
Measurement Technologies for Formula One Engines

Nagao YANAGISAWA* Naoki HANADA* Takeru HAMAKAWA*
Kazushi OGIYAMA* Tetsuo GOTO*

ABSTRACT

In order to attain an accurate grasp of physical phenomena in the high-speed measurement environment of a Formula One engine, it is necessary to be equipped with measurement systems capable of high-volume, high-speed sampling. In addition, the accuracy of sensors and the vibration resistance of measurement equipment are important factors. It is also necessary to reduce the size and weight of measurement systems in order to conduct measurements during circuit driving. To respond to these performance demands, a variety of high-performance engine measurement systems were used in Formula One development projects.

This paper will discuss combustion diagnosis using a misfire detection system, measurement of combustion pressure and crankshaft behavior during circuit driving, oil pressure measurement, friction measurement, and the visualization and measurement of the fuel spray and in-cylinder flows.

1. Introduction

For all automotive engines, including the engines used in Formula One vehicles, engine development is inextricably bound to technological progresses and evolutions in the field of measurement. It has become standard procedure throughout the industry to determine specifications through the analysis of phenomena such as the vehicle's dynamic behavior, as typified by vibration and other parameters, combustion pressure, which is intimately related to the level of power of the vehicle, and the internal pressure of the inlet and exhaust pipes, which determines filling efficiency.

As Table 1 shows, the evolution of measurement technologies between Honda's second Formula One era (1983-1992) and third Formula One era (2000-2008) made it possible to conduct onboard measurements of combustion pressure, vibration, and dynamic behavior in an actual vehicle up to an engine speed of 20000 rpm. This technological evolution resulted from increased efficiency in packaging, for example the reduction of sensor size, increases in CPU speeds, and increases in measurement capacity, which helped to enable high-accuracy measurements in shorter periods.

With these advancements in measurement technologies, the range of areas in which measurements could be taken increased, and it became possible to obtain a more accurate understanding of engine phenomena.

As a result, it became possible to rapidly determine

Table 1 Comparison of contents of measurements

Item	Second era	Third era
Combustion pressure	Only one cylinder is measured (Only dyno)	All cylinders are measured (Dyno and circuit)
Crankshaft twist vibration	Only dyno	Dyno and circuit
Engine vibration	Only dyno	Dyno and circuit
Gear train vibration	Measurement is impossible	Measurement of all gears is possible (Only dyno)

engine specifications and resolve issues, and thus to supply high-quality engines within a shorter time frame.

At the end of 2006, new regulations placed restrictions on changes to almost all engine specifications. From 2007, engine development focused on the achievement of increased power and reliability by means of small changes within the scope allowed by the regulations, and it was necessary to change development methods accordingly.

It was important to make accurate decisions on whether or not to employ specific proposals within a restricted scope of potential changes, necessitating a transition to methods incorporating computer aided engineering (CAE) in order to study results in advance.

The establishment of an accurate correlation between actual phenomena and CAE results is an important factor in the introduction of CAE, and thorough studies were therefore conducted using single-cylinder engines.

This paper will provide an introduction to the latest measurement technologies for Formula One engines.

* Automobile R&D Center

2. Measurement Technologies

2.1. Combustion Measurements

2.1.1. Misfire detection system (MDS)

Because of the high speed of Formula One engines, the combustion process is completed in a short period. In addition, the on-off load when switching from wide-open throttle to fully-closed throttle is constantly repeated. Because of this, the frequency of use of the engines in an unstable state of combustion is high. A misfire detection system (MDS) that is able to diagnose the state of combustion under these conditions using ionic current was developed, and employed in all races from 2002.

Figure 1 shows the mechanism of generation of ionic current. It has long been known that radical ions are generated during the combustion process. Ionic current is detected using the following two processes, and the waveforms have two peak values⁽¹⁾:

- (1) Detection of relatively long-lived $C_3H_3^+$ radical ions (chemical ions) generated when the flame surface passes through the electrode during the initial stage of combustion.
- (2) Detection of NO_2^+ radical ions (thermal ions) generated by thermal dissociation of N_2 in combustion gases at temperatures of 2000 K or higher.

Figure 2 shows the principle of ionic current measurement. With the central electrodes of the spark plugs used as ion probes, a positive electrical potential of approximately 300 V is impressed, and the $C_3H_3^+$, CHO^+ , and NO_2^+ radical ions generated by combustion are captured.

The ignition coil energy is stored in the condenser and used as a power source.

