A REAL TIME PLATFORM FOR FEEDBACK SPARK ADVANCE CONTROL

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SUMMARY
Today increasing fuel cost and demand for low CO_2 emission require higher engine efficiency; since one of the most important parameter affecting engine performances is spark advance, actually managed by the ECU in the map based open loop way, the authors research in the field of spark timing feedback control for fuel consumption and CO_2 emissions reduction. The present work deals with the realization of a hardware platform for the real-time feedback control of spark advance on a four cylinder series production engine. The system was realized by means of two power transistors, specifically designed for automotive ignition systems, and two data acquisition and generation boards, controlled by two calculators. The platform, put to the test in two different yet very simple mode, proved to perform a real time closed-loop control on spark timing. A relatively long loop period has been found, but this is mainly due to the pilot quantities employed; however, in this first step, no importance has been attached to the control pilot quantity, which could be easily substituted.
In the future the real time system will be employed to explore in-cylinder pressure based techniques for "faster" and reliable spark advance feedback control.

ABBREVIATIONS AND SYMBOLS

BDC	Bottom dead centre	S_A	Spark advance
BTDC	Before top dead center	RMS	Root mean square
CA	Crank angle	SNR	Signal to noise ratio
DAQ	Data acquisition	Q_P	Pilot quantity
ECU	Electronic control unit	TDC	Top dead centre
IGBT	Insulated Gate Bipolar Transistor	TTL	Transistor to transistor logic
IR	Infra-red	WOT	Wide Open Throttle
P-P	Peak to peak		

1. INTRODUCTION

Today increasing fuel cost and the demand for low CO_2 emission require higher engine efficiency, and, as far as the spark ignition engine is concerned, the fuel saving technologies range from variable compression ratio, to downsizing and turbocharging, from gasoline direct injection to variable valve actuation. Some of this technologies are already adopted, while other require some more effort in order to be introduced in series production engines. A step forward could also be made in the field of engine control strategies: it is known, in fact, that one of the most important parameter affecting engine performances is spark advance, but actually this fundamental parameter is controlled in open loop, that is by means of three-dimensional maps stored in the memory of the ECU during the calibration process. This spark timing management system present some drawback, for instance:

- The mapping process is time consuming and subject to error
- The setting chosen at each operating point may not be optimal
- The number of operating points in the map is limited, the mapping process can not explore every load and speed condition
- There may be variations between the test engine used for mapping process and the single production engine
- Apart from the engine operative conditions, the optimal spark advance depends on many variables, such as the ambient pressure, temperature and humidity, engine ageing and wear, fuel quality

In order to take account of coolant and air temperature variation or transient operation, other maps provide corrections to spark advance value.
A management system adopting a closed-loop spark timing control can overcome all of these problems, allowing the ECU to choose the best spark advance in every load and speed conditions. This kind of system could be used both in the calibration process, in order to speed up the engine mapping, and in normal engine operation, in order to let the ECU choose always the best spark advance apart from boundary conditions variation.

2. REALIZATION OF THE SPARK TIMING CONTROL SYSTEM

The authors of the present work focused on the realization of a hardware platform for the feedback control of spark advance on a four cylinder series production engine. The aim was to set up and test a system capable to take the spark timing control of a modern engine, leaving the management of the other parameters (e.g. injection time) to the series ECU. Taking the control of spark advance require a deep understanding of the ignition principle and process and of the hardware requirements and troubles. The main task of an ignition system is to heat up a local portion of mixture to make it reach the auto-ignition temperature. This will let the flame kernel start and propagate through out the combustion chamber. Moreover, since combustion is not instantaneous, but take a short time to develop and complete, the ignition must be properly timed with respect to the piston movement in order to obtain the maximum torque.
A simple generic feedback control system performs continuous adjustment on a variable on the base of the indication obtained by means of the measurement of a pilot quantity. The feedback control of a variable can be pursued mainly in two different way:

- Using a target value for the pilot quantity, the controller evaluates the error between target and actual quantity values and determines the amplitude of the correction to perform on the controlled parameter

- Without a target value of the pilot quantity, the controller aims to maximize (or minimize) the pilot quantity acting on the controlled parameter

The choice between this two kinds of control depends mainly on the pilot quantity that will guide the spark advance regulation. Since this work is not focused on the pilot quantity, but rather on the development and test of the control system, it has been chosen to adopt simple and easy to measure pilot quantities, such as engine torque and angular speed, which require the second kind of control.
The feedback spark timing management system realized is composed of an ignition module, which represent the high power side of the system and is dedicated to the spark generation, and a control module, the low power side, mainly dedicated to data processing and to signal acquisition and generation.

