

Development of Spark Plug for Ion Current Misfire Detection System

Kaori Doi, Yoshihiro Nakamura and Ken Hanashi
Denso Corp.

Katushi Hashizume
Toyota Motor Corporation

ABSTRACT

In this paper, the authors introduce the spark plug for misfire detection system by ion current. In order to realize high accuracy misfire detection, the signal of ion current must be larger than that of noise. For maintaining ion signal in all designed lifetime, the configuration and initial condition of spark position are derived by an experiment and consideration about degradation in use. Additionally, the cause of noise is determined by an observation and a theoretical study, and we indicate the method to inhibit noise efficiently. Finally, effect of the methods found by these two approaches is confirmed with an engine, and we propose specifications of spark plug satisfying the condition that realize high accuracy detection by ion current.

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INTRODUCTION

In recent years, vehicle emission regulations, mainly LEV (Low Emission Vehicle) and ZEV (Zero Emission Vehicle), have become strict with more concerned about the environment. Because of these increasing restrictions, a need for engine misfire detection by OBD (On Board Diagnosis) system is growing (Figure 1). Detecting misfire has already been specified with monitoring engine according to prescribed operating condition in OBD2 (from 1994, North America), E-OBD (from 2000, Europe), and J-OBD2 (from 2008, Japan). Especially in North America, identification of misfire cylinder should be required in case of misfiring at only one cylinder.

For these needs, we mainly use the method of engine rotation speed fluctuation. This method measures crankshaft speed fluctuation with a crankshaft speed sensor, and determines misfire indirectly with rate of change (value of a rotation variable). In case of measuring at 10-cylinder-over engine, it is too difficult to detect misfire accurately because torque fluctuation under one cylinder misfire gets smaller (Figure 2).

Therefore, the method of ion current detection is used for the 10-cylinder and larger engines. Ion current detection uses spark plugs as sensing devices. Positive ions in the frame are trapped with electrodes of the spark plug and detected as ion

current [1][2][3][4]. This method can detect misfire directly because the electrodes position of spark plug is the sensing part is origin of frame. Additionally, determining misfire cylinder is easier because every cylinder has at least one spark plug. Therefore, the method by ion current detection is effective in detecting misfire more accurately at each cylinder for a multicylinder engine that has over 10 cylinders.

In order to realize accurate misfire detection with this method, it is required to keep S/N ratio of ion current. That is, ion current signal should be kept large, and noise should be reduced. Other studies for existing engines had been considered and confirmed to achieve a necessary S/N ratio for accurate misfire detection. In our survey using this method with the developed engines, the existing spark plug could not meet it. Then, we thought not only detection circuit or system but also specifications of spark plug itself should be improved to achieve the condition. If the spark plug has functions to keep ion current signal larger and to suppress noise more, it does not only contribute for development of the new engine, but robustness improvement can be expected for other engines. In this paper, we introduce the development outline of improved spark plug exclusively for ion current misfire detection system.

	2000	2010	2015
North America		OBD2	
Europe		E-OBD	
Japan			J-OBD2

Figure 1. Trend of OBD constitution

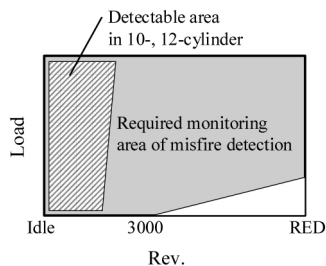


Figure 2. Required monitoring area and detectable area by crankshaft speed fluctuation

1. OUTLINE OF ION CURRENT DETECTION

1.1. SYSTEM FUNDAMENTAL AND STRUCTURE

Structure outline of ion current detection system is shown in figure 3, and fundamental of ion detection at electrodes in figure 4. Ion current detection system adds power and circuit for ion detection in igniter, and IC for ion signal processing in ECU to the general ignition system. Detection voltage is applied between center electrode and earth electrode of spark plug from the power for ion detection in igniter. Positive ions ($C_3H_3^+$, CHO^+ , H_3O^+ , NO_2^+) generated during combustion are trapped and detected as ion current^[5]. The ion signal that suggests the presence or absence of the ions in a frame is outputted from the circuit of ion detection to the ECU. Therefore it is enabled to determine misfire or ignition from the signal value (Figure 5).

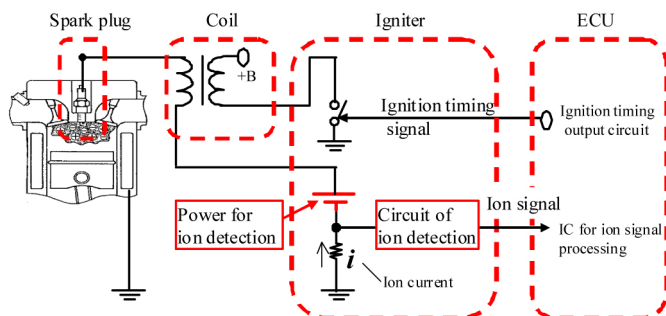


Figure 3. Schematic view of ion detection system

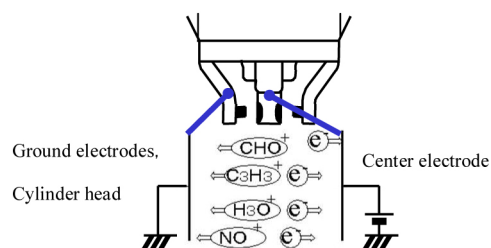


Figure 4. Outline drawing of ion current detection system

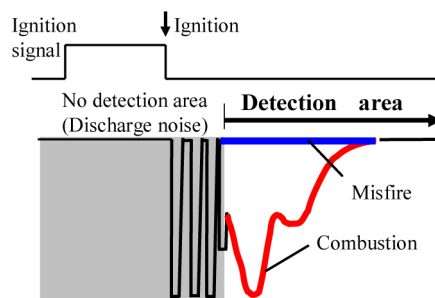


Figure 5. Outline of ion signal waveform

1.2. PROBLEMS OF ION CURRENT DETECTION SYSTEM

In order to realize accurate misfire detection by ion current, ion signal “S” should be larger than misfire threshold “ I_{th} ” at each condition, and noise “N” should also be smaller than the “S”. This system requires conditions equations (1) for decision of normal combustion.