Honda's Formula One engines utilized a condenser discharge ignition (CDI) system with a discharge time of 70 μs . This minimized the effect of ignition noise, helping to enable the greater part of the combustion period to be monitored.

Lean air-fuel mixtures are used during low fuel consumption operation, but in this state engine hesitation can occur and acceleration performance out of corners can decline. Engine hesitation results from misfires, or combustion states close to misfire, due to

the leanness of the air-fuel ratio falling below the limit for combustion with a rapid increase in the volume of intake air.

The MDS was developed in order to analyze this phenomenon.

Figure 3 shows a comparison of detected MDS values for the A/F setting for maximum power and a lean A/F ratio during acceleration. For the maximum power A/F ratio setting, the transition from a lean to a rich ratio occurs in a short period. The period during which MDS values are generated is also minimized, and combustion stabilizes rapidly. However, for the lean A/F ratio setting, the period during which MDS values are generated continues, and an unstable combustion state continues. This generates conspicuous hesitation.

The development of a technology that helped to enable monitoring of the state of combustion during vehicle operation made it possible to set appropriate A/F ratios for the atmospheric conditions of each circuit.

2.1.2. Combustion pressure sensor integrated with spark plug (PS plug)

Combustion pressure measurements were conducted constantly during the Formula One engine development program, but the following technological issues arose with regard to measurements using combustion pressure sensors:

- (1) Low degree of freedom of layout

Limitation of areas for mounting of sensors due to engine configuration, resulting in inability to measure pressure in all cylinders.

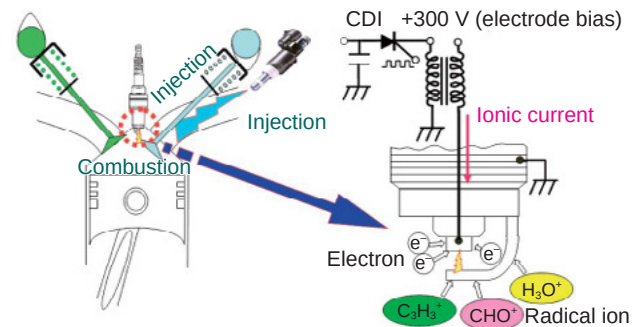


Fig. 2 Ionic current measurement principle

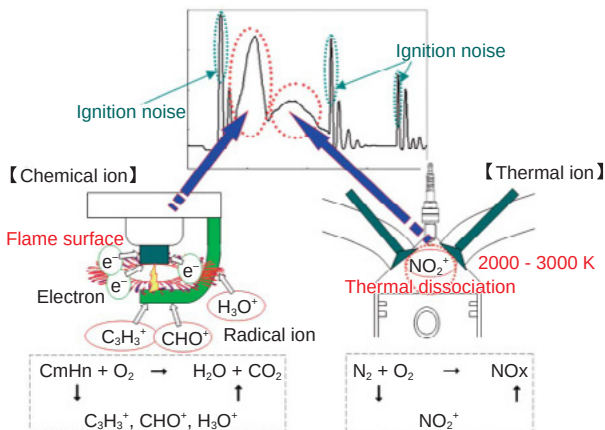


Fig. 1 Mechanism of ionic current

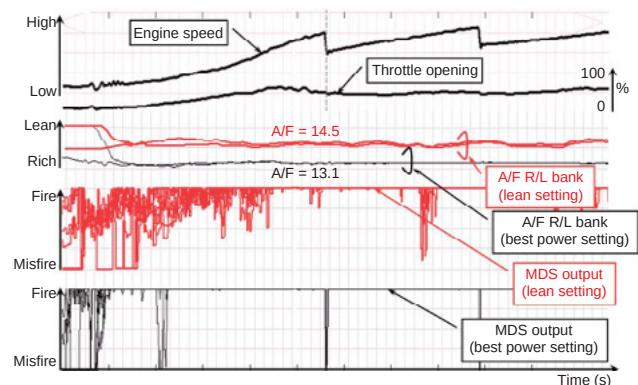


Fig. 3 Detected misfire

(2) Low level of durability and reliability

Sensors damaged by a high level of vibration due to high engine speeds.

Given this situation, a combustion pressure sensor integrated with a spark plug (termed a "PS plug" below) was developed as a technology for conducting pressure measurements in all cylinders.

Figure 4 shows the shape of the PS plug, and a measured combustion pressure waveform.

Comparison of combustion pressure measurements obtained using the PS plugs in test bed tests with pressure measurements taken using existing sensors showed that the plugs performed well.