2.1. Ignition module
Today's ignition system are controlled by the ECU whose microprocessor, in order to generate a spark between the electrodes plug, sends a digital pulse to a power transistor, called IGBT (Insulated Gate Bipolar Transistor): this electronic components (limited by the broken line in Fig. 1) act as a switch, closing (or opening) the circuit among collector and emitter if the gate voltage is over (or under) a certain threshold level. Thus if the gate receive a pulse with the positive level over the threshold value, the IGBT will close the primary coil circuit on the battery for the whole duration of the pulse. Since ignition coil can be considered a solenoid with resistance *R* and inductance *L*, the current *i* which flows through the primary is an exponential function of time with an asymptotic value of *V/R*. The energy stored in the magnetic field of the coil

$$E_{coil} = \frac{1}{2} L\, i^2 \qquad 1)$$

(about 60 ÷ 120 mJ) will be discharged by the secondary coil through the electrodes spark when the level at the gate will fall down below the threshold value (BOSCH, 2000).

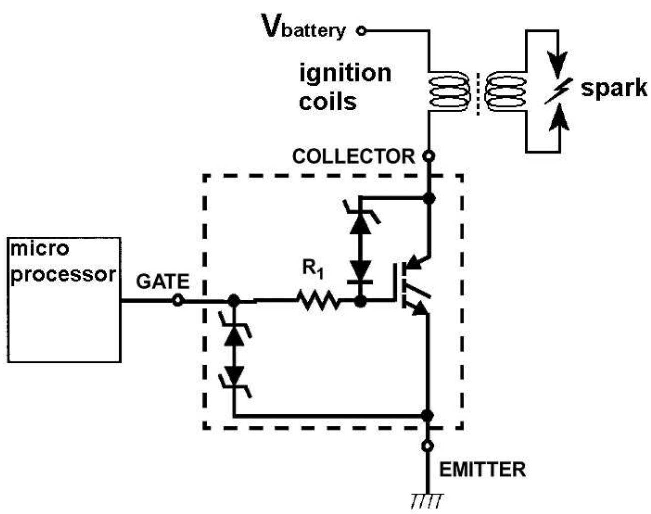

Fig. 1 Schematic diagram of an IGBT connected both to the micro-controller and to the ignition coil

The authors decided to maintain the two by two ignition coils connection, thus performing a "waste spark" ignition control: in this way the two couple of cylinders, 2-3 and 1-4, are ignited alternatively once a half turn, no matter which cylinder is at compression TDC. For this reason the ignition module was constituted by two identical sub-systems, each one dedicated to a couple of cylinders and composed of an IGBT transistor connected, as described in Fig. 1, with the collector at the primary coil, the emitter at ground and the gate to the digital pulse source; each transistor was locked on a finned surface for heat dissipation purpose (the primary coil current can rise up to 14 ampere in this application). The transistors employed are two Fairchild automotive ignition IGBTs, fully clamped up to 420 Volt, that means no high voltage fluctuation caused by ignition can return back to the gate and damage the microprocessor. Alternatively, for greater safety, it is advisable to interrupt the physical connection between the gate and the microprocessor with an optoinsulator.

2.2. The control module

The control module represents the software/hardware sub-system able to acquire and analyse all the necessary data, and send the digital pulses to the transistors' gate in order to produce a spark in the combustion chamber. This control module was realized by the combined use of two National Instruments data acquisition and generation boards: the first, a NI 6062E DAQcard, dedicated to the acquisition of the external signals (engine speed, torque, knocking, throttle opening, battery voltage) communicates with the second, a NI 6040E, assigned to the ignition pulses generation.

A general purpose Labview function has been chosen for the digital pulse generation; this function uses a digital counter (a common National Instruments multifunction board have two) to generate a TTL compatible pulse of assigned width and delay with respect to a trigger event. So it has been sufficient to give the counter the following three information:

§ The trigger event

The rising (or falling) edge of a digital pulse, generated by means of a phototransistor, constituted by an IR emitter and an IR receiver, placed one in front of the other and periodically interrupted by the passage of an opaque element; naturally the two trigger signals (one for every couple of cylinder, *trigger 1/4* and *trigger 2/3* in Fig. 5) must be generated within an interval of 180° CA between each other;

§ The pulse width

This is a very important parameter for the ignition spark generation. During the ignition pulse the primary coil cumulates the energy that will be discharged by the secondary coil through the electrodes spark (see eq. (1)). Since this energy depends on coil's current and this one rise exponentially with time, the pulse width determines the ignition energy. A short pulse can cause misfire to occur because of a too low ignition energy, while long pulses cause fast electrodes wear and too high primary currents.

§ The pulse delay respect to the trigger signal

This parameter affects the spark advance, in fact, as can be seen in Fig. 2, the sum of pulse delay, pulse width and spark advance gives the trigger edge advance respect to TDC, which has been fixed to 140°CA. So the pulse delay is calculated once assigned ignition pulse width and spark advance.

