

Study on Combustion Monitoring System for Formula One Engines Using Ionic Current Measurement

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ABSTRACT

A combustion monitoring system has been developed by applying ionic current measurement for malfunction diagnosis and combustion management of Formula One engines. In this system the spark plug's center electrode acts as an ion probe for ionic current measurement, which eliminates the need for additional sensors. The system allows the onboard monitoring of each of the cylinders for their combustion status under all operational conditions. The accuracy and reliability has ensured that the technology can be effectively used for the management of Formula One engines with car-to-pit communication carried out via telemetering. It is capable of various types of controls including detection of misfire, hesitation, detonation and the lean-burn condition. In addition to these points, this paper reports on the relationship between the spark plug center electrode configuration and the absolute quantity of ionic current.

1. Introduction

In recent years, passenger cars are using onboard diagnosis (OBD) systems in order to prevent air pollution due to the risk of large volumes of hazardous exhaust gas being emitted from malfunctioning vehicles. These systems include systems for high-rpm, high-power engines that detect misfiring by measuring ionic current. Figure 1 shows a vehicle that utilizes the ionic-current misfire detection system.

A Formula One engine, on the other hand, consists of the combination of a wider rpm range and larger bore diameter for high power. These features have posed a problem in achieving stable combustion throughout the wide rpm range. Additionally, in case a technical failure or malfunction should occur, the engine is required to detect the problem location and identify the cause with high accuracy and take the necessary measures in a limited period of time.

This paper reports on ionic current measurement technology for mass production vehicles being developed and used effectively in Formula One engines in order to resolve the issues mentioned above.



Fig. 1 Vehicle with ionic current measuring system

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2. Mechanism of Ion Generation and Measuring Principle

It has been known for a long time that ions are generated during engine combustion. It is thought that ionic current is generated via two different generation processes explained below. As a result, the ionic-current waveform has two peak values (Fig. 2).

- (1) One peak detecting relatively long-lived ions including $C_3H_3^+$ generated when the flame surface ends pass through the electrode during the initial stage of combustion.
- (2) The other detecting the NO^{2+} ions generated as a result of thermal dissociation of N_2 in combustion gasses with a temperature of 2000K or higher.

Figure 3 shows the principle of ionic current measurement. An ion probe installed inside the combustion chamber is energized with positive electrical potential at approximately 300V. With the energization, ions of $C_3H_3^+$, CHO^+ , NO^{2+} and others are generated due to the engine's combustion and these ions are captured. The center electrode of the spark plug is used as an ion probe and the ignition coil energy is stored in the condenser making use of the energy as a power source. This configuration, which ensures simplicity, is the one most commonly used. However, the system is not capable of measuring the current when discharge is taking place. In particular, when used in conjunction with a full transistor ignition system, which is characterized partly by a prolonged inductive discharge of approximately 1msec., measurement accuracy tends to deteriorate due to an overlap of induced discharge over the period of combustion. In the case of Honda's Formula One engine, the discharge process is completed in approximately 70 μ sec., which is achieved due to the incorporation of a condenser discharge ignition (CDI) system. This allows almost the entire combustion process to be monitored.

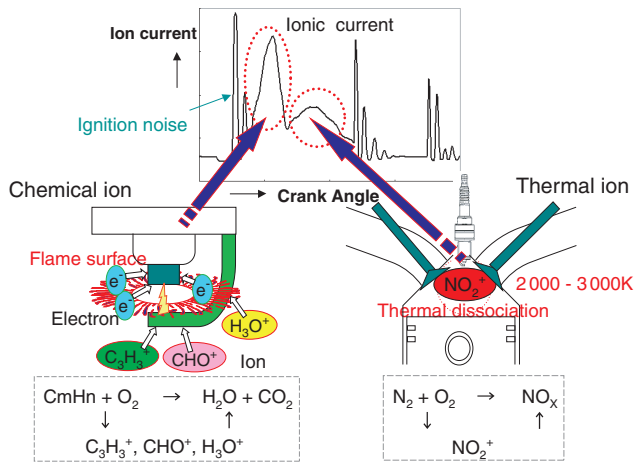


Fig. 2 Mechanisms of ionic current generation

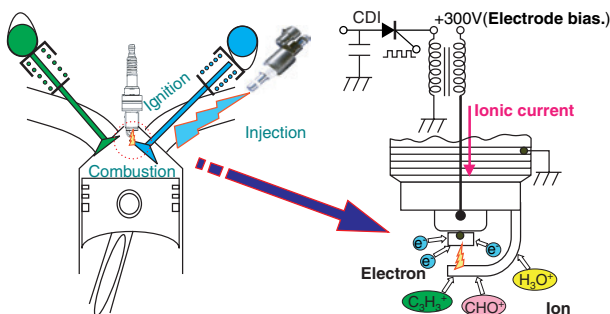


Fig. 3 Principle of ionic current measurement

3. System Configuration

With the CDI system incorporated, the energy stored in a large-capacity condenser of the CDI unit is led to the primary coil by the thyristor, generating high voltage at the secondary coil unit. This ionic current detection system regulates part of the energy outgoing to the ground due to ignition by means of a 300V zener diode. The energy thus regulated is then stored in a condenser, forming a part of the misfire detection system unit (MDS unit). This system was designed so that the energy stored at a voltage level of 300V would provide positive bias voltage to the spark plug center electrode after the completion of discharge. The reason why a positive voltage is applied is that it is thought that it is possible to detect greater amount of ionic current by capturing electrons instead of positive ions, which have larger mass per charge and move over shorter distances when an electric field is applied. Figure 4 depicts the relationship between the bias voltage direction and the ionic current detection amount⁽¹⁾. It shows that capturing positive ions inside the combustion chamber with its relatively large surface area, and capturing electrons with the central electrode with its relatively smaller surface area results in detection of a larger amount of ionic current. This allows improvement in the signal-to-noise (S/N) ratio of the system and raises the detection precision.