The use of the PS plugs made it possible to bypass the limitation on sensor mounting positions and measure pressure in all cylinders, and thus to understand the differences in combustion pressure between cylinders.

Figure 5 shows the results of combustion pressure measurements taken during circuit driving and results for engine power calculated from the indicated mean effective pressure (Pmi) from the measurement results.

The indicated power calculated from the Pmi on the circuit displays identical values to those obtained from a torque meter mounted on the gearbox, indicating that the PS plug accurately measures combustion pressure even during circuit driving.

2.2. Crankshaft Torsional Vibration

Normally, the excitation of torsional vibration of the crankshaft is determined by the sum of the inertia of the reciprocating parts such as the pistons and the conrods,

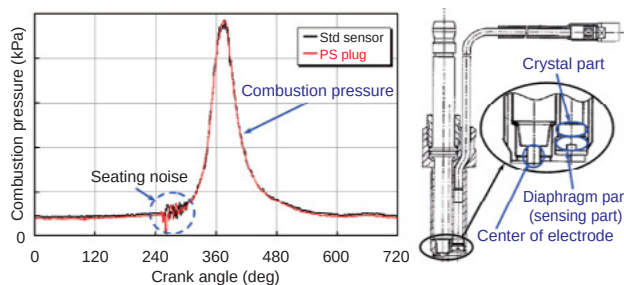


Fig. 4 Combustion pressure force and shape of PS plug

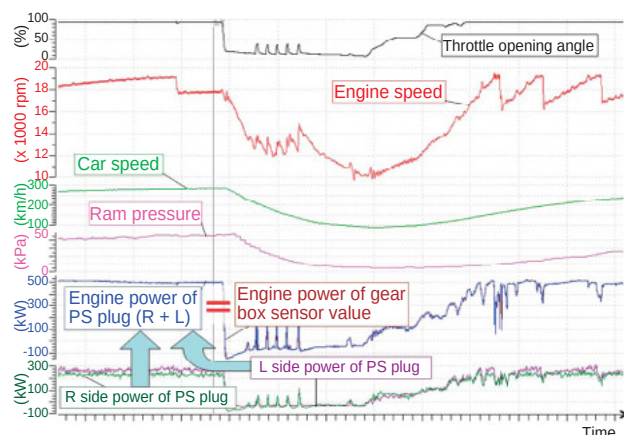


Fig. 5 Circuit running data

and the rotational torque resulting from combustion pressure.

Because Formula One engines operate at high speeds, the inertia of the reciprocating parts is dominant in the load on the crankshaft pin journals, and the load exceeds 50 kN at its maximum.

The crankshaft has a specific vibration frequency determined by its specific torsional stiffness and rotational inertia. However, resonance is generated by the excitation force mentioned above, and this can result in large torsional vibrations, the amplitude of which exceeds 1 deg.

Because Formula One engines use a central oil supply system, as shown in Fig. 6, part of the crankshaft is hollow, resulting in a decline in strength against a solid crankshaft. For this reason, torsional resonance might cause breakage of the crankshaft.

In the 2002 Formula One engine, torsional vibration resonating in three engine speed orders at high speeds under a motored condition became an issue. In terms of circuit driving conditions, this corresponded to closed-throttle in the straight ends; the frequency of such use is high, and this has an effect on the durability of the engine. In fact, crankshafts broke twice on circuits. Because torsional vibration occurred at high engine speeds, it represented an impediment to increasing the speed of the engine in order to increase power.

The analysis system configuration shown in Fig. 7 was used to measure the torsional vibration of the crankshaft on the bench and on the track, and the origins of the phenomenon were analyzed.

Because high-speed sampling was necessary, a data logger able to measure up to 200 kHz was used to record pulse signals for the detection of crankshaft rotation signals. These signals were converted into frequencies and the changing component of the signal was isolated. A Fourier transform was further applied to the changing signal component, helping to enable the torsional vibration of the crankshaft to be understood.

