A Method of Torque Estimation Utilizing Ionization Sensing Technology in Internal Combustion SI Engines

Guangyu DONG, Liguang LI, and Shui YU and Xusheng ZHANG

Abstract—**This paper describes a method of torque estimation by using in-cylinder ionization sensing technique in a internal combustion SI engine. Through the characterization of the ion current signal measured across the spark plug electrode with four parameters, two peaks of ionization signal were investigated and used to build the relationship between the net torque of engine and the ion current signal. From the experiment results, a conclusion can be drawn that the averaged ionization signal over 20 consecutive combustion cycles is well correlative with the variation of torque, especially in the case of higher torque conditions. The intensity and position of the second peak of this signal are most sensitive to the change of torque.**

***Index Terms*—Ionization Sensing technology, SI Engine, Torque estimation,**

I. Introduction

THE need for improvements in the on-line estimation of automotive engine performance variables and model parameters pertaining to the fueling and emission control subsystems is increasing nowadays as a result of more stringent emission controls and fuel economy requirements[1]. For the better control of engine, improvements can be done if more combustion information could be feedback in real time. The net torque estimation appear to be one of such improvements which provides a feasible alternative to the use of the engine torque maps in a modern torque-based engine management system[2]. By the estimation of net torque, some new ideas for many application areas such as engine diagnostics, torque-based engine control, traction control via engine control, and vehicle dynamics control may be provided accordingly.

Since 1990s, there has been a greater interest in the ionization sensing technique for spark ignition (SI) engines. The advantage of utilizing ionization sensing over crankshaft velocity fluctuation measurement for 100% misfire detection at all speeds and loads as required by OBD-2 [3]. This is especially the case for engines with more than 4 cylinders. And also, many attempts have been reported to utilize this signal for knock control, cam phasing, air/fuel-ratio control, and combustion monitoring[4]. The reasons for this interest in ionization sensing technology are quite simple. The ionization current contains information about the combustion process. It reflects many parameters in the combustion, and among of them the pressure can be indicated as well. And also, the spark plug as ionic current sensor does not require any additional space or expenses. Generally, the combustion of fuel inside the engine cylinder produces ions and free electrons. A current can be generated and detected by locating two electrodes in the combustion chamber and applying a low DC potential difference between them. So the spark plug can be use as a ion sensor without any ancillary components.

In this paper a torque estimation approach is attempted by the use of ion current signals. To achieve torque estimation on vehicles in real time, several methods have been provided such as using a piezoelectric pressure sensor, or a complex crank-angle based model [5]. But these methods have their own shortage. For the application on vehicles, the piezoelectric pressure sensor is too expensive and not very reliable, The crank-angle based model need a ancillary sensor. These shortages can be avoided by use of ionization sensing technique. So the aim of this paper is to investigate the relationship between the net torque output from engine and the ion current signal.

II. Basic theory of ionization sensing tecihnology

Ion current signals have long been investigated as a combustion diagnostic tool. The ionization process during combustion of fuel in the cylinder is basically composed by a complex set of thousands of chemical reactions [6]. Generally speaking, this process can be divided mainly into two phases by the essential mechanism of the ionization process in different periods [7].

As shown in Figure 1, the first peak in ignition phase is due to the combustion process, and it is the ringing phenomenon in the coil after ignition. The first phase of ion current signal which arosed by the combustion is defined as the 'flame front phase". This phase is related to the combustion process in the flame kernel. It depends on the front flame propagation and the

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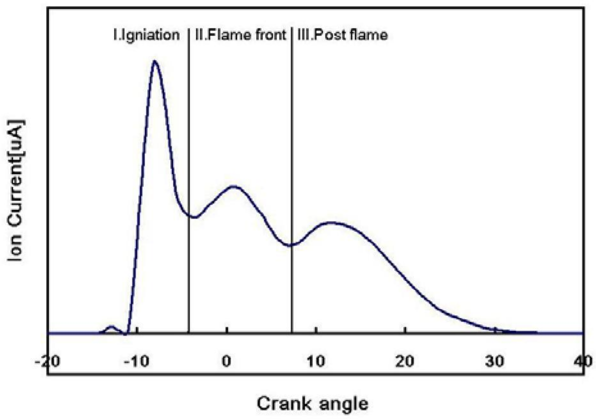