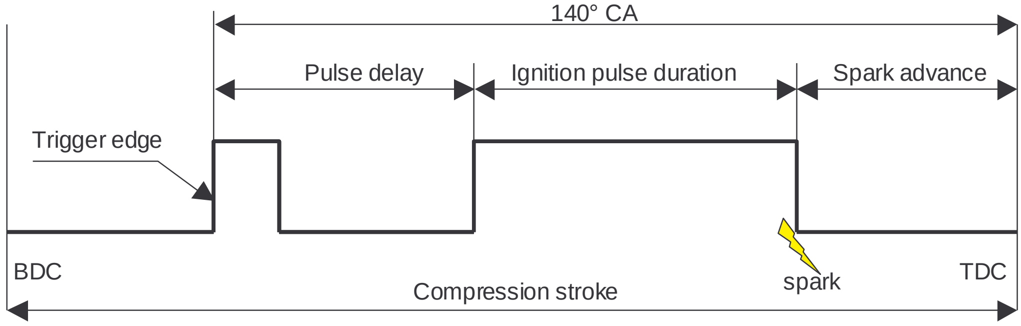

Fig. 2 Ignition pulse diagram

Since every ignition sub-system require the use of a digital counter, none of the two 20 MHz counters present on a DAQ device were available for the data acquisition, so a second DAQ device has been employed for this purpose. The system realized permitted both the feedback and the map based spark advance control, the latter performed using engine speed and throttle opening for map indexing.

The control module task was to calculate, cycle by cycle, the spark advance setting (both in the map based and in the feedback control) and to send the ignition pulse to the ignition module.

The necessary data to acquire for the spark timing control were:

§ Engine speed: required for the conversion of crank angle into time interval and for map based control; it has been also used as pilot quantity during “on-road” feedback control (see paragraph 3-The experimental setup). The measure of the angular speed has been obtained by the acquisition of the engine ring gear signal.

§ Engine Torque: needed for torque based feedback control; it’s measure has been obtained by the acquisition of the eddy current dynamometer analogue output.

§ Throttle valve opening: necessary during map based spark advance control, has been measured directly by the acquisition of the engine throttle position signal.

§ Knock signal: during medium to high load conditions (from 0,6 WOT up to full load), the research for the best spark advance led the engine to run next to the knock limit, so, in order to preserve the engine from damages, it is advisable to measure and control knocking phenomenon. This as been done acquiring the signal generated by an accelerometer, a Brüel & Kjær Cubic DeltaTron 4502, with a natural frequency of 50 kHz bonded on the engine block between the two inner cylinders. It has been observed that the knocking phenomenon, independently of the engine speed and load, took place during a time window of about 4 ms before the rising edge of the *trigger 1/4* signal (see Fig. 3), so it has been thought to use the latter as trigger for the knock signal acquisition, which has been performed at a sample frequency of 100kHz; the accelerometer signal has been conditioned in two step: first, a pre-sampling high pass filter with a cutting frequency of approx 318 Hz has been used to remove the DC component due to thermal drift effect, and hence the acquired signal has been bandpass filtered between 3 and 30 kHz to remove unwanted background noise due to valve closing and piston slap.

As regards knock intensity evaluation, a preliminary test carried out using four different knock intensity definitions (Millo and Ferraro, 1998) based on the analysis of the filtered accelerometer signal (peak to peak value, maximum first derivative, root mean square and integral of the absolute value) showed the most secure to be the first two: as example it can be seen in Fig. 4 that, during the test, this two methods revealed higher percentages of knocking cycles[1] than the other two. The peak to peak method has been chosen for the faster calculus required.