Ionic current is detected as a voltage value according to the detection resistance (shunt), and then digitized via two operational amplifiers, one for integration and the other for resetting. Following this, the digital signal is transmitted to the engine control unit (ECU) either through pulse width modulation (PWM) or via high-speed serial communication and from there is used for engine control and for provision of information to the pit via telemetering. The configuration of the ionic current measurement system is shown in Fig. 5.

The MDS unit is compact in size and the case is made of magnesium alloy for reduced weight. Also, two Deutsche Auto Sport connectors are used, one for power supply and one for input/output, to ensure reliability. The MDS unit can be seen in Fig. 6.

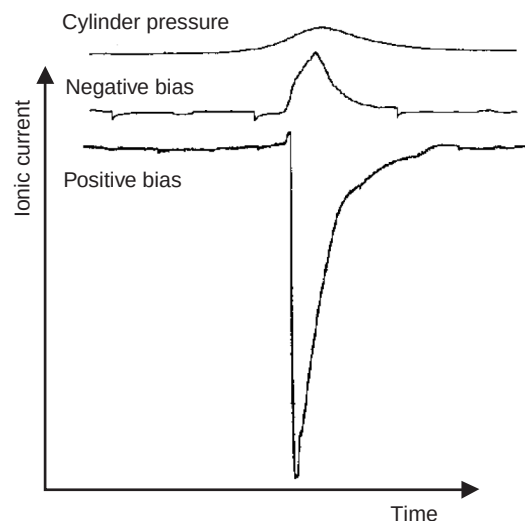


Fig. 4 Relationship between direction of bias voltage and amount of ionic current

The ignition coil uses an exclusive pin as an output terminal for measurement of ionic current in addition to two ordinary pins for the CDI input and ground. This makes the induction discharge time extremely short, about 70 μsec . Figure 7 is a picture of the ignition coil for ionic current measurement.

The MDS unit is located at the side of the body, close to the ECU. In order to minimize the negative effect of the stray

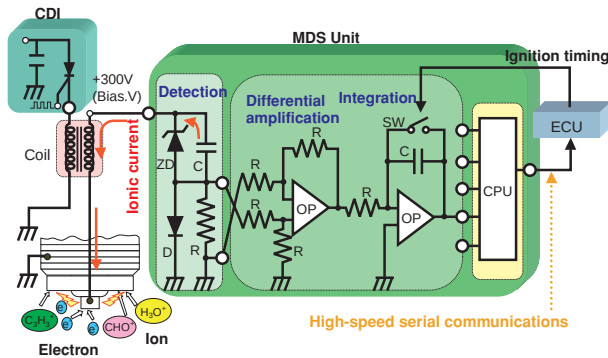


Fig. 5 Configuration of ionic current measuring system

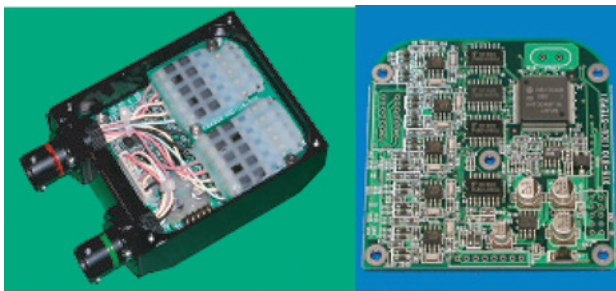


Fig. 6 MDS unit

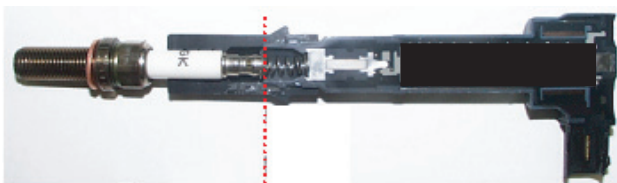


Fig. 7 Ignition coil for ionic current measurement



Fig. 8 Example of system installation

capacitance of the wiring harness, a measure against noise was taken for the circuit and sealed wiring was eliminated. An example of the system installation on a vehicle is shown in Fig. 8.

4. Misfire Detection System

The diagnosis system was so designed that it would provide a comprehensive detection of malfunctions in addition to misfire through synchronization with other sensors, to identify which component was displaying the failure, and measure the frequency of the failure and grasp the state of the malfunction in detail (Fig. 9).

As for the misfire detection flow, the ionic current is integrated in the designated area for gating. The system judges that misfire has occurred if the value is lower than a predetermined threshold. Furthermore, if the threshold is not satisfied for a specific number of times, the system determines that a malfunction exists. The gating range was set up to eliminate electric vibration occurring inside the ignition coil during and after discharge (Figs. 10 and 11).

