enable the amount of movement of the contact points with the valve stems to be reduced and their positions to be located in the center of the valve stems.

3.2.2. Development of intake and exhaust valves

In order to increase volumetric efficiency in the Formula One engine, it was necessary to increase the diameter of the head sections of the intake and exhaust valves while reducing the diameter of the valve stems. It was also necessary for the valves to be capable of withstanding the inertial forces and seating loads generated by acceleration of more than 6000 G under combustion gas temperatures of 700 °C or more. Considering these demands, materials possessing high heat resistance strength were developed, and CAE was employed to enable selection of appropriate valve shapes (Fig. 6). Combustion gases and intake air generated a

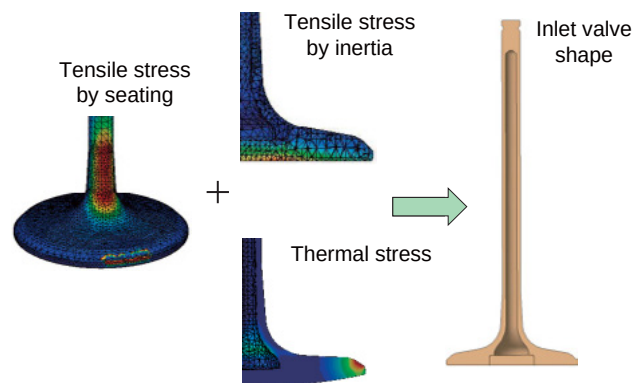


Fig. 6 CAE for inlet valve

significant difference in ambient temperature between the fireface and the back of the intake valves, and there were concerns that high levels of heat stress might be generated on the exteriors of the heads, resulting in seat chipping. Analyses were therefore conducted of stresses generated by heat and by inertial forces, and an umbrella shape was developed that would prevent the level of stress from exceeding the fatigue strength of the material during operation. The swaying of the valves at high speeds also generated partial contacts when the valves were seated on the valve seats. This caused stress to be concentrated at the points of connection between the valve heads and valve stems. As a countermeasure, the valve stems were tapered in order to reduce stress.

Honda began using titanium aluminum (TiAl) materials in 2002, and employed them in race vehicles until 2005. The use of these materials enabled the diameter of the valve stems to be reduced from $\phi 6.6$ to $\phi 4.5$ and the reciprocating mass of the valves to be reduced by 5.0 g against conventional titanium (Ti) materials. TiAl alloys are intermetallic compounds, and the particular machining employed for these materials produces cracks around which residual compressive stress exists. Because of this, the valves frequently broke during their first period of use. In order to resolve this quality issue, quality control was implemented by subjecting all valves to eddy current testing rather than fluorescent penetrant inspection in order to detect cracks, enabling the realization of a level of durability and reliability high enough to meet the standards of the long mileage regulations.

From 2006, restrictions were placed on materials in Formula One, and Honda had no option but to change its materials. It was necessary to hollow the valve umbrellas and valve stems in order to achieve an identical or lower weight using Ti as had been possible using TiAl. However, in the initial stages, insufficient strength and stiffness resulted in frequent breakages of the valve heads. Measurements of the stress on the valve heads and the temperature of the heads were therefore taken, and analyses were conducted of factors including the motion of the valves during firing. The optimal umbrella shape was selected by feeding the results back into CAE, enabling the realization of a low weight and a high level of stiffness, equivalent to those available from TiAl.

3.3. Optimization of Cam Profile

The cam profile has a wide range of effects on performance. The achievement of increased volumetric efficiency by increasing valve lift and the optimization of the duration angle and the opening and closing timing of the valves enables low- and medium-speed torque to be increased. The stabilization of combustion increases drivability, and the realization of a higher compression ratio increases fuel efficiency. Figure 7 shows the lift curve for the intake valves employed in Honda's 2008 Formula One engine. Study of the valve lift curves of Formula One engines using 3D η_v simulations showed that the positive acceleration of the lift curves reached

50 mm/rad² or more.

In the design of the valvetrain, considerations of reliability and durability and the realization of increased speed made it essential to set a level of valve lift acceleration that considered the achievement of a balance between the lift load for the PVRS and inertial forces. A Bezier curve was therefore applied to the lift curve. This type of curve enables designers to freely set valve lift acceleration, and at the same time, vary the lift curve in real time, simplifying the realization of the desired lift curve. By this means, the negative acceleration of valve lift was optimized with consideration of the PVRS pressure characteristic, enabling the valve lift load and inertial forces to be balanced to the limit point and the maximum allowable speed for the valvetrain to be increased by 1000 rpm. In addition, in order to balance increased lift with a high compression ratio, the positive acceleration of the valve lift was designed to display two stages, with the level of lift being reduced only when the clearance between the pistons and the valves was low. This enabled the compression ratio to be increased by 0.3. Figure 8 shows the two-stage acceleration designed using the Bezier curve.