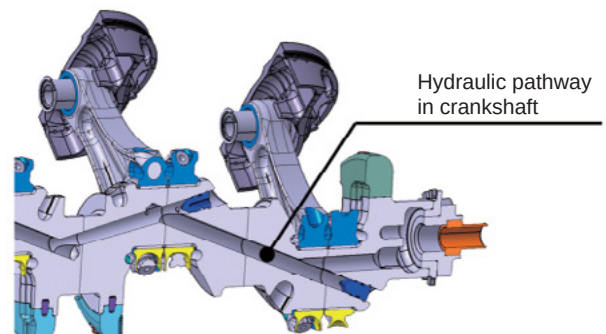


Fig. 6 Section of Formula One crankshaft

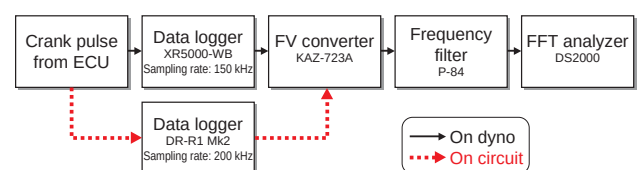


Fig. 7 Analysis system configuration

The results showed that the increase in torsional vibration originated in the bank angle used to lower the center of gravity. In the 2003 Formula One engine, the bank angle was reduced from 94° to 90° , reducing torsional vibration of the crankshaft.

Results were also verified using the vibration simulation Blinks, manufactured by AVL Japan, K.K., in parallel with the measurements.

Figure 8 shows the simulation results obtained using Blinks and the measurement results.

The level of vibration at high engine speeds under a motored condition, which was an issue in the 2002 Formula One engine, was alleviated in the 2003 engine.

The good correlation between the simulation results and the results of vibration measurements in an actual vehicle demonstrated the effectiveness of the simulation.

As indicated by the discussion above, understanding the torsional vibration of the crankshaft when operating at high speeds necessitated high-speed sampling, and advances in data logger technology made these measurements possible.

2.3. Hydraulic Pressure Measurements

The major issues for the durability and reliability of the conrod bearings are wear resistance and seizing resistance. To address these issues, changes were made in the bearing materials, and the viscosity, amount, pressure and aeration of the lubricating oil were modified.

Formula One engines employ a central oil supply system, in which the centrifugal force of the crankshaft is used to supply oil to the conrod bearings.

Because of this, only the pressure in the hydraulic pathway of the crankshaft could be measured in order to measure actual hydraulic pressure. This necessitated a technology to output the signal from pressure sensors in the hydraulic pathway to the exterior of the engine.

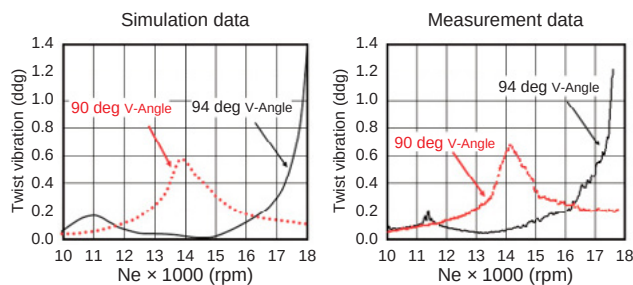


Fig. 8 Simulation results and measurement results

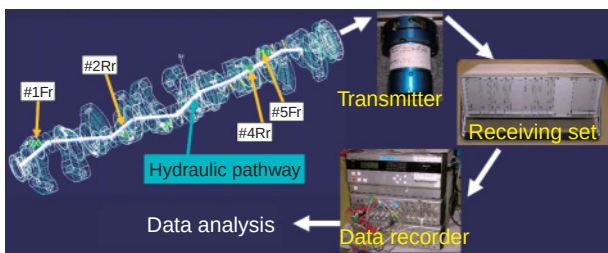


Fig. 9 Analysis system configuration

Figure 9 shows the configuration of the hydraulic pressure measurement system.

Previously, a contact-type slip ring using mercury as a physical signal path had been employed to guide signals from the crankshaft. However, engine speeds continued to increase, and the range of speeds at which this method could be used was limited. This was a result of the limits of the capacity of seals to deal with the heat generated and the fluid leaks occurring when mercury flowed at high speeds in the cylinders.

To replace this method, wireless technology was employed to transmit the signal outside the crankshaft. By contrast with the use of the slip ring, the wireless method involved no contact, and therefore resolved the associated issues. In addition, increases in the computational speed of the CPU of the receiver helped to enable measurements within the actual range of engine speeds. The noise resistance of this method was low compared to the contact method, but insulating materials were used to protect the receiver.

Figure 10 shows an example of measurements taken in a hollow crankshaft.

Because in a hollow crankshaft the hydraulic pathway does not have to pass the center of rotation of the crankshaft, the decline in hydraulic pressure downstream (due to pressure loss in internal pipes and pressure loss due to Coriolis force), a constant issue in central oil supply systems, was minimized and the average hydraulic pressure increased. The effect of the hollow crankshaft was estimated in simulations, but pressure measurements in the internal hydraulic pathway of the crankshaft verified the effect. In addition, the effect of noise was minimized, and a good understanding of the differences between specifications was obtained.