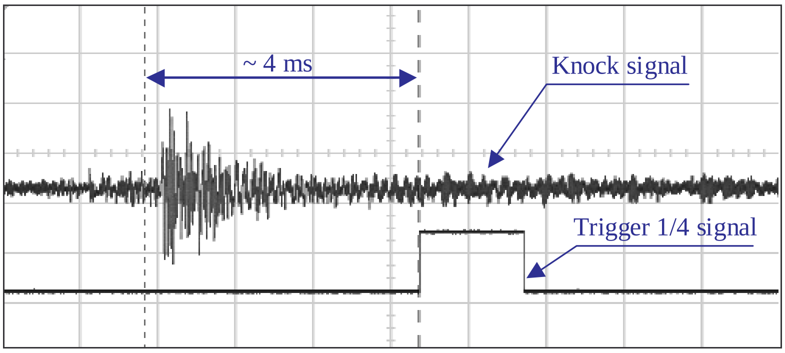

Fig. 3 Oscilloscope image showing knock and trigger 1/4 signals

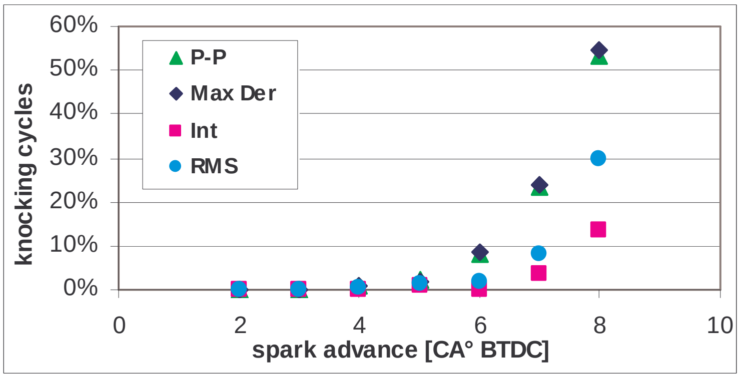

Fig. 4 Percentage of knocking cycles according to spark advance (250 cycles - WOT - 1500 rpm)

§ Battery voltage: this information is essential for the calculation of the ignition pulse duration, since the primary coil's current, and hence the energy stored (see eq. (1)), depends on the voltage applied to the coil, i.e. the battery voltage. Since this voltage is not constant during engine operation, the coils charging time must be extended or reduced as a result.

3. THE EXPERIMENTAL SETUP

The feedback spark advance control system realized is based on the real time acquisition and processing of some data, and on the immediate generation of the ignition pulses. A complete control loop can be followed in Fig. 5, which represents the main components of the test bed. The engine used was connected to an eddy current dynamometer, which, in a first stage, has

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[1] A knocking cycle is revealed by a SNR, the ratio between knock intensity and background noise (this one is approx a linear function of engine speed), greater than two.

been set to a constant speed braking characteristic; in this case the control system searched for the maximum brake torque spark advance.

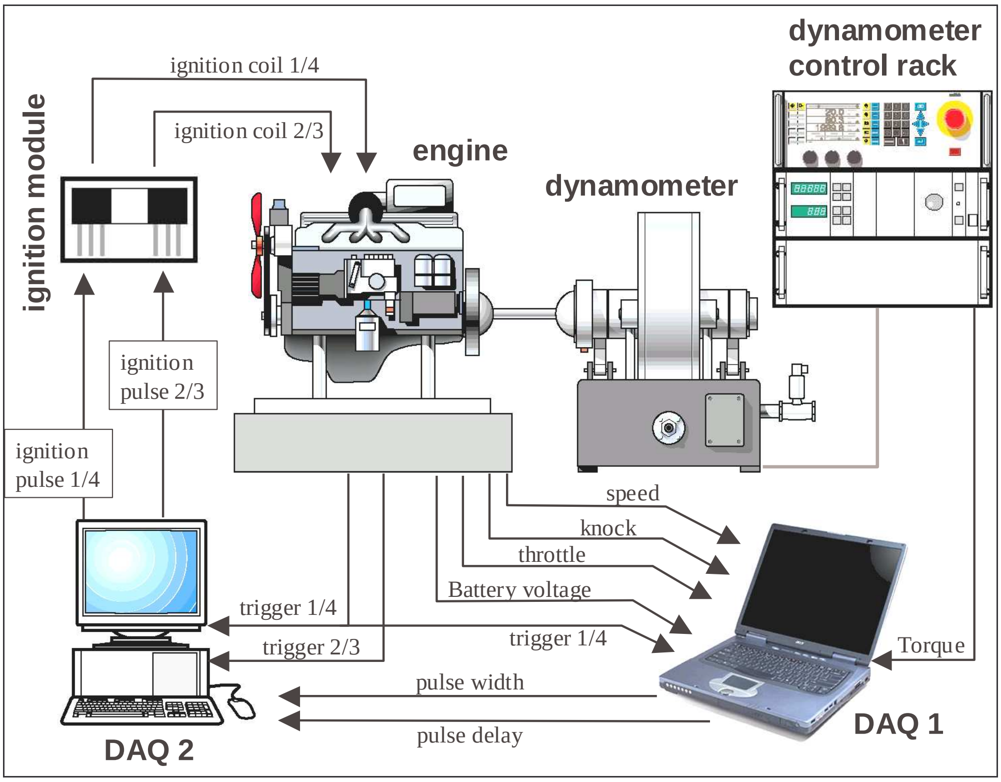

Fig. 5 Engine test bed

In a second stage the dynamometer has been set to a "road load" characteristic, so as to simulate the vehicle behaviour during on-road operation: in this case the pilot quantity was the engine speed, since torque variations (due to spark advance changes) produce speed variations, as can be seen in Fig. 6.