Figure. 1. A typical figure of ionization signal show the three phases : the ignition phase, flame front phase and the post flame phase.

ion probe position within the combustion chamber. The source of the current during this phase is mainly related to chemical-ionization processes as Equation (1) and (2):

$$CH + O \rightarrow CHO^{+} + e^{-} \qquad (1)$$

$$CHO^{+} + H_2O \rightarrow H_3O^{+} + CO \qquad (2)$$

A results can be deduced that the main content in this phase is H_3O^+ according the fact that the reaction rate of reaction (2) is fast than (1).But according to the reaction (1), the concentration of H_3O^+ is decided by the concentration of CH and O. So the ion production in this phase is strong correlative with the air-fuel ratio [8].

The second phase is defined as the "post flame phase". The ionization during this phase is due to the high temperature inside the combustion chamber. And the most dominative ion production mechanism in this phase is the slow forming Nitric Oxide by means of the extended Zeldovich mechanism [8] as Equation (3), (4) and (5):

$$O + N_2 \rightarrow NO + N \qquad (3)$$

$$N + O_2 \rightarrow NO + O \qquad (4)$$

$$N + OH \rightarrow NO + H \qquad (5)$$

Because the NO is formed mainly by the prompt of temperature, this phase is strong correlative with the in cylinder temperature and pressure history, as well as the IMEP in cylinder [9].

III. EXPERIMENT SETUP

A The Engine Setup

The engine data was collected in a HuaPu 1.47 liter four cylinder 16 valve engine with fuel injection. The specification of the test engine is shown in Table.1.

TABLE I
SPECIFICATIONS OF THE ENGINE

Engine	JL479QA
Bore and Stroke	78.7×77.0 mm
Compression Ratio	9.8
Cylinder Number	4
Ignition Sequence	1-3-4-2
Fuel Injection Type	PFI
Fuel Type	93# Gasoline
Ignition Coil	1-4, 2-3

The measurements of torque were made using an Powerlink dynamometer, and the ignition advanced angle and TDC signal were collected by a multi-channel data acquisition system.

B Ionization Measurement

A conventional spark plug was used as an ion current sensor in this experiment. By connecting a positive DC voltage to the combustion chamber an electrical field is created, as Figure 2.

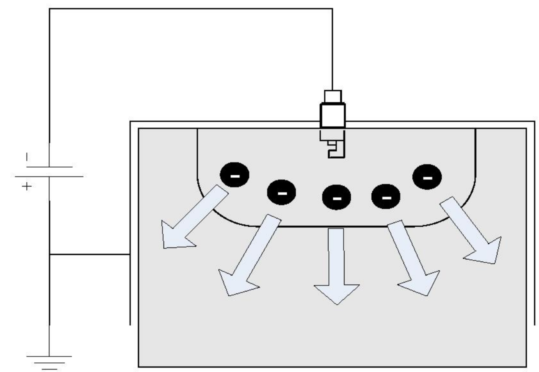

Figure. 2. The movement of free electrons produced by the combustion in a electrical field made by a DC voltage.

The electrical field will attract the negative charged species and a small current is generated from the electrical ground to the positive electrode of spark plug. The electrical ground is the piston and the combustion chamber walls. In fact, it is the electrons that are responsible for most of the current due to their lower mass and therefore higher drift velocity in the so called "ion signal", though the majority of the electrons are attached and only a minority are free [10] . In this paper a DC voltage (U) of 410V was applied across the electrodes gap of the spark plug. As shown in figure 3, the ion current was detected by measuring the voltage over a resistance of 75 k inserted in the electrical circuit. The ion current was also sampled by a DAP 5400a/627 data acquisition system**,** which can sample up to twelve channels simultaneously, it has a maximum capacity of 200K samples / sec.