2.4. Linking Method

The use of the linking method to conduct measurements is not a new technology, and is used in mass production engines. However, in high-speed Formula One engines, the acceleration component of the inertial force on the links is 10000 G at 19000 rpm, approximately twice the force in a mass production engine. This difference necessitates high-stiffness and ultra-low weight links, and therefore significantly affects the design of the linking mechanisms.

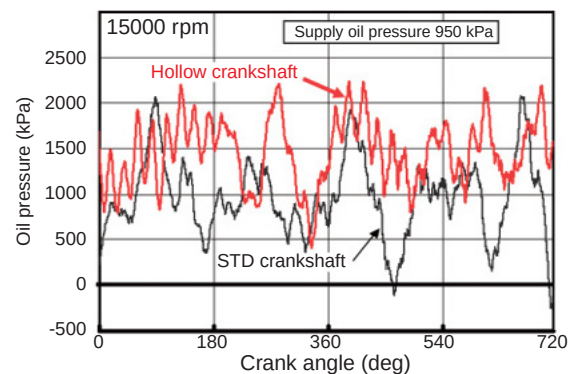


Fig. 10 Pressure in hydraulic pathway

Figure 11 shows a linking mechanism used in a Formula One engine.

For Formula One engines, the linking mechanisms were incorporated in the single cylinder engines used for analyses.

To reduce weight, the linking mechanisms were cut from aluminum alloys. The covers used to hold the lead wires were all produced from CFRP in order to further reduce weight. In addition, to maintain stiffness, a box section was used for the sectional shape of the linking, helping to ensure a secondary moment acting on the section. Small NTN bearings with an internal diameter of 7 mm and an external diameter of 11 mm were employed in the connections to help ensure a smooth sliding motion.

In conrods, the end connected to the piston, which displays a linear reciprocal motion, is called the small end, and the end connected to the crankshaft, which displays a rotary motion, is called the big end. The two ends are joined by the shaft. Because the shafts of the conrods are constantly subject to complex forces representing a combination of linear and rotary motion, stress concentrates in this section, and the magnitude of this stress can exceed the breakage limit of the shaft material. Conrod shaft breakages occurred during Honda's third Formula One era, and the reliability of the conrods formed an important development agenda.

Figure 12 shows an example of a conrod breakage, the result of a CAE analysis, and the set-up used in the linking method.

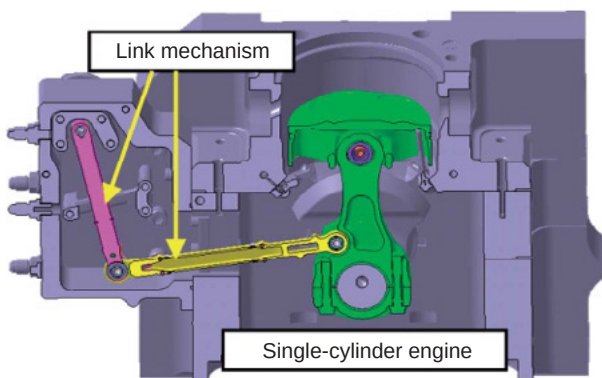


Fig. 11 Link mechanism for Formula One engines



Fig. 12 Failure example, CAE result, linking system type

The point of breakage of the conrods was close to the small ends, where strength was lower. To analyze these breakages, CAE analysis was employed to suggest potential reasons for the concentration of stress. Following this, the development of a measurement method using the linking method proceeded, and analysis of the phenomenon in single cylinder engines commenced in 2004.

Figure 13 shows the results of measurements of conrod torsional resonance using the linking method. The measurement results showed that torsional resonance was produced in the conrods at full engine loads. In addition, the fact that resonance did not occur when no load was acting and the inertial force was therefore dominant indicated that the conrods were twisting due to excitation by gas pressure and bending of the crank pins.

As this demonstrates, the linking method as used in Formula One analyses demonstrated a sufficient level of accuracy even in measurements at 19000 rpm, and the link mechanism also displayed sufficient durability. This made it possible to understand internal engine phenomena such as reciprocating motion, and technologies for the quantification of these phenomena contributed in numerous ways to engine development.