3.4. Reduction of Fluctuation in Cam Angular Velocity

Torsional vibration was one of the factors that had a negative impact on valve motion. This generated a nonlinear resonance phenomenon in the camshafts. Fluctuation in the angular velocity of the camshafts is thought to occur due to fluctuations in the motion of the camshafts as a whole resulting from resonance with the

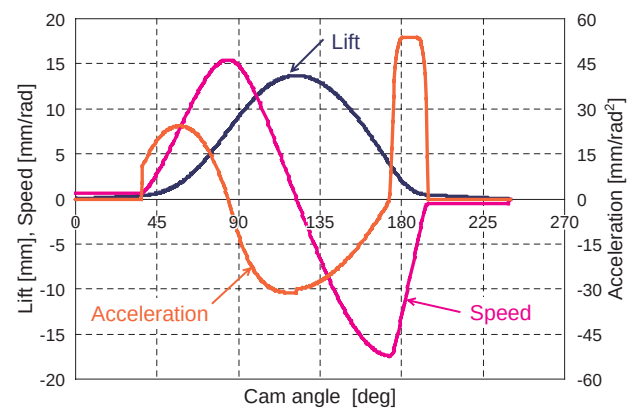


Fig. 7 Inlet lift curve of 2008 model

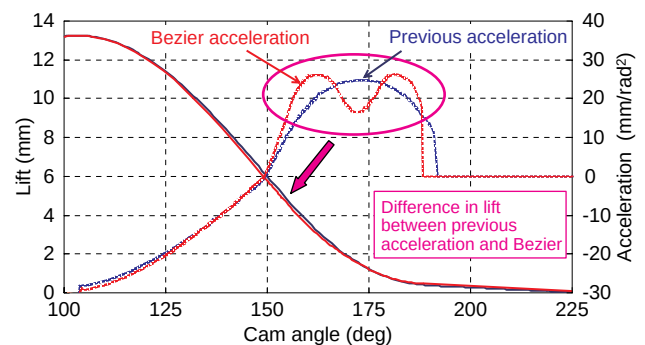


Fig. 8 Bezier lift curve

gear train, and the twisting of the camshafts between cam lobes due to the reaction force of the valve lift. It instantaneously increases or decreases the speed of rotation of the cams, reducing the motion of the valves. This makes it necessary to reduce the fluctuation of the angular velocity of the camshafts at high speeds. The following factors can be indicated as reducing fluctuations in the angular velocity of the cam:

- (1) The drivetrain moment of inertia
- (2) The drivetrain spring constant
- (3) Gear backlash
- (4) Cam drive torque
- (5) The damping coefficient of the dampers, etc.

Given that the cam drive torque is determined prioritizing vehicle dynamics performance in a Formula One engine, the remaining four factors were focused on. In addition, it was essential to reduce variation in the angular velocity of the cams without increasing the weight of the engine or raising its center of gravity, two factors that have a significant effect on vehicle body performance.

3.4.1. Angular Velocity Reduction System (AVRS)

The AVRS was a mechanism that reduced fluctuation in the angular velocity of the cams by attaching weights to the rear ends of the camshafts (on the side opposite the gear train) in order to increase the moment of inertia and shift the resonant frequency of rotational vibration to the low-speed range. Figure 9 shows the configuration of the AVRS and Fig. 10 shows its effect in reducing fluctuation in the angular velocity of the cams.

The use of weights to increase the moment of inertia of the camshafts and the adjustment of gear backlash

in order to control fluctuation of the angular velocity of the camshafts in the high-speed range increased the valve motion speed by 1500 rpm, and reduced friction by 6 kW.