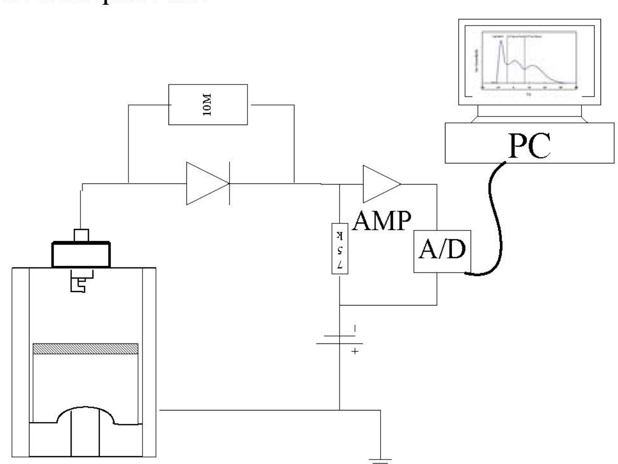

Figure. 3. Ionization signal measurement system.

IV. RESULTS AND DISCUSSIONS

Since the ion signal is measured locally in the combustion chamber, the signal can vary from cycle to cycle as shown in figure 4 in which the ion current was measured with a same engine operation condition.

The problem of fluctuation of ion currents occurred in this process must be settled. For the purpose of achieving the measurable parameters from this signal, an average over 20 consecutive combustion cycles under constant external

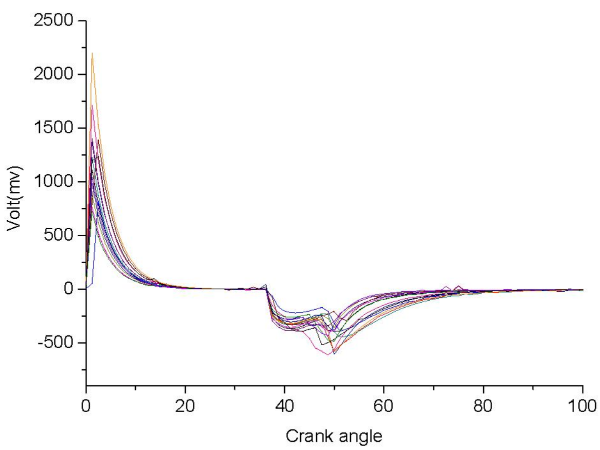

Figure. 4. The fluctuation of ionization signal collected in a same engine operation condition.

conditions was used to estimate the torque. Accordingly, the torque output from each cylinder can be seen as a averaged value in a duration of 20 cycles and the torque output from crankshaft can be seen as a 4 times value of the torque output from the first cylinder in which the ion signal was detected. And also, the relationship between the ion current signal collected in the first cylinder and the torque can be build directly.

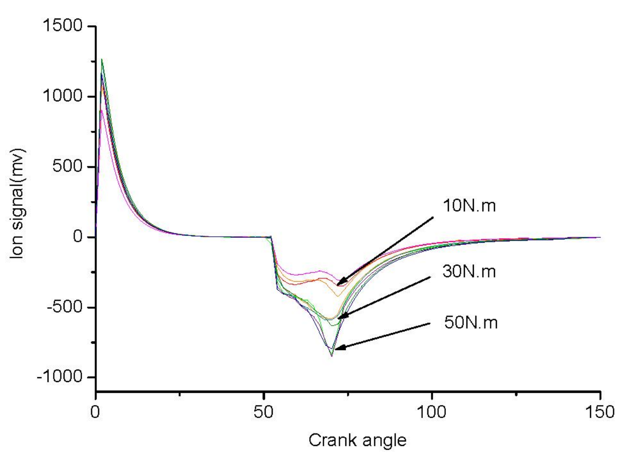

Figure. 5. A comparision between the ion signals and the indicated torque under a same speed of 3000 rpm and a constant ignition timing.

