(12) UK Patent Application (19) GB (11) 2552187 (13) A

(43) Date of A Publication **17.01.2018**

(21) Application No: **1612146.9**

(22) Date of Filing: **13.07.2016**

(71) Applicant(s):
GM Global Technology Operations LLC
(Incorporated in USA - Delaware)
300 Renaissance Center, DETROIT,
Michigan 48265-3000, United States of America

(72) Inventor(s):
Stefano Nieddu
Andrea Mollar

(74) Agent and/or Address for Service:
Greg Sach
Kopf, Westenberger, Wachenhausen, Briennerstr. 11,
80333, München, Germany

(51) INT CL:
F02D 41/40 (2006.01) ***F02D 41/02*** (2006.01)
F02D 41/30 (2006.01) ***F02D 41/38*** (2006.01)

(56) Documents Cited:
US 20120123703 A1 **US 20120118053 A1**
US 20100199951 A1 **US 20100147058 A1**

(58) Field of Search:
INT CL **F02D**
Other: **EPODOC, WPI**

(54) Title of the Invention: **A method of operating an internal combustion engine**
Abstract Title: **Method of determining fuel injection quantity**

(57) Disclosed is a method of operating an internal combustion engine 110 comprising a fuel rail 170 in fluid communication with a number of fuel injectors 160 and with a fuel pump 180 configured to perform a discharge stroke after each fuel injection performed by the fuel injectors 160. The method comprises the steps of operating a fuel injector 160 to perform a fuel injection; deactivating a first discharge stroke of the fuel pump 180 following a start of the fuel injection, thereby preventing the first discharge stroke from delivering fuel into the fuel rail 170; calculating a value of a pressure drop caused in the fuel rail 170 by the fuel injection; calculating a value of a fuel quantity injected by the fuel injection on the basis of the calculated value of the pressure drop. This information may then be used to correct future energisation times of fuel injectors. The fuel injectors may be solenoid controlled electromechaincal fuel injectors. The method corrects for fuel injection variation caused by drift and aging of the fuel injector. A corresponding apparatus including an electronic control unit, ECU, and computer program for carrying out the method are also disclosed.