Figure 12 shows the state of ionic current generation with and without a misfire. As can be seen from this figure, in the case that misfire occurs, no ions are generated by combustion, which results in a low ionic current integral value, whereas a large number of ions are generated during normal combustion and the difference between the two is very clear. The difference between the two is

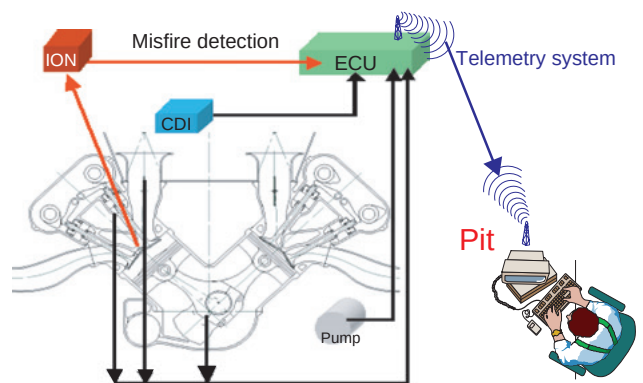


Fig. 9 Diagnosis system configuration

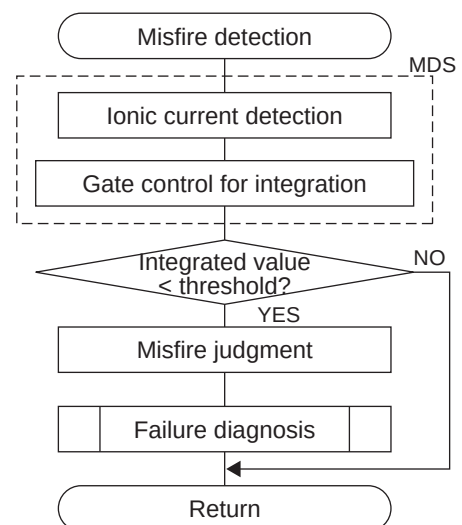


Fig. 10 Misfire detection flowchart

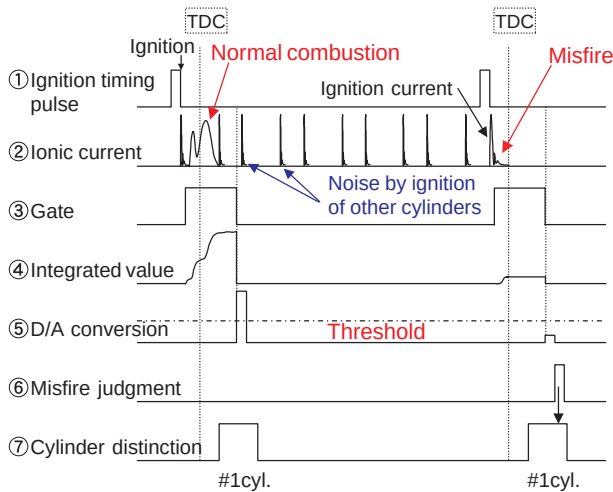


Fig. 11 Timing chart

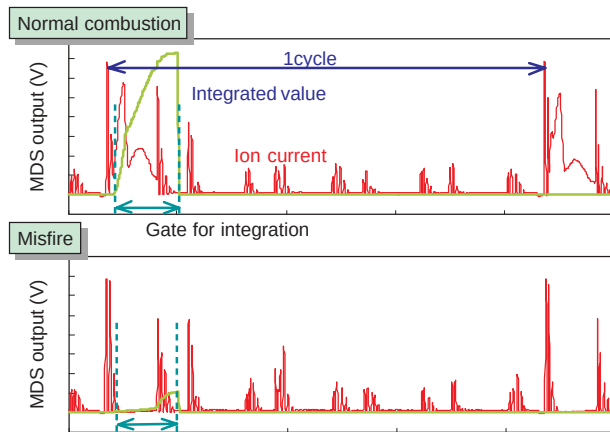


Fig. 12 Test results under misfire and normal combustion

so prominent that it can be judged that an appropriate S/N ratio is achievable. Also, misfire was detected during the actual vehicle test with fuel supply intentionally shut off. It was confirmed that a malfunction flag is set when a predetermined frequency threshold is exceeded (Fig. 13).

5. Lean Burn Controls

5.1. Ionic Current for Lean Combustion

In order to make clear the relationship between the air-fuel ratio and the ionic current, a universal exhaust gas oxygen (UEGO) sensor was used to measure the air-fuel ratio and verify its correlation with the ionic current. In general, a leaner air-fuel ratio improves fuel economy. However, if the lean limit is exceeded, the frequency of misfiring increases and fuel consumption actually increases (Fig. 14).

There is also a correlation between the air-fuel ratio and the ionic current and it has been verified that the generation of ionic current is lower during lean combustion (Fig. 15).

Looking at the relationship between air-fuel ratio and ionic current according to cylinder, it is confirmed that a cylinder presumed to be with a higher air-fuel ratio and indicated mean effective pressure (IMEP) generates a large amount of ionic current. These characteristics may be used for simple air-fuel ratio detection among the cylinders (Fig. 16).