2.5. Friction Measurement Using the Floating Liner Method

The friction generated in the various parts of the engine is one of the factors that impedes the achievement of increased power, and the accurate measurement of friction is therefore an important issue. Friction in the reciprocating parts represents approximately 60% of total engine friction, and its mechanism has still not been clarified. This section will discuss the floating liner method, a new method of measuring friction in the reciprocating parts.

Broadly speaking, friction in the reciprocating parts can be divided into the following three types:

- (1) Sliding friction between the pistons and the sleeves
- (2) Sliding friction between the conrod bearings and the crank pins
- (3) Friction due to agitation of the oil in the crankcase

Of these, the floating liner method was developed to measure (1), sliding friction between the pistons and the sleeves.

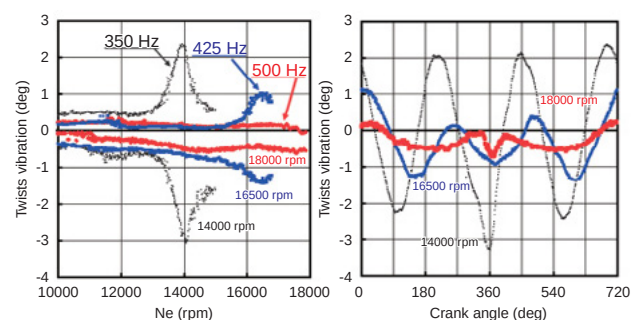


Fig. 13 Twist vibration measurement results for connecting rod

Figure 14 shows a cutaway of the test apparatus used in the floating liner method.

The feature that sets this apparatus apart from standard floating liner test apparatuses is the fact that it has been designed for use at high speeds. Standard test apparatuses are constructed of iron alloys or aluminum alloys, and they have a range of measurement of up to 5000 rpm. However, at high engine speeds the liner resonates in the same direction as the motion of the pistons, and measurement accuracy declines. To resolve this issue, the liner in the new apparatus was constructed from beryllium in order to reduce its weight and control the occurrence of resonance. In addition, the load sensor was positioned at the top of the liner to help ensure stiffness in the mounts. This positioning prevented the mechanism from being used for the measurement of firing, but in a later specification, combustion pressure was artificially produced to simulate firing conditions. Using a mechanism to introduce air to the combustion chamber, the pistons could be used to compress the air, making it possible to freely increase pressure up to 10 MPa.

Figure 15 shows an example of measurements using the initial apparatus specifications.

The graph on the left shows figures from the load sensor in the up-down direction (the direction of piston motion). Adjustment of the crank angle made it possible for the floating liner method to be used to analyze friction in each stroke. The integral of each rotation corresponded to the sliding friction between the piston and the sleeve in each cylinder, making it possible to quantify sliding friction.

The graph on the right shows figures from the load sensor in the left-right direction (the direction of the rotating surface of the crankshaft, orthogonal to the direction of piston motion). These results show the

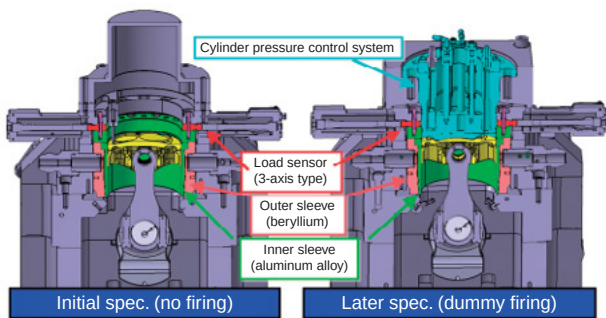


Fig. 14 Floating liner mechanism

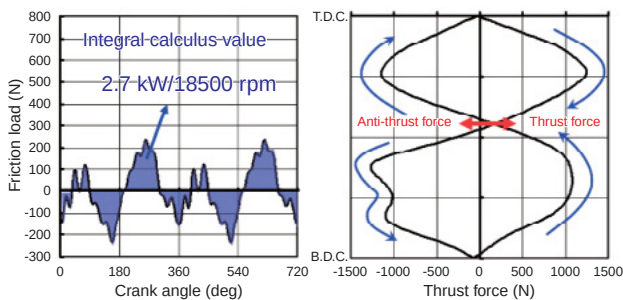


Fig. 15 Sliding friction measurement result

changes in thrust and anti-thrust force for each stroke.

As the discussion above indicates, it became possible to measure the friction in each stroke and use the results in analyses of the form of the piston skirt and other parameters.

2.6. Visualization Technologies

2.6.1. Fuel spray visualization technology

Due to the latent heat of vaporization, the atomization of the fuel cools the intake air, increases filling efficiency, and advances combustion. These effects result from the droplet diameter and the penetration, which change with the fuel injection pressure, but a measurement method for quantifying these parameters was previously unavailable.