3.4.2. Angular Velocity Reduction System with Gears (AVRS-G)

Figure 11 shows the configuration of the AVRS-G. Figure 12 shows fluctuations in the angular velocity of the camshafts. When the AVRS was employed, the fluctuation in the angular velocity of the rear ends of the camshafts became higher than that of the front ends, and there was therefore a margin for further reduction of fluctuations. The issue was considered to originate in the fact that the rear ends of the camshafts to which the weights were affixed were the free ends of the shafts. The AVRS-G was therefore developed. This mechanism employed gears to connect both the front and rear ends of the intake and exhaust camshafts, and increased the spring constant of the camshafts in their entirety. The use of the AVRS-G reduced the difference in twisting between the front and rear ends of the camshafts at the same time as reducing fluctuations in angular velocity, thus assisting in reducing the stiffness of the camshafts. This enabled the high specific gravity tungsten alloy used for the rear weights in the AVRS mechanism to be replaced by steel rear gears and the hollow diameter of the camshaft to be increased, resulting in a weight saving of 2 kg around the camshaft while maintaining identical valve motion.

3.4.3. Cam damper

While never employed in racing due to Honda's withdrawal from Formula One, the achievement of even

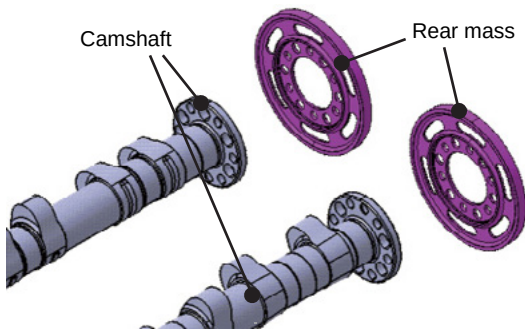


Fig. 9 View of AVRS

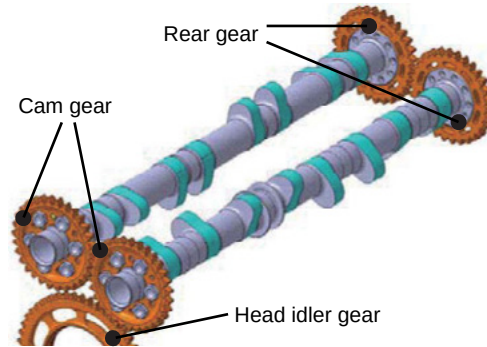


Fig. 11 View of AVRS-G

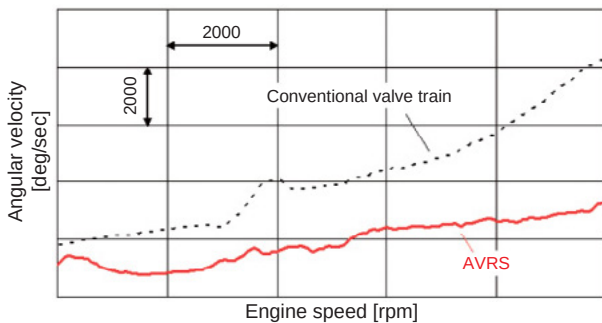


Fig. 10 Angular velocity of AVRS (2002 engine)

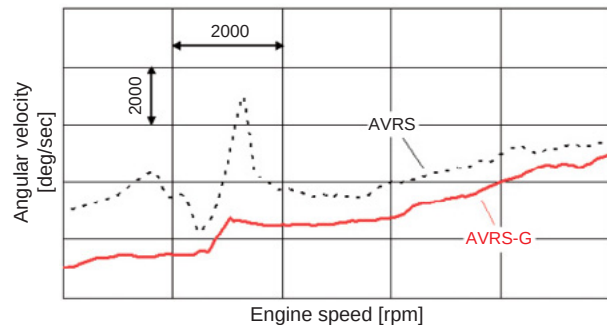


Fig. 12 Angular velocity of AVRS-G (2003 engine)

higher lift was studied in order to further increase power, making it necessary to correct a resulting decline in valve motion. As a means of achieving this goal, cam quills with a damping effect were developed to be fitted between the cam gears and the camshafts, and viscous dampers were attached to the rear ends of the camshafts. Figure 13 shows the configuration of the cam damper system, and Fig. 14 shows its effect in reducing fluctuations in angular velocity.

The stiffness of the quill shafts connecting the cam gears and camshafts and the viscosity of the silicon encased in the viscous damper were adjusted to achieve the desired damping coefficient. Cam drive torque and resonant frequency were calculated for each specification, and specifications that did not produce extreme peaks of fluctuation in angular velocity in simulations were employed.

The combined use of the quills and the viscous dampers reduced fluctuations in angular velocity, and increased the valve motion speed by 1100 rpm against the AVRS-G.