5.2. Hesitation Detection

Hesitation is most likely to occur under acceleration when the air-fuel mixture ratio is set for lean in order to achieve improved fuel consumption. This has a negative effect on acceleration after exiting a corner. To control this phenomenon, the ionic current measuring system was applied. Hesitation occurs in the following process; an abrupt increase in the volume of air introduced to the injection system results in the mixture being leaner than the combustible limit. Then, IMEP is observed equivalent to that for misfire or the condition close to misfire, causing hesitation. A leaner air-fuel mixture results in less amount of ionic current and a longer

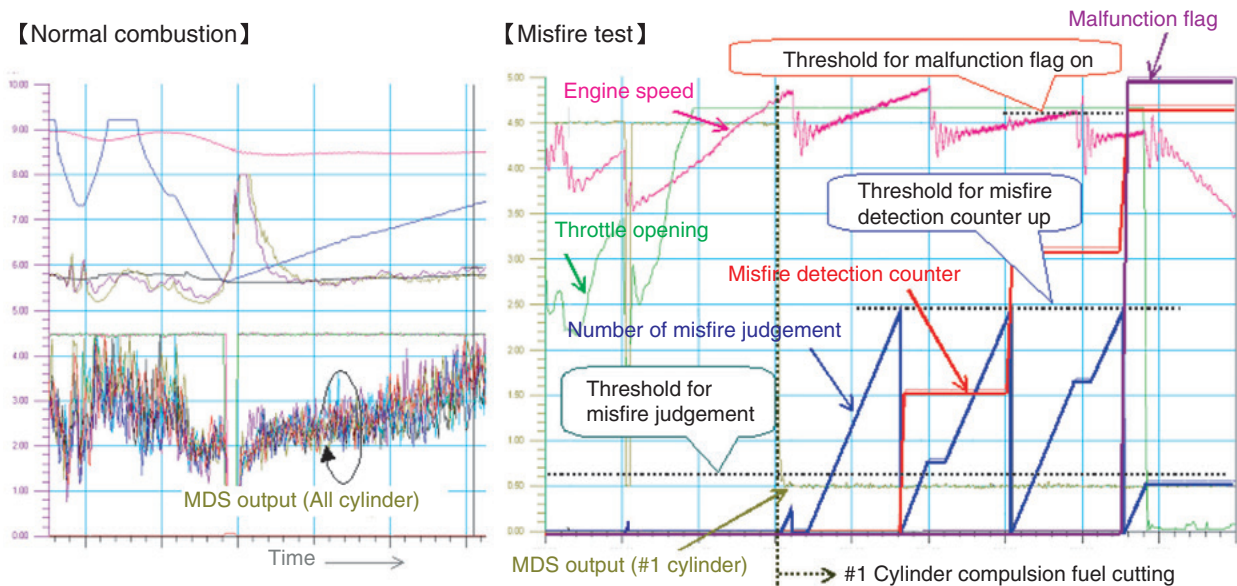


Fig. 13 Test results with actual vehicle

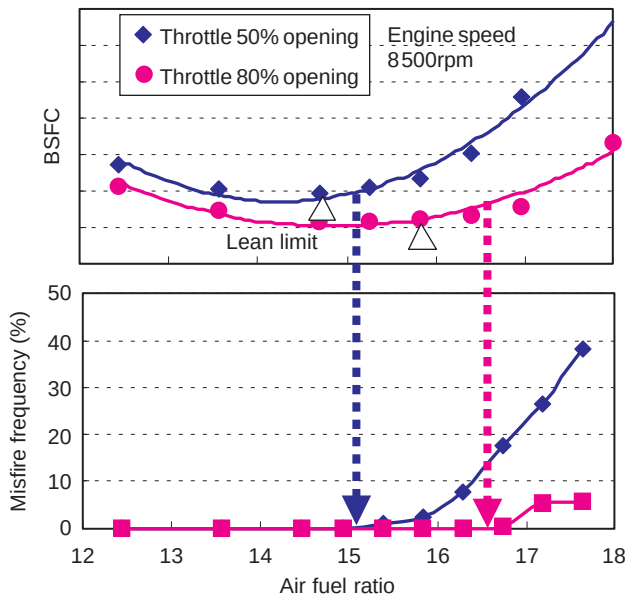


Fig. 14 Lean limit and frequency of misfire

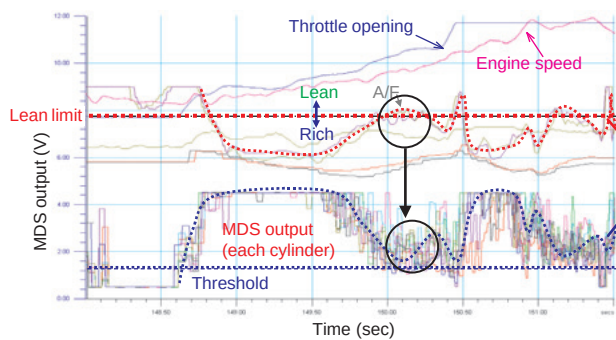


Fig. 15 Lean-burn test with actual vehicle

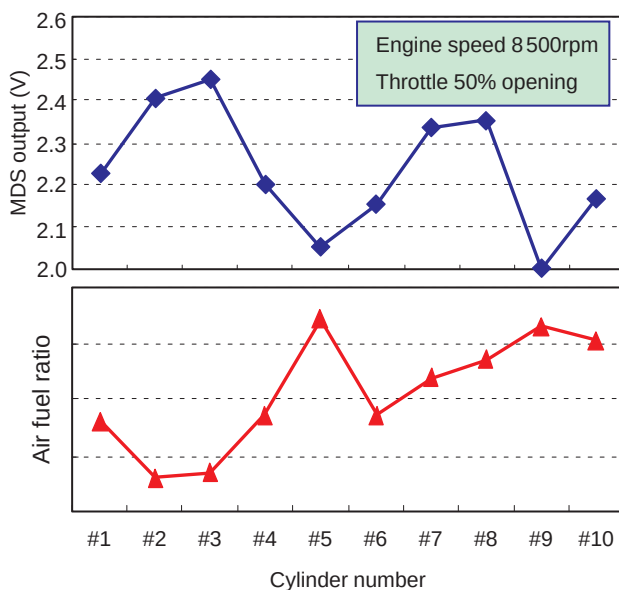


Fig. 16 Cylinder-to-cylinder variations of air-fuel ratio and ionic current generation