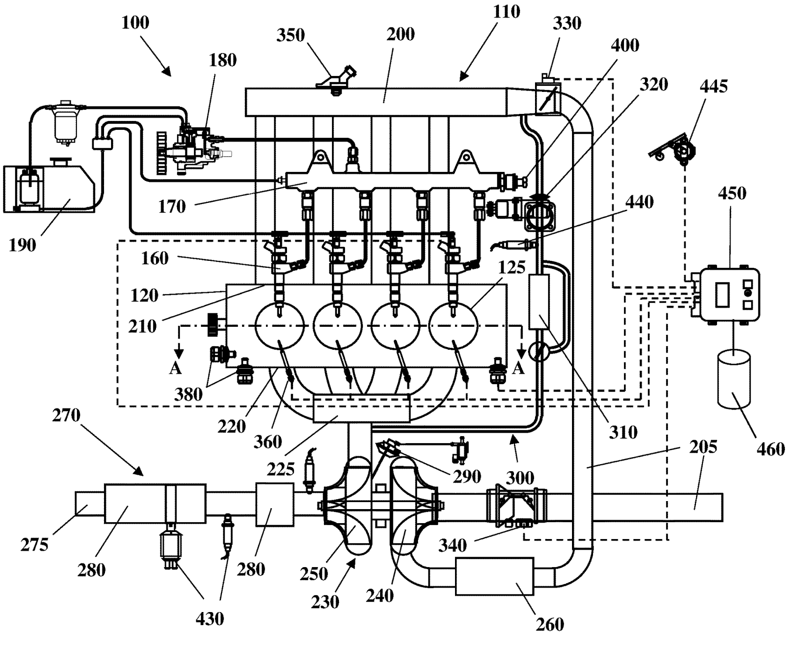

FIG.1

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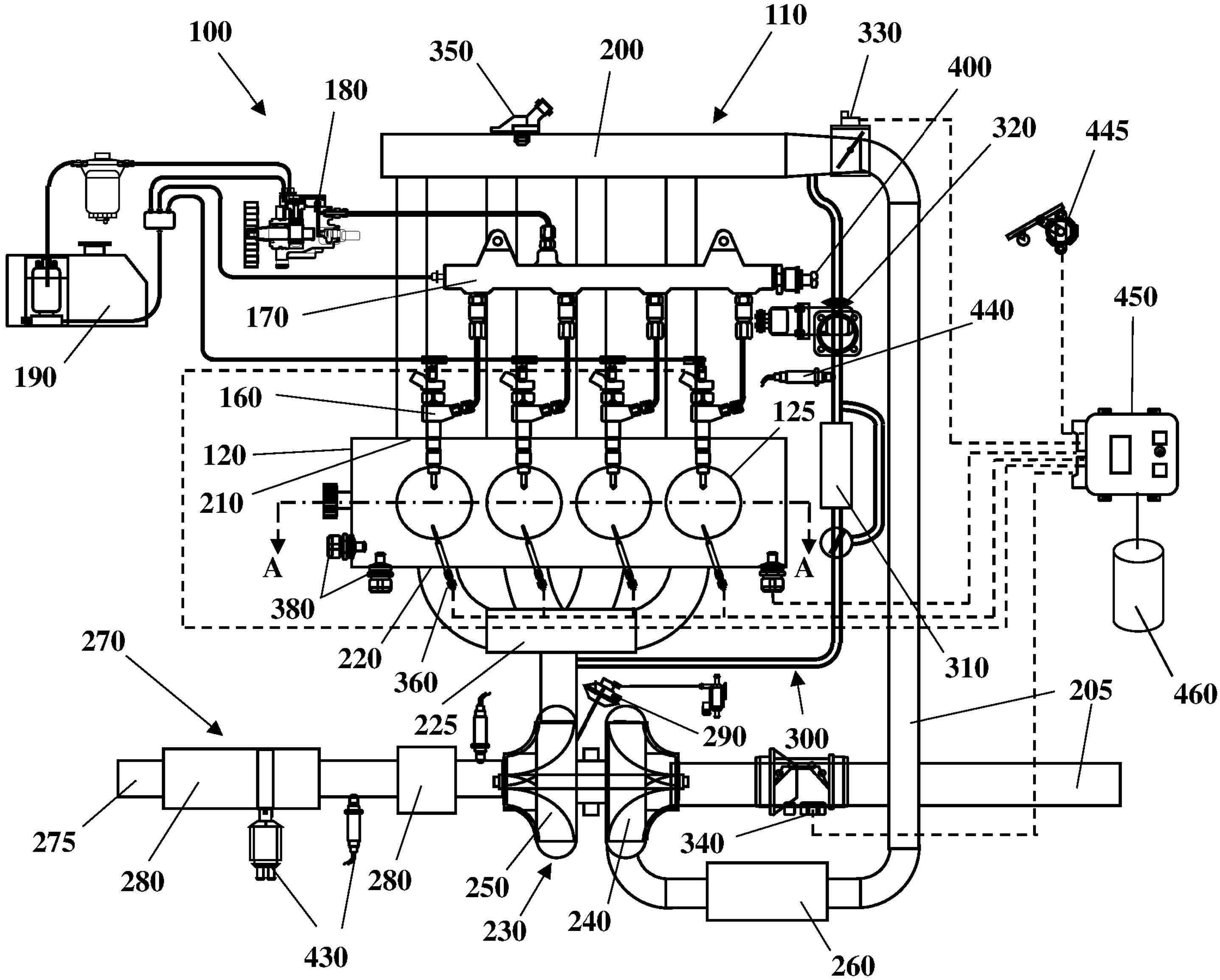
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FIG.1