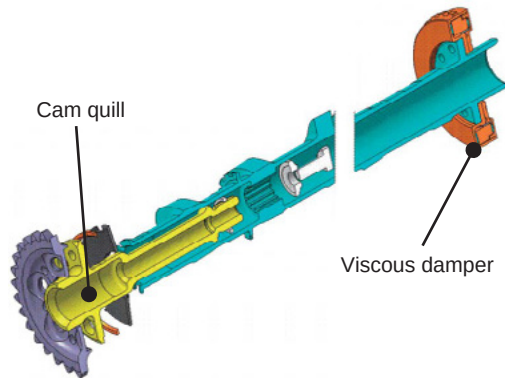


Fig. 13 Cam damper system

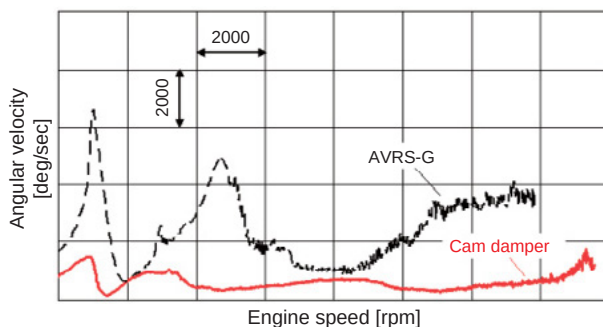


Fig. 14 Angular velocity of cam damper (2008 engine)

4. Friction Reduction Technologies

4.1. Progress in Friction Reduction

Figure 15 shows the progression of reduction of the motored friction of valvetrains in Honda Formula One engine developments from 2000 to 2008.

In the initial stage of development for Formula One, the reduction of reciprocating mass and the control of fluctuations in the angular velocity of the cam enhanced

valve motion and reduced lift load. In addition, the reduction of the level of oil in the PVRS cylinders was studied, and in 2005 the employment of a J-valve mechanism in an evolution of the PVRS enabled the oil level to be reduced to zero. These advances reduced friction by 20 kW in the 2005 V10 engine.

4.2. J-valve Mechanism

4.2.1. Aim of development of J-valve mechanism

PVRS is generally employed in the valvetrains of Formula One engines, which are high-speed engines, and Honda also employed the system from 1992.

Conventional PVRS used a check/relief mechanism, and supplied and discharged air with one-way valves fitted at the inlet and outlet of the PVRS cylinder to control pressure. However, the volume of air that could be used on a race was determined by the capacity of the bottle fitted in the vehicle, and it was necessary to control the volume of air consumption from the outlet. To enable this, a system was designed in which oil accumulated in the PVRS cylinder, and the discharge of the oil was prioritized over the discharge of the air. However, the oil generated agitation resistance during valve lift, and became a factor in increased friction.

Figure 16 shows the differences between the check/relief and J-valve mechanisms. Figure 17 shows the correlation between the level of oil in the cylinder, friction, and air consumption. The newly developed J-valve mechanism controlled air consumption by using a single orifice for supply and discharge of air. By separating air consumption from the production of

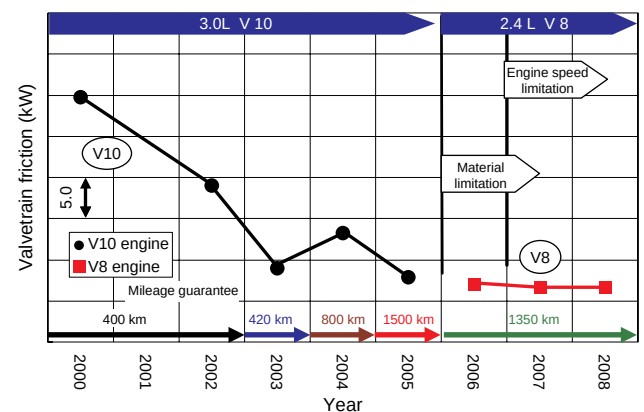


Fig. 15 Valvetrain friction performance

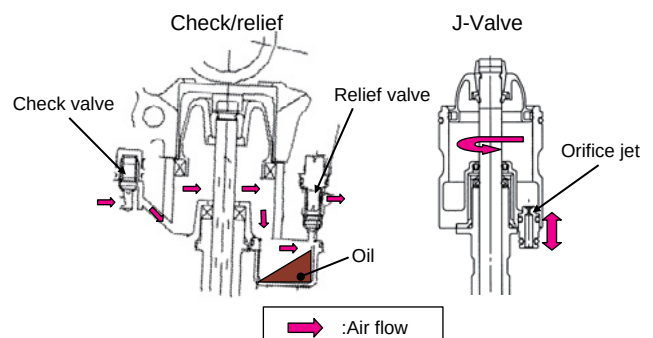


Fig. 16 Comparison of PVRS layout

friction, this mechanism obviated the necessity for oil in the PVRS cylinder, and reduced friction by 3 kW. In addition, doing away with the one-way valves and the air channels on the cylinder heads resulted in a weight saving of 1 kg.