period of hesitation. The developed system detects hesitation in accordance with the principle mentioned above. The system flowchart can be seen in Fig. 17. Figures 18 and 19 show the measurements from dynamometer tests and from actual vehicle tests.

In the system flow the system identifies the period of time when the ionic current measurement is below the stipulated threshold. In case the condition is longer than the predetermined period, the system judges that an excessively leaner mixture is being supplied, which triggers a system command for a richer mixture ratio. If the period of time is shorter than the threshold, this means that there is available margin for making the mixture leaner and accordingly the system opts for a leaner setting in order to achieve improved fuel consumption.

As shown in Figs. 18 and 19, a leaner mixture ratio contributes to prolonged hesitation. Focusing on the signal from the UEGO

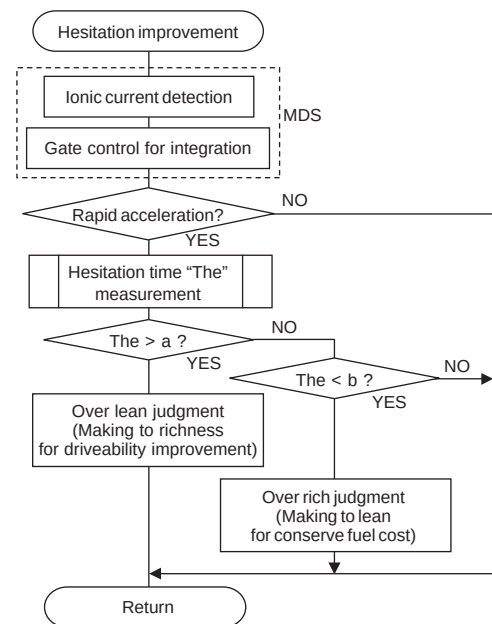


Fig. 17 System flow chart for Hesitation control

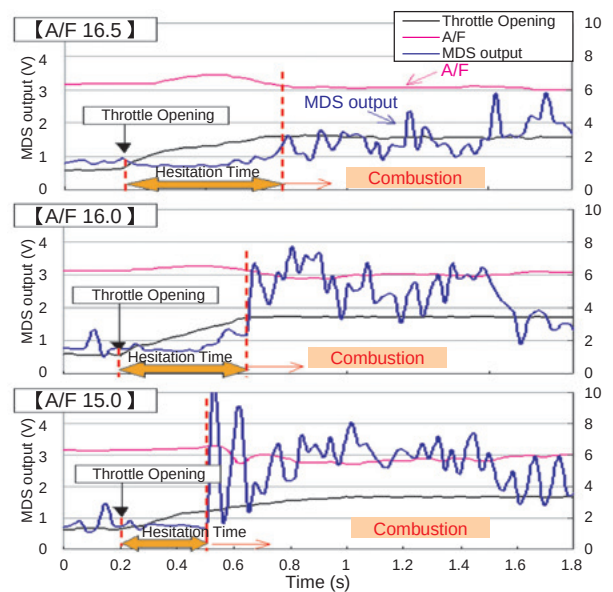


Fig. 18 Dynamometer measurement result about lean-burn condition

sensor, with a mixture set close to the stoichiometric ratio, the mixture becomes leaner under acceleration and then becomes richer, supporting acceleration. A similar phenomenon, however, cannot be observed under a condition close to the lean-burn limit. Because of the non-availability of the acceleration support effect, severe hesitation occurs. In the worst case, the period of time of hesitation may be prolonged by as much as three times.

6. Detonation Detection

It is well known that knocking, and pre-ignition and other forms of detonation, tend to occur under high-speed, high-load conditions with a lean air-fuel ratio.

Examples of detonations caused due to hot surface ignition are shown in Fig. 20. The cases shown in the top and middle rows in the figure were observed during a Formula One race whereas those shown in the bottom row are from detonations produced during

