

Misfire and Partial Burn Detection based on Ion Current Measurement

2011-24-0142

Published
09/11/2011

Nicolo Cavina
Univ. degli Studi di Bologna

Luca Poggio and Giovanni Sartoni
Ferrari Auto Spa

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doi:[10.4271/2011-24-0142](https://doi.org/10.4271/2011-24-0142)

ABSTRACT

The paper presents the implementation of a combustion diagnosis system that integrates crankshaft speed oscillations analysis with ion current signal processing, for V8 and V12 high performance engines.

Ion current sensing has been introduced in the last V8 and V12 Ferrari models in order to improve combustion control by implementing ion current based closed-loop spark-advance control systems, both under knocking and non-knocking conditions (respectively based on measured knocking level, and on ion current peak position control).

Another area where ion current sensing can improve the engine controller performance is related to the ability of detecting and isolating missing and partial burn combustions. The typical approach to misfire detection (based on engine speed oscillation measurement) is in fact particularly critical for engines with a large number of cylinders, and ion current sensing provides additional information not only about presence (or absence) of combustion, but also about the causes that generated the fault. Moreover, the paper shows that real-time analysis of specific ion current signal features allows isolating incomplete and inefficient combustion events, thus providing extremely useful information to the engine control system, which can for example be used to activate multi-spark discharge ignition mode.

The first part of the paper shows the main critical aspects of speed-measurement based misfire detection, and introduces the ion current signal main features during regular engine operation. Then, ion current signal is analyzed during

abnormal combustion events: absence of combustion (both due to missing injections and missing ignitions) and partial burn cycles. It is shown how it is possible to isolate missing and incomplete combustions in a relatively straightforward way, and also how the causes that induced the fault may be isolated by integrating standard diagnostic functions with specific ion current signal processing algorithms. Finally, the performance of the diagnostic system that integrates engine speed oscillation analysis and information extracted from the ion signal has been evaluated during on-board tests, and the main results are presented at the end of the paper.

INTRODUCTION

A cylinder misfire takes place when the injected fuel mass (diesel engines) or the air-fuel mixture (port or direct injection gasoline engines) does not ignite or it burns incompletely. Misfire events occur due to various reasons. One cause is a fault in the spark ignition or fuel injection control system. For example, when a disturbed sensor signal leads to an erroneous calculation of fuel mass or injection/ignition timing, or when a hardware component (injector, spark plug, coil) is damaged. Other important causes of misfiring include defective fuel injection and air intake systems, as well as bad fuel quality. Besides the irregular engine running, further consequences of regular misfires are long-term increases mainly in hydrocarbon and carbon monoxide emissions. Sustained misfiring can also damage the catalytic converter in the exhaust system. In 1989, for the first time detection of misfire events in gasoline engines was legislated for by the Californian Government [1]. Today, one of the most important parts of on-board diagnostics (OBDII) is the one related to the requirements regarding misfire detection [2]. The diagnostic system must be able to detect a

single misfire and also to determine the specific cylinder in which the misfire event has occurred. Whenever the rate of misfire exceeds a specific threshold (corresponding either to excessive catalyst temperature or to increased HC emissions), the driver must be alerted by the on-board diagnosis system so that maintenance in a garage can be scheduled. In the past, misfire detection has been performed by various systems using different types of sensors. While numerous approaches have been attempted in these last decades [3, 4, 5, 6], most of the strategies that have been successfully implemented are based on the crankshaft speed signal analysis [7, 8, 9, 10]. One positive aspect is the availability of such information to the Electronic Control Unit (i.e., no need for additional sensors), but the main reason is the existence of a strong physical correlation between the presence (or absence) of combustion - in one or more cylinders - and the engine speed trend. In fact, the misfire event implies a lack of positive torque on the crankshaft during the corresponding expansion stroke, and therefore a sudden decrease of engine speed. A significant disadvantage of this method is the fact that various disturbances acting on the crankshaft (e.g. driveline torque reaction) may lead to erroneous misfire detections.