4.2.2. Configuration of J-valve mechanism

Figure 18 shows the system configuration of the J-valve mechanism. One section of the system incorporates an air bottle, a primary decompression mechanism, and an electric air regulator designated P2 (P2 EAR), which regulates the supply pressure via an air injector. Air is supplied to the engine from this section. The outlet side is provided with an electric air regulator designated P3 (P3 EAR), which similarly regulates discharge pressure using an air injector. The development of these two EAR units enabled variable control of pressure.

Figure 19 shows a section view of the PVRS cylinder. Two concerns in the development of the J-valve mechanism were: 1) the feasibility of a configuration of the seal rings that helps prevent oil from flowing into the cylinder; 2) the durability and reliability of the stem seals in the absence of oil accumulation. To respond to these concerns, the seal rings were formed from PTFE jackets with a ripple shape and rubber rings with an X shape. This produced a stable tensile force and enhanced oil discharge performance. The durability and reliability

of the stem seals was increased by reexamining the configuration of the cylinder heads and employing a layout that enabled forced oil supply only to the seals.

4.2.3. Control

The J-valve mechanism was fundamentally designed as a configuration in which there was no oil inflow to the PVRS cylinder. However, the seals did allow tiny amounts of oil into the cylinder, which would increase the internal pressure of the cylinder if not dealt with. An increase in the internal pressure of the cylinder would lead to increased friction, and in addition seal ruptures and sliding abnormalities could occur and lead to engine troubles. In addition, the volume of oil inflow to each PVRS cylinder was unknown. To respond to this issue, a system of air line purge control was developed enabling forced discharge of the oil that had accumulated in the PVRS cylinder. Air line purge control enabled variable control of the pressure in the PVRS cylinder by means of electronic control of each EAR unit, and forced air flow through the air channels. Figure 20 shows a diagram of the P2 EAR unit.

The forced discharge of oil in the air line purge was conducted by increasing the pressure on the inlet side