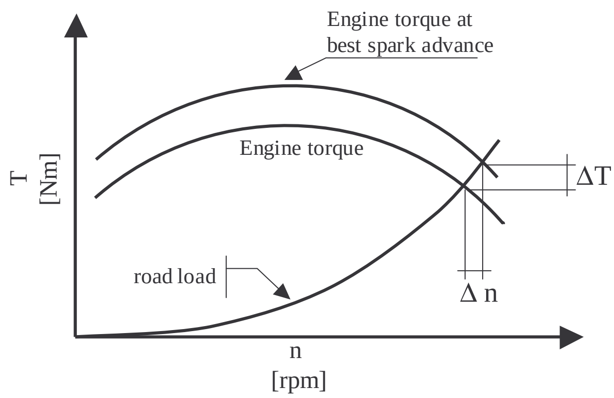

Fig. 6 Speed variation with "road load" braking torque

Under closed-loop control the DAQ 1 board (see Fig. 5) retrieves the needed information both from the engine (*speed*, *knock*, *throttle position* and *battery voltage* signals) and from the eddy current dynamometer (*torque*): the latter is not needed in the "on-road" simulation. All this data are obtained through a triggered acquisition using the rising edge of the *trigger 1/4* signal. The collected data permit the evaluation of the change to apply to spark advance (see below for the strategy), and hence of the actual values of ignition pulse delay and duration (the latter depends only on engine speed and battery voltage, so it has been mapped); these two parameters are transmitted as analogue signals to the DAQ 2 board, which generates the ignition pulses directed to the two IGBTs gate with the assigned duration and delay with respect to the *trigger 1/4* and *trigger 2/3* signals, both coming from the phototransistors integral with engine crank. The ignition module transforms these digital pulses in high power sparks between the plugs electrodes.
The strategy adopted for spark advance control is very simple: the calculator retrieves and collects the pilot quantity values at each revolution and, every N_R revolutions, interpolates the last N_R values with a 2nd order polynomial function; then uses this function to evaluate the pilot quantity variation ΔQ_P during the last N_R revolution, which is divided by the spark advance change ΔS_A to obtain the indicator I:

$$I = \frac{\Delta Q_p}{\Delta S_A}$$

if the indicator I is negative, the controller will retard the spark timing by one crank degree, otherwise, the spark will be advanced by the same quantity.
The controller also processes the accelerometer signal, searching the presence of knocking in the last N_R cycles: if some is found, the spark advance will be retarded by two crank degree. The calculator executes this control loop once every N_R cycle. In order to remove pilot quantity fluctuations, its mean value over 10 revolutions has been used.

4. TESTS AND RESULTS

The feedback spark timing control system has been put to the test under different engine loads and speeds. The spark control test always began in the map based mode, setting a retarded spark advance respect to the optimal value. Then the system was switched on the feedback control in order to verify its capability to search and find the optimal spark advance value.

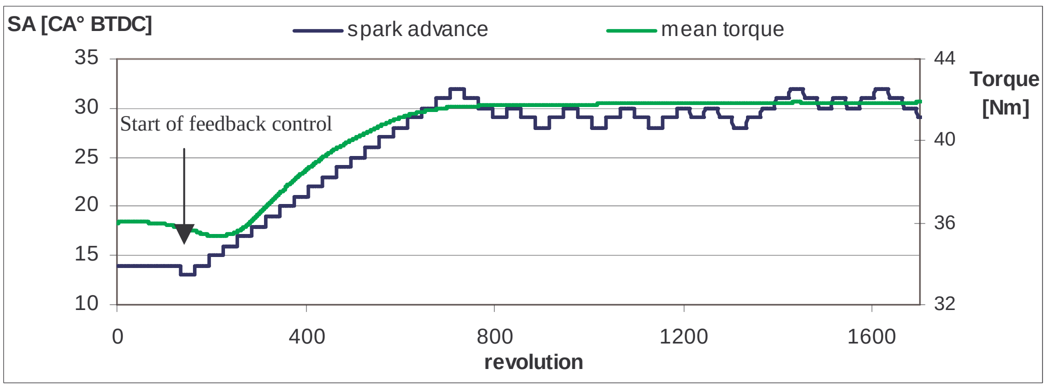

Fig. 7 Spark advance feedback control
in the torque based mode (2000 rpm – 0,3 WOT)

Fig. 7, Fig. 8, Fig. 9 and Fig. 10 show the results of the spark timing control during torque based operation, while Fig. 11, Fig. 12 and Fig. 13 refer to the “on road simulation” mode.