By this method, a comparision between the ion signals and the net torque of engine are shown in figure 5. In this figure the typical variation tendency of the averaged ion signals over 20 cycles is very regular as the torque increased from 10N.m to 50N.m. The fluctuation between the averaged ion signals with a same torque is very tiny. And the change of torque can be clearly reflected by the ion signals.

Based on the theory of ionization sensing technology mentioned above and the analysis conducted in former research, the characters of ion signal is described by four parameters. As shown in figure 6, two peak voltages in a ion signal curves were defined as H1 and H2.The P1 and P2 were the position of these

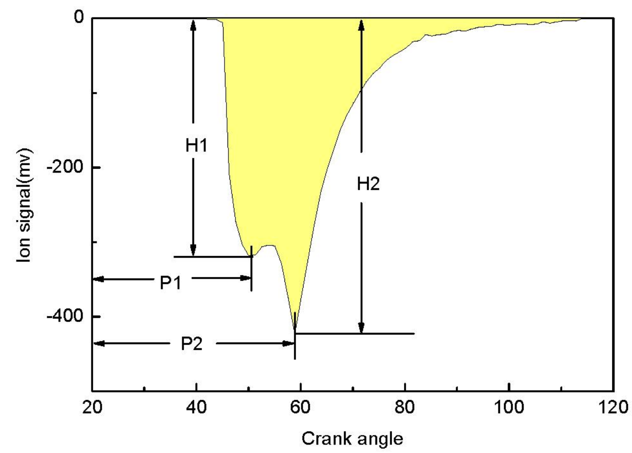

Figure. 6. Parametrization of the ionization signal.

two peak versus to the ignition timing point. The whole ion signal can be figured out by these four parameters. Thus, the following analysis is focus on the relationship between the torque and these four parameters.

In this paper, 10 averaged ion signals over 20 consecutive cycles were used for enhancing the stability of these four parameters. The working point is 3000rpm and the ignition

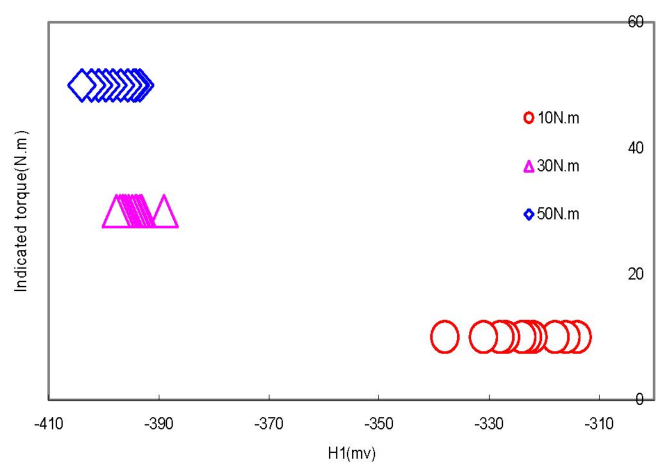

Figure. 7. The variation tendency of H1 which represents the first peak on the ion signal when the indicated torque increased.

timing was a constant value. The variation of H1 compared with the torque increased from 10N.m to 50N.m is shown in figure 7. From this figure we can see that the absolute value of H1 increased when the torque changed form 10N.m to 30 N.m. But no significant different can be observed when the torque increased from 30N.m to 50N.m.