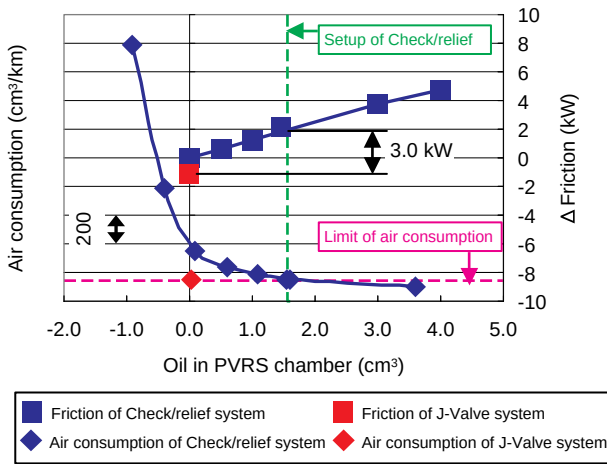


Fig. 17 Relation between air consumption and friction

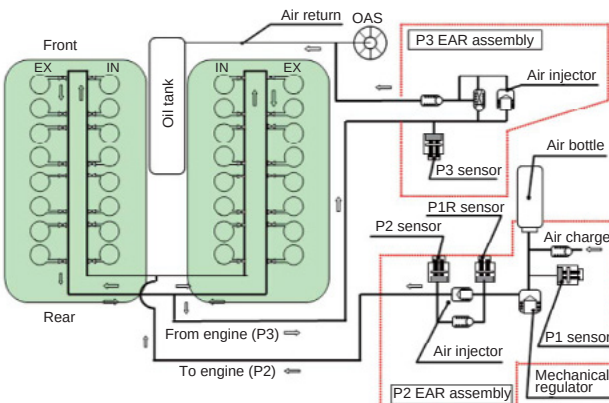


Fig. 18 J-Valve system configuration

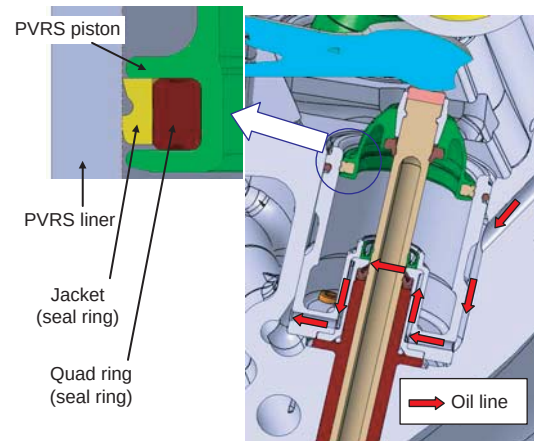


Fig. 19 Section view of PVRS cylinder

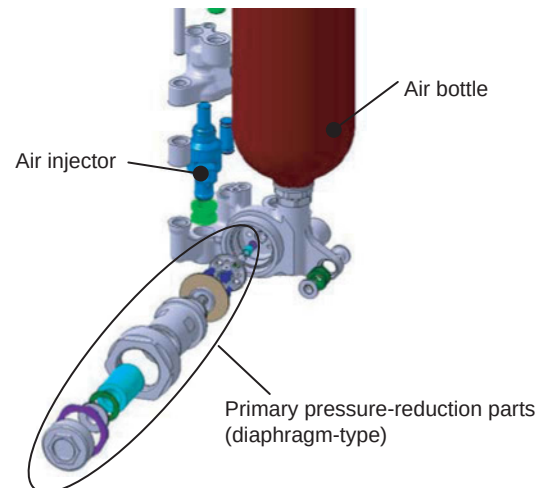


Fig. 20 View of P2 EAR

and creating a pressure differential with the outlet side. In order to achieve complete oil discharge, it was necessary to create a pressure differential that was able to generate an air flow speed of 25 ± 5 L/min, and to use a volume of 8 L or more of air. The air line purge was automatically conducted when a preset number of laps (distance) had been covered, and the oil was periodically discharged from the PVRS cylinder throughout the race. The air line purge could also be conducted manually in the event of abnormal functioning or during pit work.

When long mileage regulations for Formula One engines came into effect, the amount of use of the idling range (5500 rpm and below) increased. Because the inertial load in the valvetrain is low in the idling range and the lift load becomes dominant, cam surface pressure is high. This raised durability and reliability concerns over the sliding of the cam. To address this issue, a control method that helped prevent excessive lift loads in the idling range was developed which reduced the surface pressure of the cams and helped to ensure reliability and durability. Lift loads during idling were reduced by reducing the air channel pressure to a level lower than that of during race driving, using the P3 EAR unit. Figure 21 shows an overview of lift load switching control during idling.

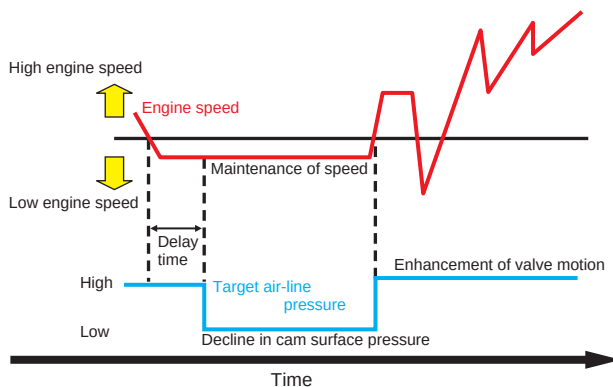


Fig. 21 Pressure control during idling

5. Conclusion

During Honda's Formula One engine development program between 2000 and 2008, the company developed a valvetrain reconciling the achievement of high speed with low friction. The following results were achieved:

- (1) Finger followers were employed as the valve drive method, and materials development was conducted and measurement technologies and CAE introduced to respond to materials and long mileage regulations, resulting in a 21.7 g (30%) reduction of the reciprocating mass of the valvetrain.
- (2) To respond to the necessity for increased power in order to maintain competitiveness, valve lift acceleration and the gear train layout were reexamined, enabling the allowable speed for the valvetrain to be increased by 2700 rpm.

- (3) The reduction of valve lift load through the enhancement of valve motion, the reduction of frictional losses through the use of a DLC surface treatment, and the reduction of oil agitation resistance through the use of a J-valve mechanism helped to reduce motored friction of valvetrain by 23 kW at an engine speed of 18000 rpm.

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