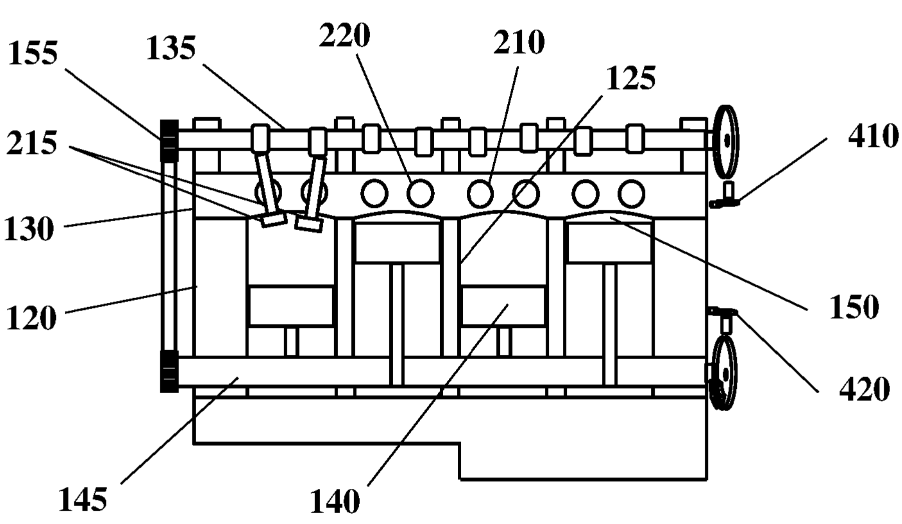
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FIG.2