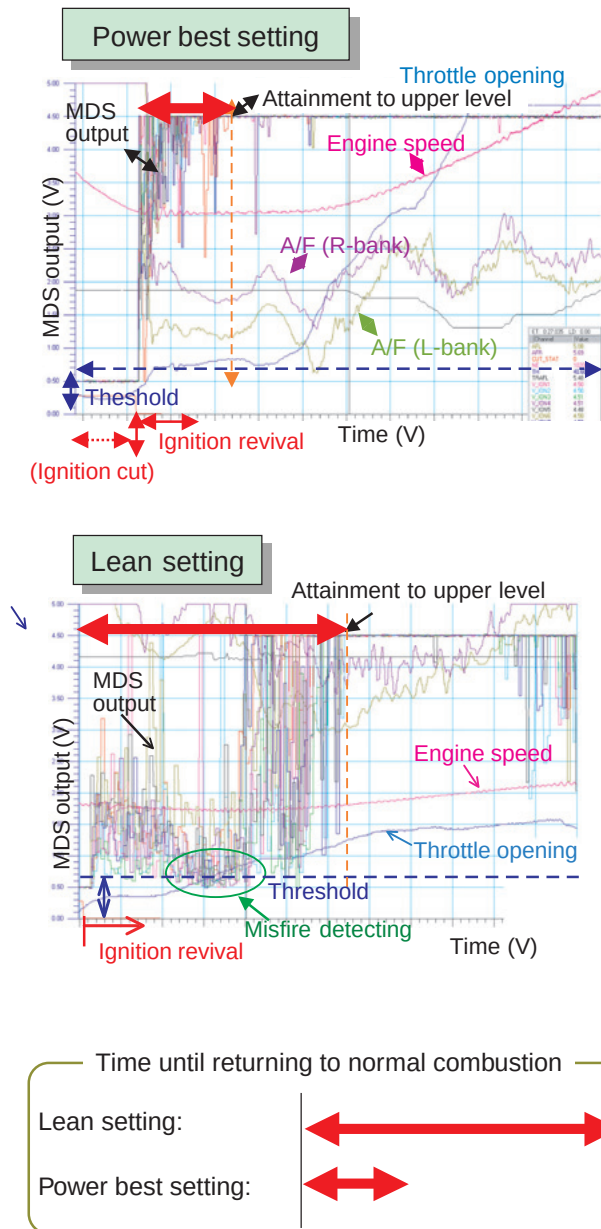


Fig. 19 Actual vehicle measurement result about lean-burn condition

reproduction tests in the lab. It could be clearly observed that the piston as well as the combustion chamber were thermally damaged. During the reproduction test, similar damage resulted from advancing the ignition timing under a lean mixture condition. Figure 21 shows the ionic current waveform in the detonation reproduction test.

It is verified during the preliminary test, that no knocking occurs even with the ignition advanced. Tests confirm that immediately after the mixture is ignited a large amount of ions is suddenly generated, reaching the highest measurement limit. The tests also verify that, with the passage of time, the combustion chamber walls reach high temperatures and detonation occurs. Ions are generated immediately after ignition without the ordinary delay in ignition. In the neighborhood of the in-cylinder pressure peak, combustion at high temperature occurs. Under this condition, a large number of ions are generated due to thermal dissociation. This phenomenon is thought to be hot surface ignition, which is similar to pre-ignition. Nevertheless, it is presumed that it should be regarded as a post-ignition phenomenon caused by hot surface ignition since there are no ions generated before ignition.

7. Ionic Current Amount

7.1. Spark Plug Center Electrode Configuration and Ionic Current Amount

The amount of ions generated during combustion remains the same but the amount of ionic current varies depending on the measuring capacity of the system. The ionic current measuring

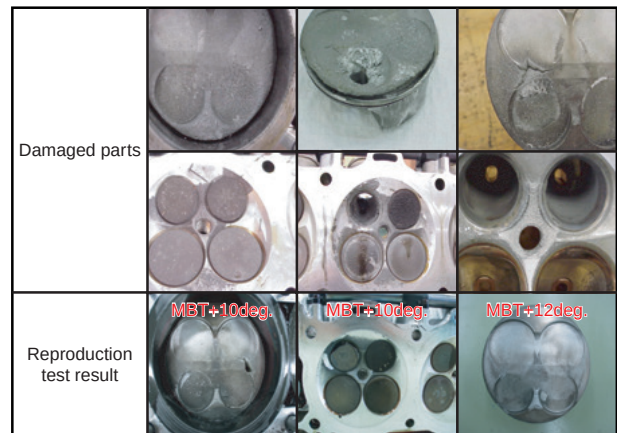


Fig. 20 Detonation caused by hot surface ignition

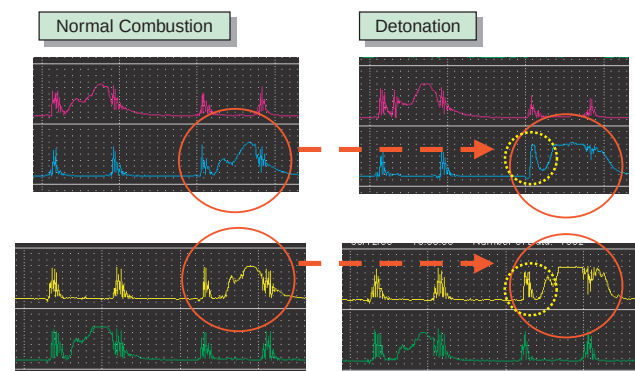


Fig. 21 Amount of ionic current during reproduction test

system used in the present research features a spark plug that also operates as the sensor. In other words, the spark plug serves as a measuring probe. The amount of ionic current detectable relies on the sensitivity that the probe offers.