The fuel injection pressure of the electronically-controlled fuel injection system (PGM-FI) used in the turbocharged engines employed during Honda's second Formula One era was 0.25 MPa. Following this, a 1.2 MPa high-pressure system was developed in 1987 and used for 17 years until 2004, in Honda's third Formula One era. From 2005, the increase in pressurization was accelerated and a 5 MPa system was used, with a 10 MPa system following in 2006. This section will discuss the fuel spray visualization technology used in the analysis of droplet diameter and penetration in this process of increasing pressure.

The fuel spray has a three-dimensional form that changes with the elapse of time. The following parameters were focused on:

- (1) Droplet diameter
- (2) Diffusion
- (3) Penetration
- (4) Form angle and form

Of these, the form angle and form could be controlled to a certain extent by means of the direction of the nozzle, but droplet diameter, diffusion, and penetration are affected by the shape of each injector hole, and a number of nozzle shapes was therefore used in measurements.

Figure 16 shows an external view of the measurement device, a phase Doppler particle analyzer (PDPA), and the measurement principle.

The PDPA bombarded the fuel spray with a continuous laser beam, and measured the droplet diameter and flow speed by applying signal processing to the scattered light. The flow speed was measured at the point where the two laser beams intersected.

Fuel particles entered this point, and the scattered

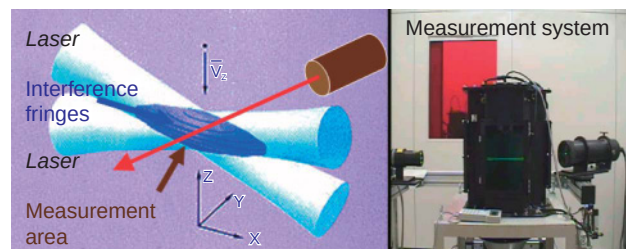


Fig. 16 External view of PDPA hardware and measurement principle

light was captured by a receiver and transformed into an electrical signal. Using a fast Fourier transform (FFT), the frequency was analyzed and the speed of the particles was calculated.

Droplet diameter was measured using the phase difference between burst signals monitored by multiple photomultiplier tubes. The droplet diameter was calculated by correcting the frequencies of the light that was diffracted differently, depending on the size and shape of the droplets.

Figure 17 shows the distribution of droplet diameters in the fuel spray, as measured using the PDPA.

To help enable detailed analysis of the PDPA measurement results, the form of the fuel spray directly underneath the injector holes was visualized using the SprayMaster magnified imaging apparatus manufactured by LaVision GmbH.

Figure 18 shows a fuel spray as imaged using SprayMaster.

Using SprayMaster, transmission images of the cross-sections of sprays were captured using a laser, and employed in parameter comparisons of fuel injection pressure and injector holes, and comparisons of the characteristics of the sprays produced by injectors with different numbers of holes.

The SprayMaster apparatus contributed to the achievement of increased efficiency in the development of fuel systems, assisting in tasks including the determination of specifications in injector development and the simulation of in-cylinder fuel distribution.

2.6.2. Optical engine technology

Understanding the flow and turbulence phenomena of the air-fuel mixture in the combustion chamber is

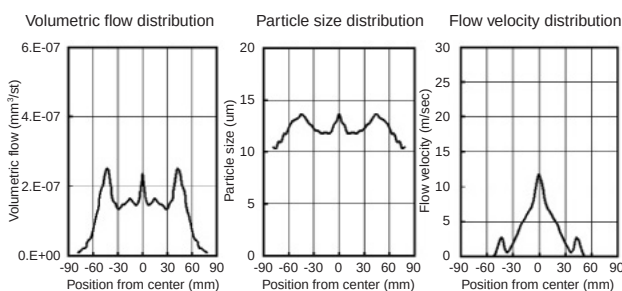


Fig. 17 Fuel spray measurement results

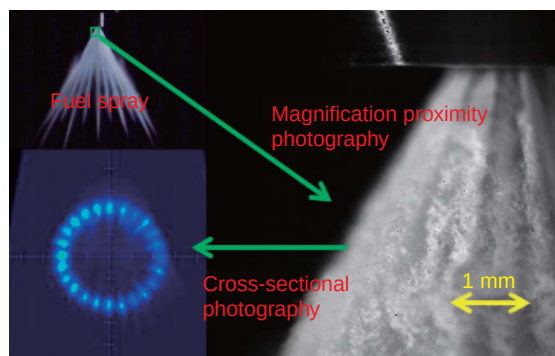


Fig. 18 Macrophotography using SprayMaster

important to the realization of rapid combustion. The optical engines were used to enable measurement of flow and turbulence in the combustion chambers of Formula One engines.