$$\begin{aligned} S &> I_{th} \\ S/N &> 2 \end{aligned}$$

(1)

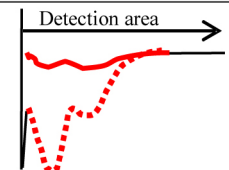
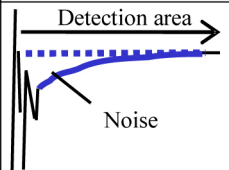
The equations (1) show that S/N ratio needs 2 or more in this system in consideration for margin of safety ratio. It is important to keep “S” larger and “N” less in order to detect misfire accurately. If the equations (1) are not fulfilled, there are the following 2 patterns of false decision (Table 1).

- 1). Mistake combustion for misfire because ion signal “S” is smaller than misfire threshold “ I_{th} ”.
- 2). False combustion misfire because of excessive noise “N”.

Pattern 1) means system mistakes misfire because ion signal is too small and doesn't exceed the misfire threshold “ I_{th} ” in spite of normal combustion. For this problem, we focused on the relation that ion signal correlates with exposed surface area of center electrode; which is sensing device of ions in a frame. Therefore, we examined the initial specification in consideration for reduction of ion signal level caused by ware on electrode itself and fouling with combustion deposits. Meanwhile, pattern 2) means system

mistakes for combustion because generated noise is too large and exceeds " I_{th} " in spite of misfire. It is possible that spark plug itself becomes noise source because of applied high voltage for spark discharge. Therefore, we revealed a phenomenon occurred on spark plug in more detail, and examined a solution to suppress it. There are more about details to solve these 2 problems in the next section.

Table 1. Pattern examples of false detection

1) False misfire detection	2) False combustion detection
	

2. KEEPING LEVEL OF ION SIGNAL "S"

2.1. EXAMINATION OF NECESSARY SURFACE AREA OF CENTER ELECTRODE

Ion signal "S" is detected as an ion current by the ions in a frame trapped with center electrode as sensing device. It is assumed that the value of ion signal is proportional to the exposed surface area of center electrode "A". Here put system demand minimum signal value " S_{th} ", and put necessary surface area of center electrode " A_{th} ", it is necessary to satisfy following equation (2).

$$S_{th} \leq f(A_{th}) \quad (2)$$

We prepared several spark plugs with different surface areas of center electrode, and examined A_{th} to keep S_{th} by tests with target engine. V-12 gasoline 5000-cc engine was used for test. Test condition was idle (500r/min.) because the ion signal gets smallest at this condition. The test result is shown in figure 6. As exposed surface area of center electrode is increased, ion signal value raised. These results mean that it is possible to output ion signal more than a certain value by keeping necessary exposed surface area. Therefore, we determined the necessary surface area of center electrode " A_{th} " is 11.8mm² from the value of $\bar{X} - 4\sigma$ in consideration for variations in assembly, dimensions of parts, and detection.

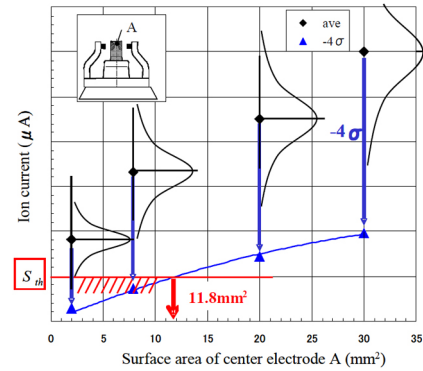


Figure 6. Relation between surface areas of center electrode and ion current

2.2. SELECTING OF BASIC ELECTRODE SHAPE FOR REDUCTION OF SURFACE AREA

Ion signal decreases with the increasing hour used on engine. This is assumed to be due to two factors. One is reduction of surface area caused by electrode wear. Electrode wear cannot be avoided because of spark discharge and oxidation in high-temperature atmosphere. It is necessary to determine initial exposed surface area with the reduction by wear in order to keep a necessary value of ion signal during product lifetime. The other factor is adhesion of deposits on the center electrode from fuel additive or engine oil. Also in this case, ion signal declines because deposits on the electrode block trapping of ions in a frame. This effect should be considered in designing initial dimension for electrode wear.

Based on these considerations, we surveyed differences of electrode wear and residual state of deposits related to electrode shape with spark plugs removed from the market (Table 2). There was poor correlation between reduction rate of surface area of the center electrode from wear and electrode shape. The residual rate of deposits, however, was affected according to the differences of electrode shape. The deposits remained less on the electrode type B or C, which are type of side surface discharge, than that of A which is a common overhang-typed spark plug. This is because deposits are burnt and cleaned by spark discharge. For type A, deposits cleaning area is only on the end face of electrode. On the other hand, deposits can be cleaned by a larger area on type B or C because side discharge typed spark plug has larger discharge area than overhang-typed plug. Additionally, it seems that type C is better than type B because it has two electrodes and can clean an even more large area. Figure 7 is a summary of these results. It is clear that type C is the best in remaining cleaned surface area of center electrode. In this development, we chose type D based on type C. Type D has wear resistance and can clean deposits as same as type C, and it has platinum-alloy tips on center electrode and earth