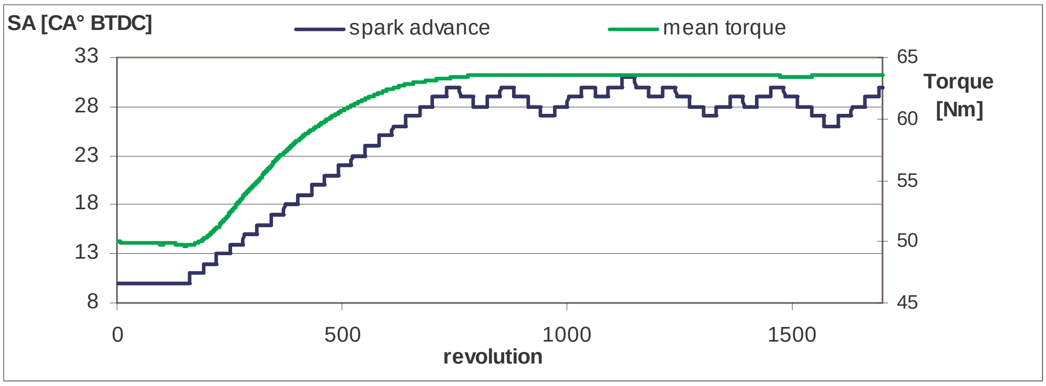

Fig. 8 Spark advance feedback control
in the torque based mode (2200 rpm – 0,6 WOT)

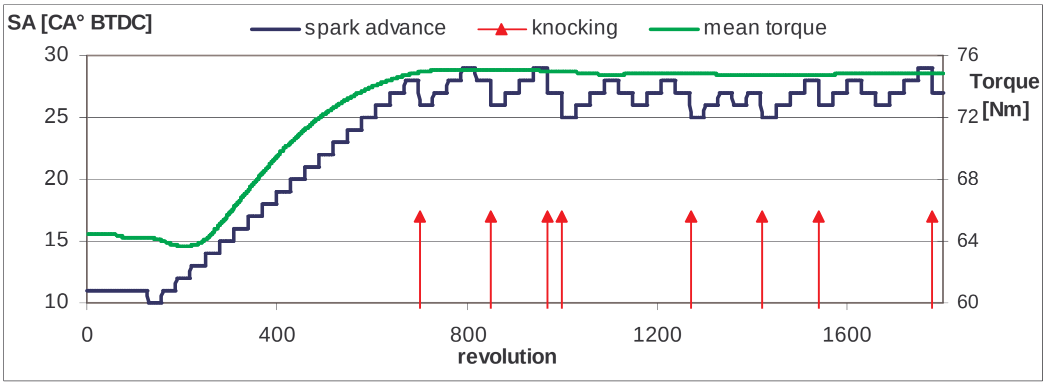

Fig. 9 Spark advance feedback control
in the torque based mode (1800 rpm – 0,6 WOT)

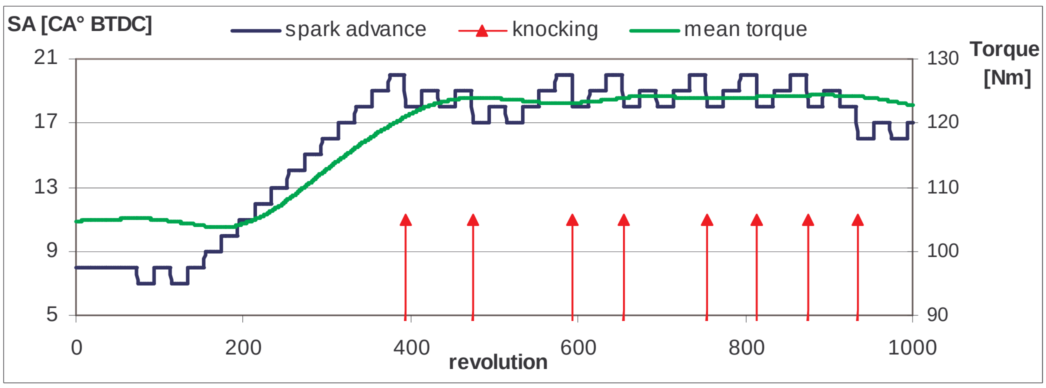

Fig. 10 Spark advance feedback control
in the torque based mode (2500 rpm – 0,9 WOT)

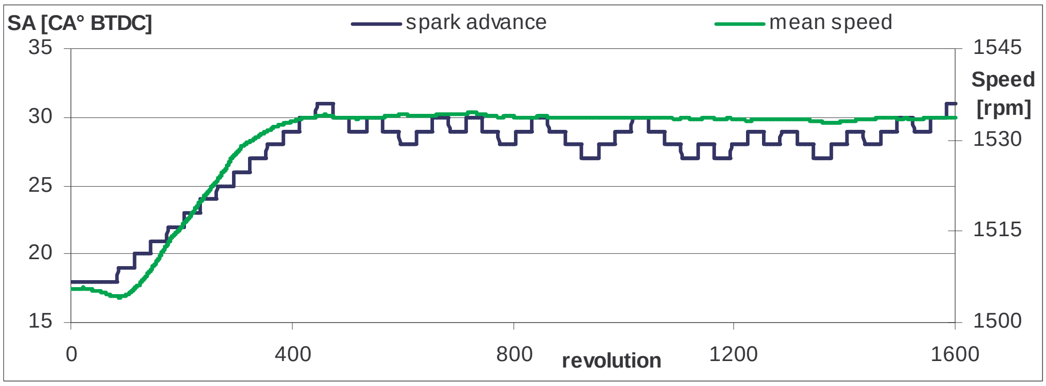

Fig. 11 Spark advance feedback control
in the "on road simulation" mode (1500 rpm – 0,3 WOT)