But the parameter of H2 is great changed with the torque increment as shown in figure 8. A absolute value of 320mv is increased to 530mv when the torque varied from 10N.m to 30N.m.And from 30N.m to 50N.m this value is increased to

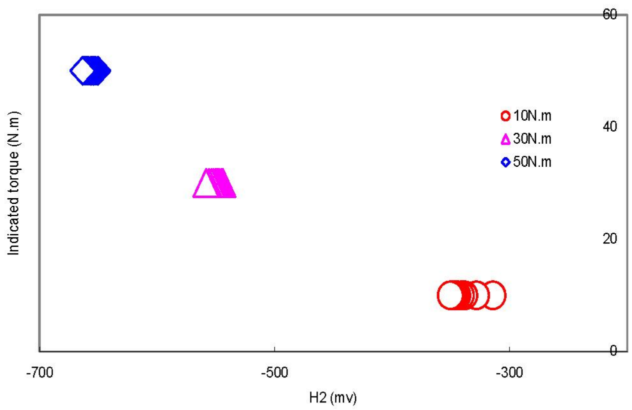

Figure. 8. The variation tendency of H2 which represents the second peak on the ion signal when the indicated torque increased.

690mv as well. The variation tendency of this parameter is well fitted to the increase of torque. Moreover, the fluctuation of H2 is very tiny. This character also can be seen in figure 5 in which the averaged ion signal curves are overlapped with each other, especially at the work point of 30N.m and 50N.m. So, the value of H2 is a important parameter to estimate the torque.

Figure 9 show that the variation of the parameter P1 versus to the increment of torque. No distinct tendency with P1 when the torque got higher. Most of these values are in the range of 38 to 41 crank degrees after the ignition timing point.

In the range of 48 to 51 crank angle from the ignition timing point, the transformation of the P2 versus to torque is shown in

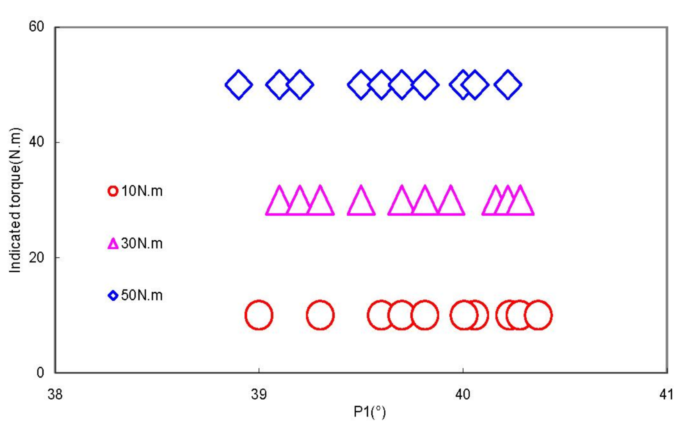

Figure 9 The variation tendency of P1 which represents the position of the first peak on the ion signal when the indicated torque increased.

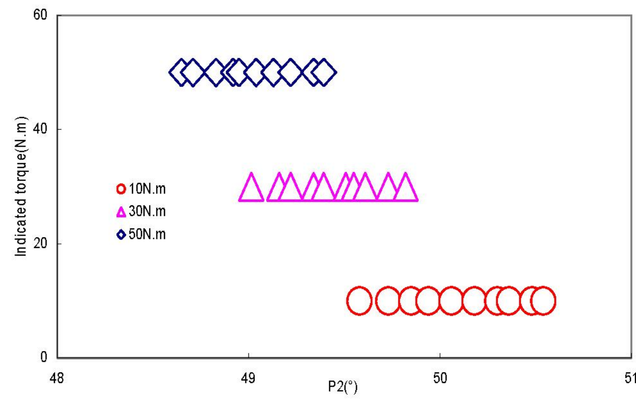

Figure .10. The variation tendency of P1 which represents the position of the first peak on the ion signal when the indicated torque increased.

figure 10.Here a clearly tendency can be seen that the position of the second peak of ion signal is moved forward tiny but regularly. This facts show that the position of the second peak in the whole ion signal figure is also an important parameter for the torque estimation.

Finally, another team of experiment is also conducted with the same method mentioned above, but the working point is 2300rpm, and the ignition timing is also a constant value. The results achieved in this team are shown in figure 11.