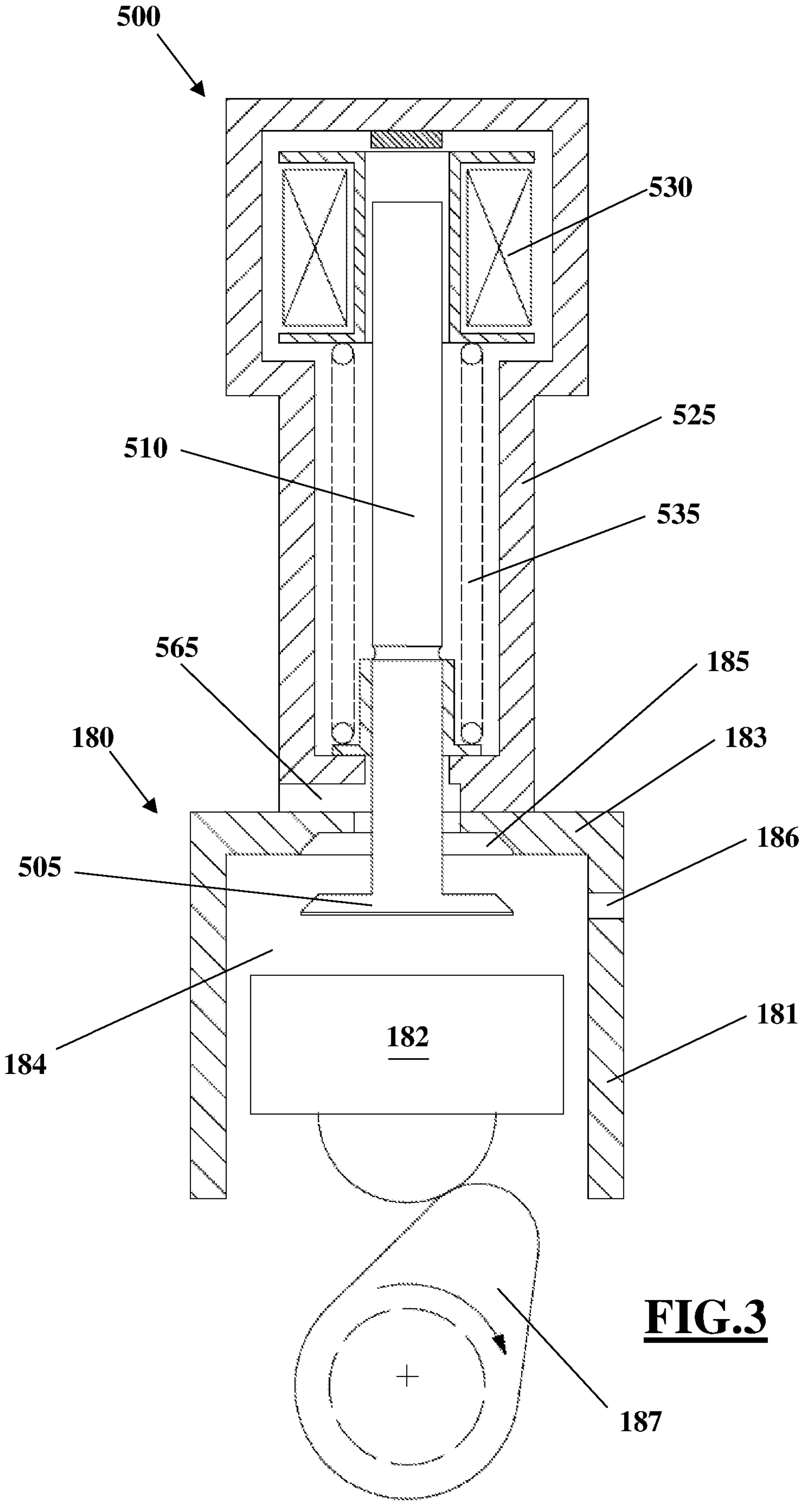

FIG.3

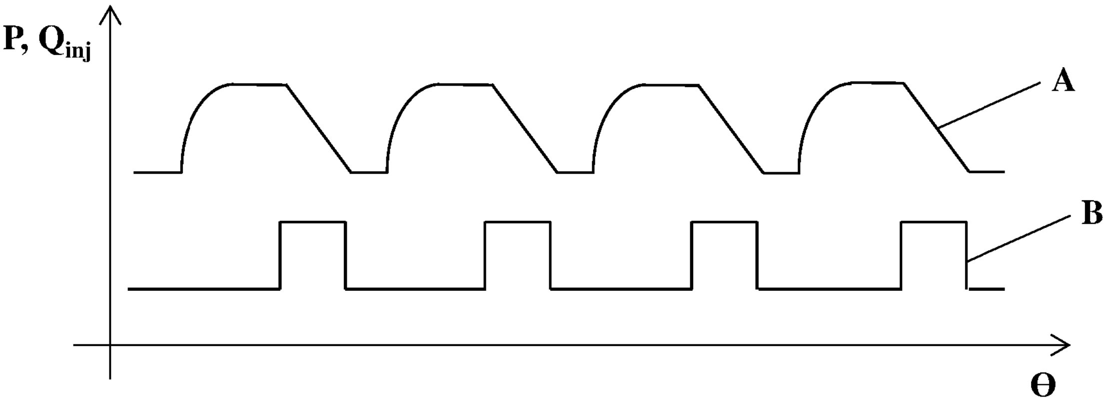

FIG.4

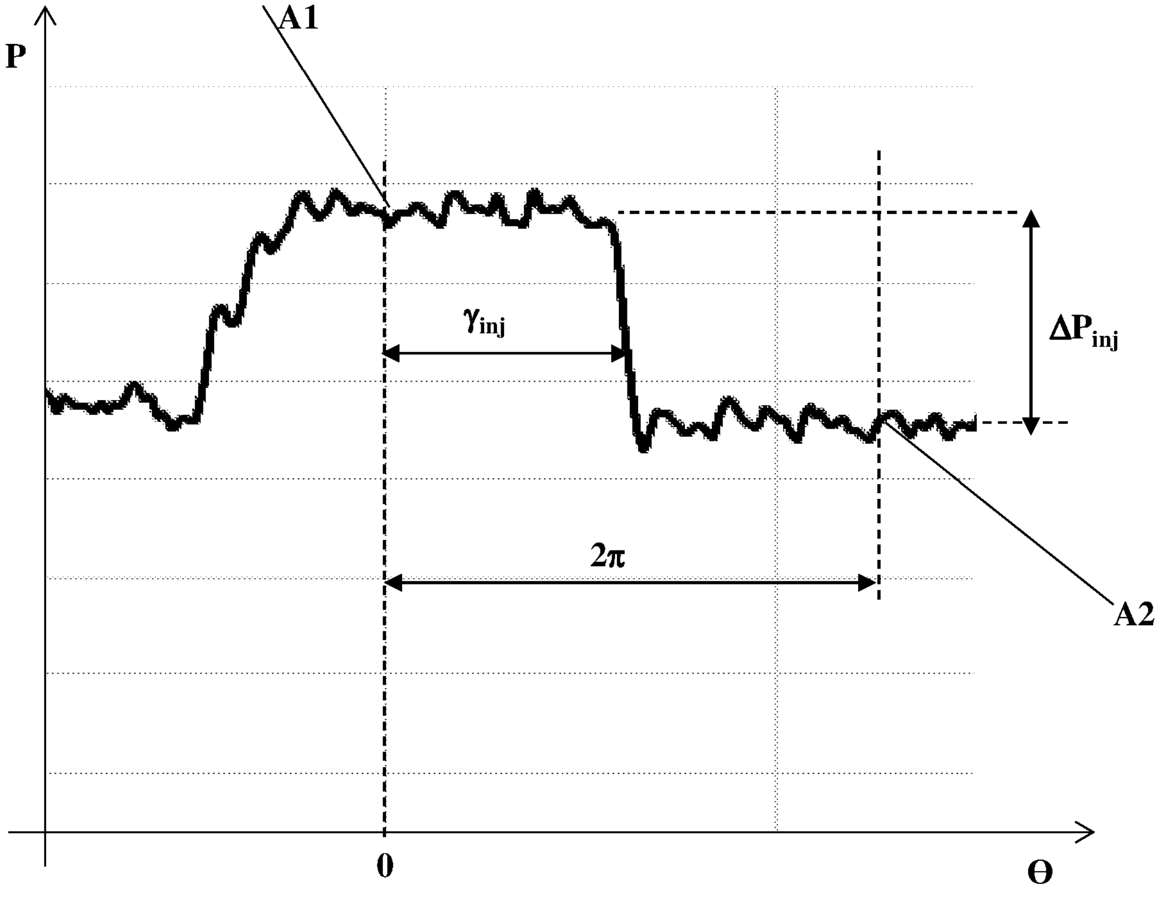

FIG.5

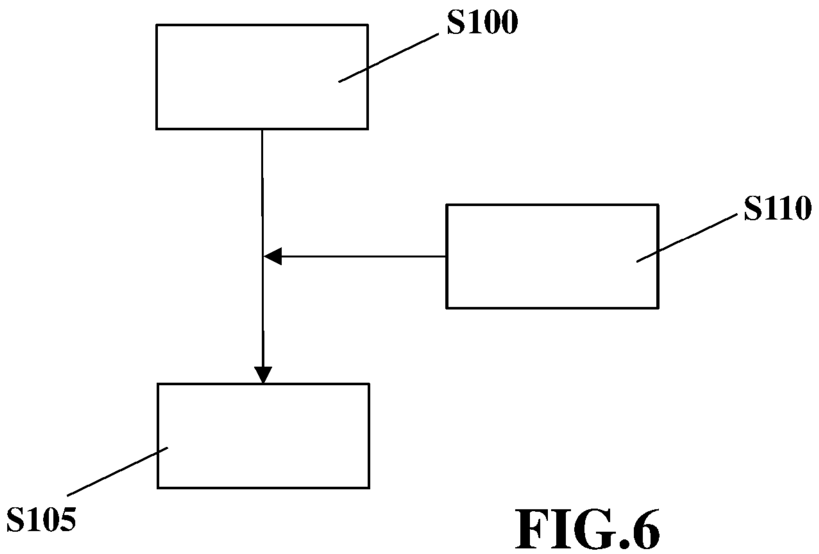

FIG.6

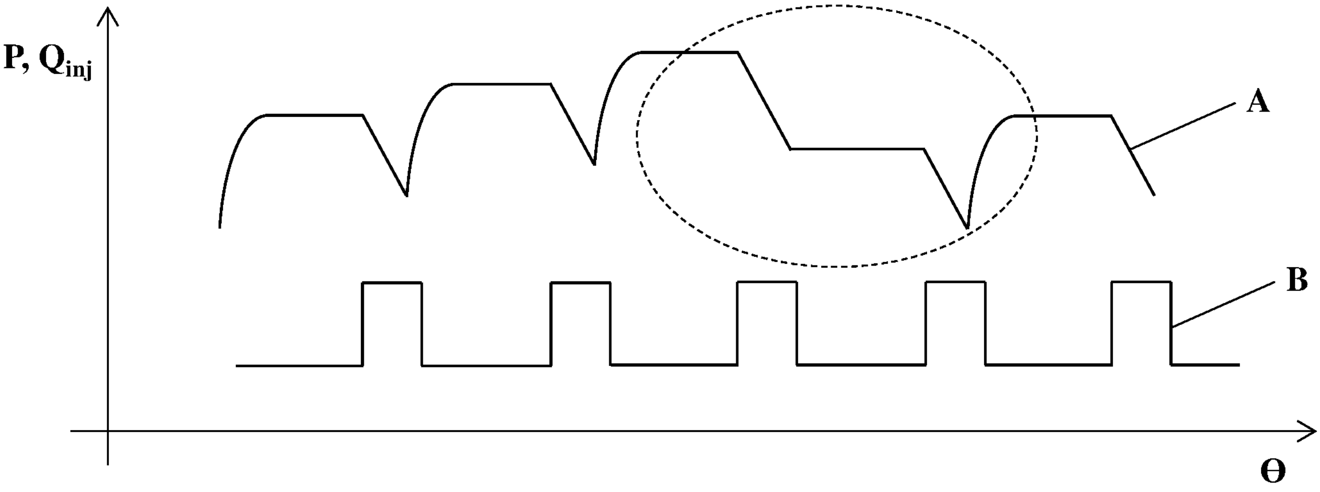

FIG.7

Intellectual
Property
Office

Application No. GB1612146.9 RTM Date :27 January 2017

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WiFi

A METHOD OF OPERATING AN INTERNAL COMBUSTION ENGINE

TECHNICAL FIELD

The present disclosure generally relates to a method of operating an internal combustion engine of a motor vehicle, such as a Diesel engine or a Gasoline engine. More particularly, the present disclosure relates to a method of determining the fuel quantity that is actually injected by a fuel injector.

BACKGROUND

It is known that an internal combustion engine of a motor vehicle generally comprises a fuel injection system (FIS) including a fuel rail and a plurality of fuel injectors in fluid communication with the fuel rail and configured to perform fuel injections into the combustion chambers of the engine.

The fuel injection system may further comprise a high pressure fuel pump, which is embodied as a piston pump driven by the engine and configured to perform a discharge stroke after every fuel injection, in order to deliver into the fuel rail a quantity of fuel that compensate for the injected fuel quantity.

The fuel injectors are essentially embodied as electromechanical valves having a needle, which is normally biased in a closed position by a spring, and an electro-magnetic actuator (e.g. solenoid), which moves the needle towards an open position