Figure 22 depicts the relationship between the spark plug center electrode configuration and ionic current generation, while Fig. 23 shows the relationship between the configuration of the spark plug center electrode and cylinder-to-cylinder ionic current generation. In Fig. 22 the surface area of the center electrode is plotted in abscissa and the ionic current in ordinate. Given that the configuration of the spark plug is constant, the relationship

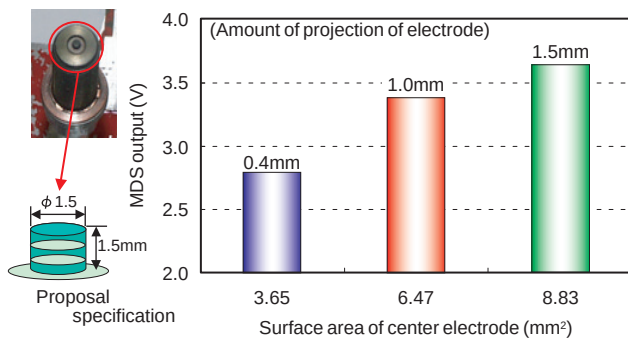


Fig. 22 Relationship between spark plug center electrode configuration and ionic current generation (detectable)

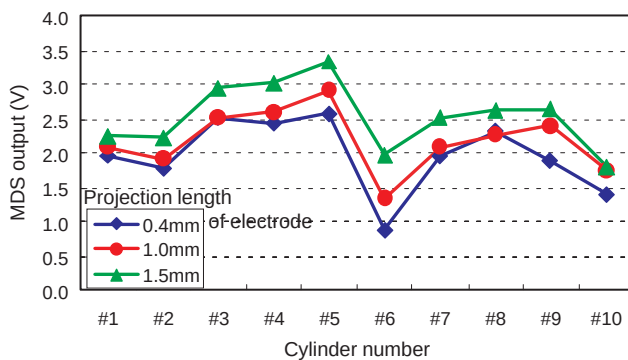


Fig. 23 Relationship between configuration of spark plug center electrode and cylinder-to-cylinder ionic current generation

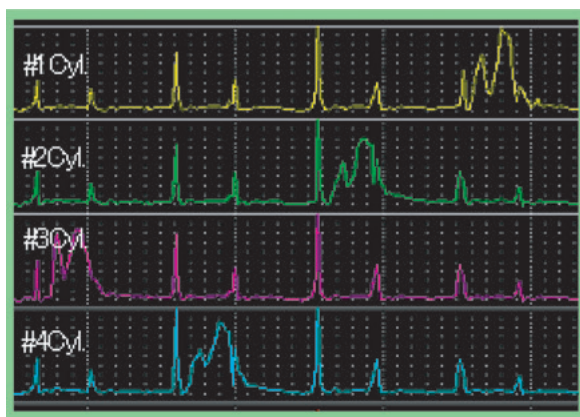


Fig. 24 Ionic current waveform measured with spark plug electrode protruding by 1.5mm

between the surface area and ionic current is approximately linear and ionic current increases in proportion to the surface area. In a similar manner, as shown in Fig. 23, a comparison between cylinder-to-cylinder variations in terms of ionic current, reveals changes in the same ratio for all cylinders.

In Fig. 24 we can see the ionic current waveform measured with a spark plug electrode protrusion of 1.5mm. Figure 25 shows the relationship between the electrode protrusion and ionic current generation measured during actual vehicle tests. With the protrusion set at 1.5mm, it was confirmed that the waveform is large and that a satisfactory level of detection was provided. During the actual vehicle test, it was observed that the waveform output varies significantly depending on the amount of projection of the center electrode.

7.2. Detected Ionic Current Amounts

When spark plugs with a center electrode surface area of 3.65 mm² (0.4mm) are used, with the detection resistance is set at 18 k Ω , the voltage across that resistor at the chemical ion peak is 19 V. As Eq. (1) shows, the ionic current at this time is 1.06 mA. Also the integrated amount of ionic charge can be expressed by Eq. (2). The integrated amounts for chemical ions and thermal ions at 15000 rpm obtained using Eqs. (3) and (4) are both 0.19 μ C. Therefore, as can be seen from Fig. 22, it can be inferred that as the surface area of the center electrode increases, the amount of ionic current captured increases as a linear function. Figure 26 shows the amount of ionic current when the chemical ions are at their maximum and Fig. 27 shows the amount of charge detected.

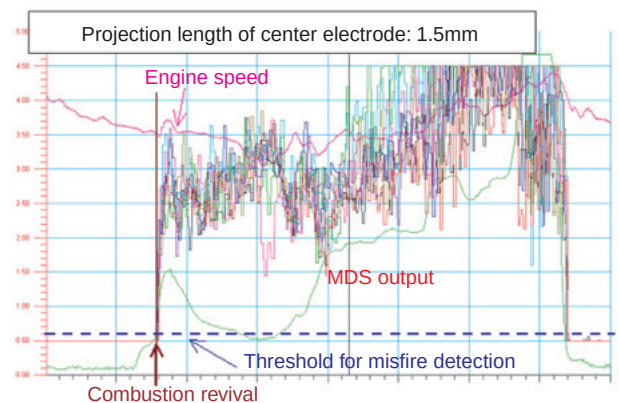
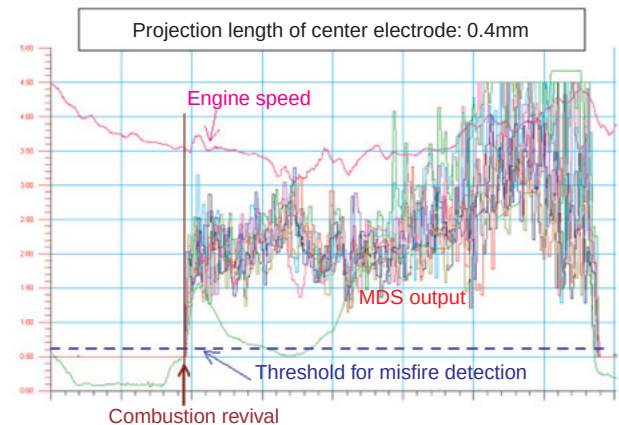