This section will discuss the engine visualization method, measurement results, and validation results of simulation.

Figure 19 shows a cross section of the optical engine.

As in the case of the linking and floating liner methods discussed above, a single cylinder engine was used for the optical engine from considerations of ease of modification and versatility. A special sleeve made from silica glass was fitted to part of the cylinder block. A glass sleeve height of 40 mm made it possible to visualize the entire cylinder stroke.

Particle image velocimetry (PIV) was used for the measurement of the flow motion of the gas in the combustion chamber. The system utilized a YAG laser with a second-order harmonic of 532 nm, and a cross-correlation CCD camera for imaging. A synchronizer was used to synchronize the two devices.

Ultra-lightweight tracers, which are hollow resins with a diameter of 40 μm or less, were used for the visualization of flows. FFT cross-correlation was used in the analyses.

Special piston with extended crown was used, and measurements were performed at engine speeds of 10000 rpm.

Figure 20 shows PIV measurement results and simulation results.

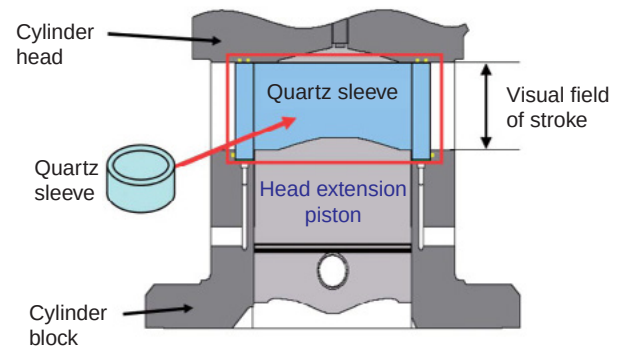


Fig. 19 Visualization engine

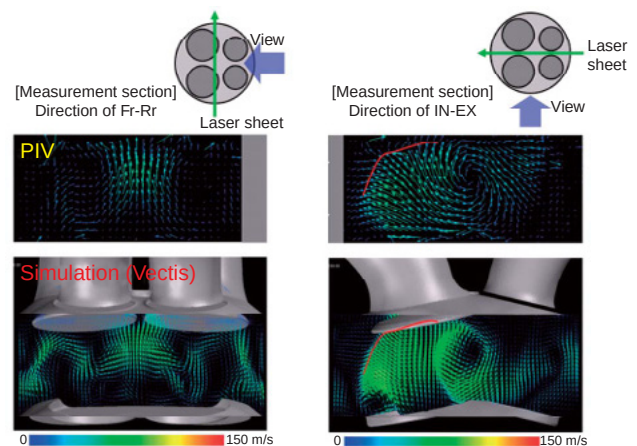


Fig. 20 Measurement result and simulation result

PIV measurements helped to enable the phenomenon of gas flow in the combustion chamber to be understood. Based on the results of visualization, validation of the gas flow simulation software VECTIS made by Ricardo plc was performed. Thereby, it became possible to accurately predict the flow motion of gas in the combustion chamber using the simulation. In addition, by performing similar validations, analysis of the behavior of fuel spray and the process of combustion (flame propagation) in the combustion chamber can be conducted using VECTIS, and the efficiency of development enhanced.

3. Conclusion

This paper has discussed measurement technologies employed in the engine development program in Honda's third Formula One era. The vast majority of these technologies were unavailable during Honda's second Formula One era, and it is no exaggeration to say that they provided the basis for the evolution of Honda's Formula One engines during the third era. The authors believe that the fusion of the measurement technologies fostered by the Formula One development process with the measurement technologies employed in the development of mass production engines, will assist in the development of environmental technologies and in increasing the efficiency of the development process.

Reference

- (1) Shimasaki, Y., Sakaguchi, J., Maki, H., Suzuki, H., Kato, A., Nishizawa, K.: Study on Combustion Monitoring System for formula One Engines Using Ionic Current Measurement, Honda R&D Technical Review, Vol. 17, No. 1, p. 56-64

■ Author ■



Nagao YANAGISAWA



Naoki HANADA



Takeru HAMAKAWA



Kazushi OGIYAMA



Tetsuo GOTO