In four cylinder engines, one of the most common engine architectures, algorithms based on the analysis of the instantaneous engine speed are able to correctly isolate the misfiring cylinder in essentially all the engine operating range, with the exception of some false alarms when the vehicle is overcoming train rails or when it is driven on bumpy roads (thus requiring rough road detection strategies [11]). For engines with larger number of cylinders (6, 8, 10 or 12), more detection problems are present, essentially because the instantaneous indicated torque waveform becomes more regular, and the lack of one combustion is hidden by the presence of other overlapping expansion strokes. Moreover, the angular sector over which the detection strategy is based becomes narrower, thus decreasing the resolution for the combustion time evaluation. Finally, another aspect negatively affecting this type of engines may be the quite different breathing capacity of some cylinders with respect to others, with a subsequent systematic or stochastic dispersion of the energy developed during the engine cycle by the in-cylinder combustion, that causes a non-uniform indicated torque waveform. This non-uniformity is reflected in an increase of the background noise present in the instantaneous speed signal used for the detection algorithm.

The misfire detection index actually being used in Ferrari applications is the so called “engine roughness index” LU. It was developed by Bosch research [12, 13], and it is based on the evaluation of the time periods spent by the crankshaft to perform the rotation of a pre-defined angular sector, related to the combustion phase of each cylinder. Knowledge of the combustion periods allows evaluating the crankshaft kinetic energy variation caused by each combustion, by means of the following expression, presented in [13]:

$$LU_i = \frac{\tau_{i+1} - \tau_i}{\tau_i^3} \quad (1)$$

τ , and τ_{i+1} are the time periods relative to two consecutive combustions, and LU_i is evaluated for each combustion. It contains information on the instantaneous crankshaft kinetic energy variations caused by abnormal combustions, such as misfires and other sources of torque production non-uniformity, or by gear shifts, cut-off. As already mentioned, such approach is particularly challenging for engines with a large number of cylinders, especially at high engine speeds, since the Signal-to-Noise Ratio (SNR) of the LU index becomes critically low.

Ion current sensing has been introduced in the last V8 and V12 Ferrari models in order to improve combustion control by implementing ion current based closed-loop spark-advance control systems, both under knocking and non-knocking conditions (respectively based on measured knocking level, and on ion current peak position control) [14, 15]. Another area where ion current sensing can improve the engine controller performance is related to the ability of detecting and isolating missing and partial burn combustions. As already mentioned, the typical approach to misfire detection (based on engine speed measurement) is in fact particularly critical for engines with a large number of cylinders, and ion current sensing is inherently unaffected by the presence of other cylinders, while at the same time it provides additional information about the causes that generated the combustion fault. Moreover, this work demonstrates that real-time analysis of specific ion current signal features allows isolating incomplete and inefficient combustion events, thus providing extremely useful information to the engine control system, which can for example be used to activate multi-spark discharge ignition mode [16].

As it is well-known, both knocking level evaluation and missing or partial combustions detection may be performed by directly measuring the in-cylinder pressure signal [17, 18], and such approach is certainly the most reliable and accurate. However, due to cost reasons, the installation of individual cylinder pressure transducers on-board the vehicle is still not feasible today, especially when considering Spark Ignition (SI) engines with a large number of cylinders [19, 20]. One of the objectives of this work is to demonstrate that, given the actual technology constraints, ion current sensing is probably the best practical solution to individual-cylinder combustion control and diagnosis. The authors are working to further expand control-oriented ion sensing applications, and the feasibility of cylinder-by-cylinder closed-loop ion-based air-to-fuel ratio control is actually being investigated.

BACKGROUND

It is thought that ion current is generated via the following two different generation processes [21]:

- Radical ions of a relatively long life, such as $C_3H_3^+$, are detected when flame surface ends pass through the electrode during the initial stage of combustion. This phase of the ion current signal is often defined as chemical phase.
- Inside combustion gasses with a temperature of 2,000 K and higher, NO_2^+ radical ions are generated as a result of thermal dissociation of N_2 . This portion of the signal is usually referred as thermal phase.

By modifying the standard ignition circuit as shown in [Figure 1](#), and by designing with particular care the coils and the electric and electronic components, the ion current signal may be measured immediately after spark discharge, and combustion related information may be recovered by real-time processing the corresponding signal. Of course, this layout allows implementing a current probe without really adding a new sensor in the hostile environment typical of a combustion chamber, and it is only viable for SI engines. For compression ignition engines, the standard solution is to install the current probe inside the glow plug [22].