The variation tendency of ion signal versus to torque in this work point is consistent with the results achieved at 3000rpm.T he value of H2 and P2 are also the most correlative parameters with the torque as shown in figure 12.The H1 increased from 556mv to 819mv when the torque shifted form 10N.m to 30N.m, and keep increasing to 978mv as the value of torque is 50N.m. At the same time, the P2 is also changed with the variation of torque. When the torque is shifted from 10N.m to 50N.m, the P2 is 41.5, 40.2 and 39.2 degrees of crank angle correspondingly. The different is also existed between these two teams of experiment. the value of H2 of these two teams are different. The H2 in the team of 2300rpm are higher than

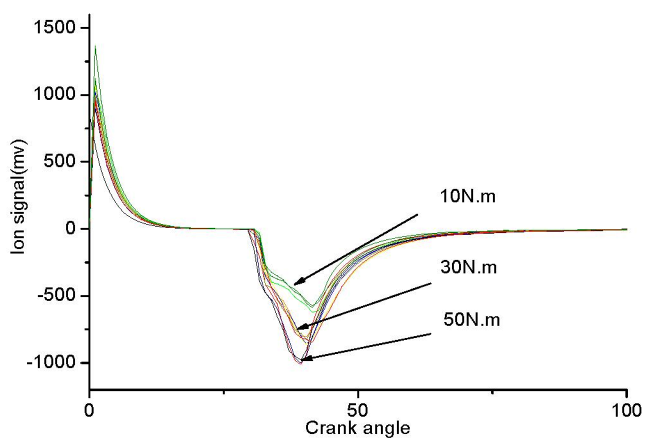

Figure 11 A comparision between the ion signals and the torque under a same speed of 2300 rpm and a constant ignition timing.

this value in team of 3000rpm with same torque. And also, with the same torque, the values of P2 in these two experiments are different. So, the information of these values must be synthesized for the purpose of torque estimation.

V. CONCLUSIONS

An experimental study of ion-current sensing in a internal combustion SI engine was conducted. From these experiments, it can be concluded that the ion signal is correlative to the torque in different engine operation conditions. And a possibility is demonstrated that the ion signal can be used for the torque estimation. The ionization sensing technology is an attractive proposition for a cost effective torque sensor, and it has been shown that the signal can be processed with adequate accuracy in this paper.

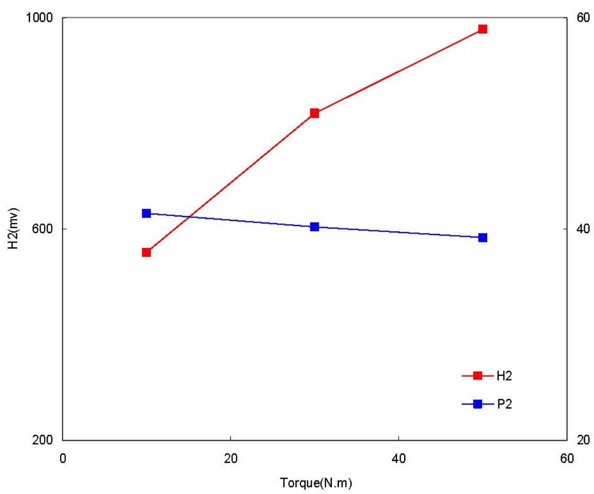

Figure. 11. The H2 and P2 measured at the speed of 2300rpm. The ignition timing of 2300rpm work point is about 10° crank angle later than that of 3000rpm.

Through the parametrization of the averaged ion signal over 20 consecutive combustion cycles, four parameters were analysed. Two parameters are very sensitive to the variation of torque. The first one is H1 which represent the second peak of the ion signal. With fixed engine speed and constant ignition timing, the second peak voltage in the ion signals are increased evidently when the torque increased. The parameter H2 which represent the position of the second peak of ion signal is also very sensitive to the torque, with the same engine and ignition timing, the position of the second peak in ion signals are advanced slightly. Both of these two parameters are greatly effected by the engine speed and ignition timing. Even the torque can be estimated by ion signal, the signal must be synthetized combined with these engine operation parameters.

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