Fig. 25 Actual test results with different protrusions of sparkplug center electrode

$$I = \frac{V}{R} = \frac{19}{1.8 \times 10^4} = 1.06 \text{mA} \quad (1)$$

$$Q = \int I dt \quad (2)$$

$$Q_{\text{chemical}} = 0.19 \mu\text{C} \quad (3)$$

$$Q_{\text{thermal}} = 0.19 \mu\text{C} \quad (4)$$

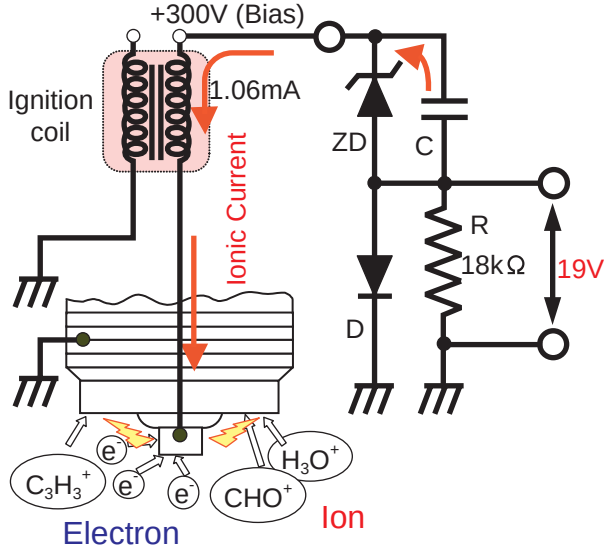


Fig. 26 Amount of ionic current at chemical ion generation peak

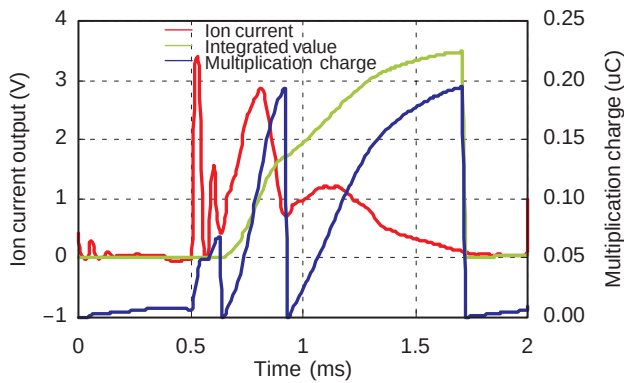


Fig. 27 Detected electric charge

8. Conclusions

A combustion state detection system featuring an ionic current measuring concept was developed in an attempt to apply it to a Formula One engine. During research and development, the following was learned;

- (1) The spark plug center electrode had the dual function of serving as a measuring probe. This discharge energy was stored in the condenser, which was consequently used as the source of bias voltage. This ionic current measuring system, when used in conjunction with the CDI system, which is characterized by its short discharge time, provided a sufficient level of measuring accuracy throughout all engine speeds.
- (2) The misfire detection system, using ionic current measurement, mainly consists of gating for the elimination of ignition noise, integration and a misfire frequency detection device. Utilizing these functions, the system diagnoses the engine to identify whether or not a malfunction occurs. It supports high detection accuracy throughout the revolution range.
- (3) During lean combustion, the ionic current decreases. It is possible to utilize this to detect and control misfiring and detect the amount of reduction in IMEP from ionic current and to control lean burn combustion. This system can also provide simplified detection of relative differences in air-fuel ratios among cylinders.
- (4) It is possible to control IMEP fall (hesitation) due to transient excessive lean air-fuel ratios by measuring the period of time during which ionic current falls. This system can be applied to air-fuel ratio setting tools and engine control.
- (5) The system detects detonation including hot surface ignition that occur frequently under high-load operation by means of ionic current generation under these conditions. In the case of severe hot surface ignition that could lead to damage to the engine, the delay in ignition is cancelled, promoting flame propagation at the initial stage of combustion. In the neighborhood of the in-cylinder pressure peak, thermal dissociation caused by high-temperature combustion promotes the generation of ions, resulting in an increase in ionic current generation.
- (6) The spark plug center electrode served as a measuring probe that detected ionic current. Provided that the configuration remains unchanged, the electrode surface area and the amount of ionic current detectable are directly proportional. The greater the protrusion of the center electrode, the higher the degree of sensitivity.

The developed system using ionic current measurement is being utilized effectively in current Formula One engines and other race engines and is becoming indispensable for dealing with malfunctions and for data logging. It is likely that in the near future it will be necessary to detect the combustion state in greater detail and control the engine. This ionic current detection system has the appropriate capacity as a forerunner and the authors are confident that it has succeeded in creating new value.

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We would also like to take this opportunity to express our deep appreciation to Noriaki Kondo and Tatsunori Yamada of NGK Spark Plug Co., Ltd. for their cooperation.

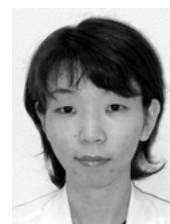
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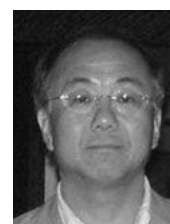
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