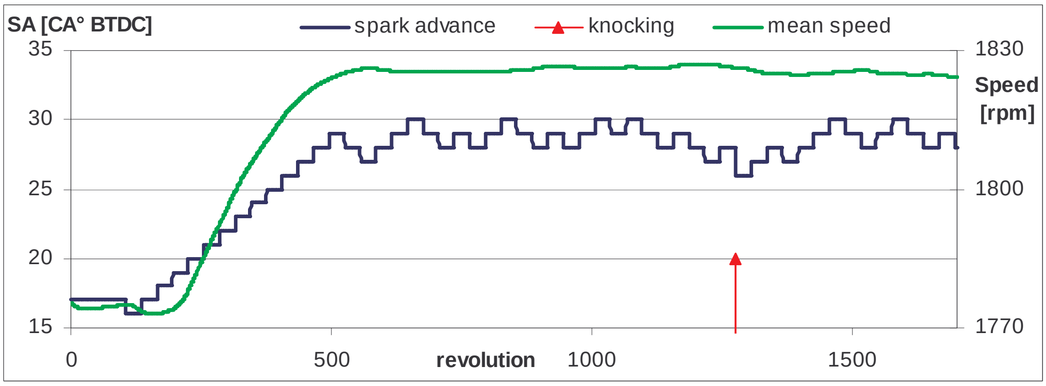

Fig. 12 Spark advance feedback control
in the "on road simulation" mode (1800 rpm – 0,5 WOT)

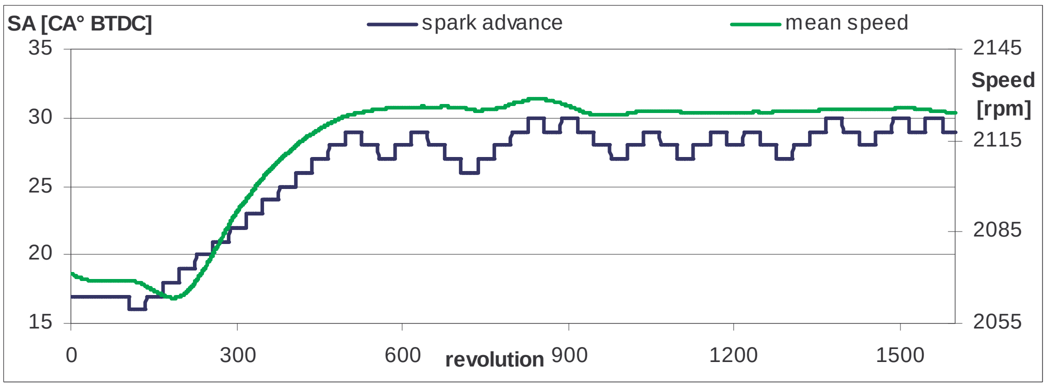

Fig. 13 Spark advance feedback control
in the "on road simulation" mode (2100 rpm – 0,6 WOT)

As can be seen, the simple platform realized permits the feedback control of spark advance in both modes, with a final oscillations of ± 2 crank angle degree. Fig. 9 and Fig. 10 show how knocking occurrence (marked by the arrows) influence the feedback control: since the controller was instructed to decrease spark advance by two crank angle degrees when knocking was recognized, at high loads the control produced torque oscillations; this confirms that at high loads (from 0,6 WOT to full load) a good spark control strategies is that simply based the knocking detection.
An important role was played by the number of revolution between two consecutive spark advance changing, N_R. The best choice would be N_R=2, i.e. feedback control cycle by cycle; unfortunately the fluctuations of mean pilot quantity (mainly due to the engine cycle by cycle variations) limit this parameter to higher value. During both torque based operation and "on road simulation" mode, it has been observed a stable control over spark advance with N_R set to 30, that means 15 cycles needed to perform a spark advance adjustment: this is a relatively high loop period. The system is however ready to run with the use of other pilot quantities, for example derived from in-cylinder pressure analysis or from instantaneous flywheel speed fluctuation, which allow a faster control over spark advance. In the "on road simulation" mode, the system realized has the advantage to perform a feedback control on spark timing with no additional sensor needed than those commonly used for the engine management system; in the torque based mode, it can be employed for faster engine mapping process.