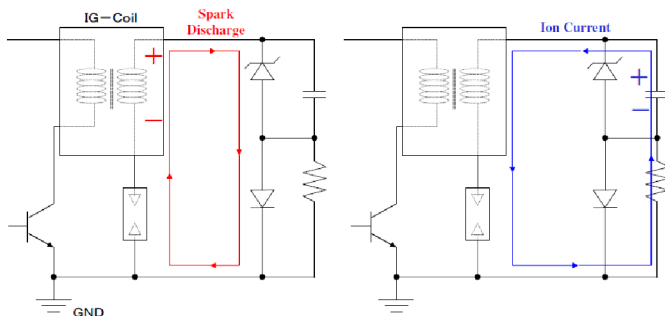


Figure 1. Simplified schematic of ignition system with ion current measurement circuit. The current loops shown in the figure are relative to spark discharge and subsequent ion current measurement phases.

The ion current intensity is directly related to flame initiation processes (depending on temperature, pressure, turbulence, mixture composition, and exhaust gas concentration), and subsequently mainly to combustion chamber (or better, spark electrodes region) temperature. [Figure 2](#) shows typical ion current signals acquired during one cycle at different engine speeds and full load (WOT, Wide Open Throttle), with the engine running regularly. They present some characteristic features that may be described as follows:

- Coil charge start peak, whose amplitude may vary between 500 and 2000 μA (not shown in the plot relative to 7500 rpm);
- Coil charge end spike (20~100 μA), corresponding to Spark Advance (SA) angular position and to the spark

discharge phase. The interval between this spike and the preceding peak is the coil dwell time (in the figure the x-axis displays the crankshaft angular position, and the dwell time may be evaluated by considering the actual engine speed).

- Spark discharge end peak (800~2500 μA): The ion current between electrodes shows some ringing after the peak corresponding to the end of the discharge event, which damps out typically in few hundredths of microseconds.
- Chemical phase: It is typically clearly observable at low engine speeds, when it can be distinguished both from the preceding peak (and associated ringing) and from the subsequent thermal phase. It is strictly related to mixture composition and to the combustion initiation process.
- Thermal phase: As already mentioned, it is mainly related to the temperature (and therefore pressure) evolution between the electrodes. It is always observable if combustion takes place, and it contains important combustion-related information (such as knock, heat release rate, combustion duration). The maximum value of the ion current during this phase ranges between 50 and 600 μA , depending mainly on speed and load. Also, thermal phase peak position is very well correlated with in-cylinder pressure peak position, and it may be used as a controlled variable to close the SA control loop, both under knocking and non-knocking conditions [14].

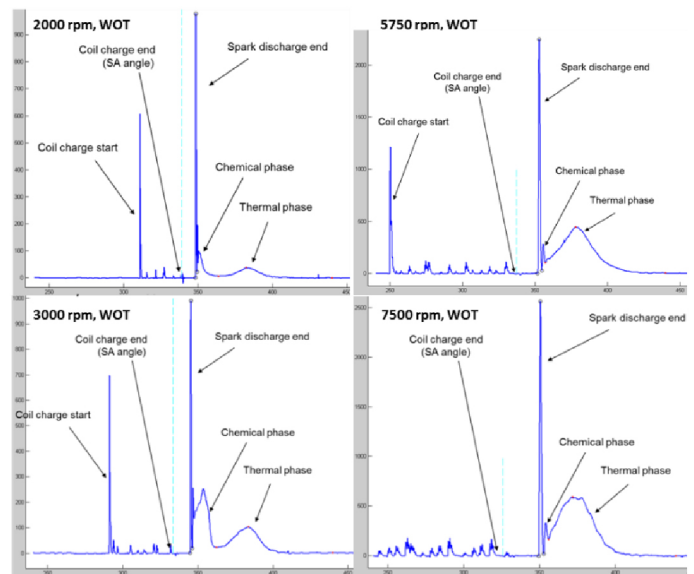


Figure 2. Examples of ion current waveforms for different engine speeds. All tests have been performed at full load (WOT) conditions. The x-axis represents Crankshaft Angle (CA) values, in degrees, while the y-axis shows ion current values, in μA .

The analysis of the waveforms shown in [Figure 2](#) is particularly helpful to understand which features of the ion current signal should be isolated and monitored in order to implement a robust combustion diagnosis strategy. It is in