5. CONCLUSIONS

A real time platform for the feedback control of spark advance has been realized and tested. It is mainly composed of two bipolar transistors designed for automotive ignition, two multifunction DAQ board from National Instruments and two calculators. The system has been tested on a test bench equipped with an eddy current dynamometer. The tests have been conducted in two modality: torque based and "on road simulation". In the fist mode, the pilot quantity was the engine torque, while in the second the controller observed engine speed variation. In both cases the system proved to work properly, searching and reaching optimal spark timing, with an oscillation of ± 2 crank angle degree around the final spark advance value.
Nevertheless the system presents a drawback in the relatively long loop period: in fact the system reached a stable control on spark advance with a loop period of 15 engine cycles both in the torque based and in the speed based mode. These long loop periods derive from the fluctuations showed by the two pilot quantity; this work however is intended to be a first step in the field of the feedback spark advance control. Faster control loop should be ensured by the use of quantity derived from the in-cylinder pressure analysis or from engine speed fluctuation during one cycle.

6. AKNOWLEDGMENTS

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References

Beccari A., Caputo C. 1987, “Motori termici volumetrici”, UTET

Peter Wibberley and Christopher A. Clark, 1989, “An investigation of cylinder pressure as feedback control of internal combustion engines”, SAE Paper 890396

Gregg W. Pestana, 1989, “Engine control methods using combustion pressure feedback”, SAE Paper 890758
BOSCH, 2000, “Automotive Handbook”, SAE

Claus Preuschoff, 2001, “Smart IGBT for advanced ignition systems”, SAE paper 2001-01-1220

Kaneyasu M., Kurihara N., Katogi K., Tabuchi K.., 1995, “An Advanced Engine Knock Detection Module Performs Higher Accurate MBT Control And Fuel Consumption Improvement”, 8th International Conference on Solid-State Sensors and Actuators. Volume 1

Dale J.D., Checkel M. D., Smy P. R., 1997, “Application of high energy ignition systems to engines”, Progress in Energy and Combustion Science, vol.23, pp 379-398

Mamileti, Robb, Shen, Taomoto, 1996, “IGBTs designed for automotive ignition systems”, Power Electronics Specialists Conference, 1996. PESC '96 Record., 27th Annual IEEE

Eriksson L., “Spark advance modelling and control”, Linkoping Studies in Science and Technology. Dissertation N° 580, 1999, www.vehicular.isy.liu.se

Millo F., Ferraro C. V., 1998, “Knock in S.I. Engines: A Comparison between Different Techniques for Detection and Control”, SAE Paper 982477

SOMMARIO

E’ ben noto che uno dei parametri di funzionamento del motore ad accensione comandata che maggiormente ne influenza le prestazioni è l’anticipo d’accensione. Attualmente la regolazione di tale parametro viene effettuata in *open-loop*, cioè sulla base di valori registrati su una mappa tridimensionale in funzione essenzialmente delle variabili carico motore (ovvero apertura farfalla o pressione nel collettore di aspirazione) e regime di rotazione. Una regolazione dell’anticipo d’accensione più efficiente è senza dubbio quella in retroazione (o in *closed-loop*), che consente cioè di ottenere, in ogni condizione di funzionamento, l’anticipo d’accensione ottimale (ovvero di massima coppia). La strategia di controllo in retroazione deve basarsi sulle informazioni da una variabile dipendente dall’anticipo stesso, denominata variabile pilota: in tal modo si può “temporizzare” l’accensione per ottenere il minimo consumo specifico a prescindere dalle altre variabili che possono avere influenza sul valore ottimo dell’anticipo stesso (condizioni atmosferiche di temperatura, pressione ed umidità, usura del motore, tipo e qualità del combustibile, etc…). Gli autori hanno messo a punto e testato una piattaforma hardware per il controllo in retroazione in tempo reale dell’anticipo d’accensione di un motore di serie quatto cilindri. Il sistema è stato realizzato per mezzo di due transistor bipolari e due schede di acquisizione: allo scopo di valutarne la capacità di controllo, sono state effettuate prove in diverse condizioni di carico e regime su un motore Renault, collegato ad un freno dinamometrico a correnti parassite. In questo primo approccio si è scelto di utilizzare, come variabile pilota per il controllo, la coppia fornita dal freno, impostato su una caratteristica a velocità angolare costante, ovvero la velocità di rotazione del motore, con freno impostato su una caratteristica “cubica di funzionamento” che simula il comportamento su strada di una vettura.

I risultati mostrano che il sistema è capace di perseguire l'anticipo di accensione ottimale, con oscillazioni attorno al valore finale di ± 2 gradi, anche se con tempi di intervento lunghi (15 cicli motore per ogni variazione di anticipo). Questi sono legati alle fluttuazioni delle grandezze pilota impiegate.

Il futuro sviluppo di questo lavoro prevede l'individuazione di variabili pilota, che siano disponibili a bordo del veicolo, alternative alla coppia ed al regime di rotazione, idonee per una regolazione sufficientemente "rapida".