in response of an energizing electrical current. The energizing electrical current is provided by an electronic control unit, which is generally configured to determine the fuel quantity to be injected by the fuel injection, to calculate the duration of the energizing electrical current (i.e. the energizing time) needed for injecting the desired fuel quantity, and finally to energize the fuel injector accordingly.

However, it may happen that the fuel quantity actually injected during a fuel injection is different from the desired one. This undesirable condition may be caused by several factors, including drift of the injection characteristics and production spread of the fuel injectors. In particular, the correlation between the electrical command and the injector needle displacement can be affected by not idealities hard to be controlled during the injectors manufacturing, such as magnetic permeability drift of the actuator, tolerance of the needle spring coefficient, aging effect, and temperature dependency.

SUMMARY

In view of the above, an object of the present disclosure is to provide a strategy for determining the quantity of fuel which is actually injected by a fuel injector during a fuel injection.

This and other objects are achieved by the embodiments of the invention having the features recited in the independent claims. The dependent claims delineate additional aspects of the embodiments of the invention.

More particularly, an embodiment of the invention provides a method of operating an internal combustion engine, wherein the internal combustion engine comprises a fuel rail in fluid communication with a number of (i.e. one or more) fuel injectors and with a fuel pump configured to perform a discharge stroke after each fuel injection performed by the fuel injectors, and wherein the method comprises the steps of:

- operating a fuel injector to perform a fuel injection,
- deactivating the first discharge stroke of the fuel pump following a start of the fuel injection, thereby by preventing said discharge stroke from delivering fuel into the fuel rail,
- calculating a value of a pressure drop caused into the fuel rail by the fuel injection,
- calculating a value of a fuel quantity injected by said fuel injection on the basis of the calculated value of the pressure drop.

Thanks to the deactivation of the discharge stroke, the pressure level within the fuel rail during the fuel injection is only affected by the quantity of fuel which actually exits the fuel rail during that fuel injection. As a consequence, knowing the pressure drop caused into the fuel rail by the fuel injection, it is possible to calculate a reliable value of the fuel injected quantity.

The proposed strategy is reliable under every engine operating conditions and even when the engine is operating at high engine speed and high load (i.e. high injected fuel quantity). Indeed, under such conditions, it may happen that the discharge stroke of the fuel pump starts very close or even before the end of the fuel injection, so that it would be normally impossible, or at least extremely difficult, to distinguish the pressure effect caused by the fuel injection from the pressure effect caused by the fuel pump. With the present solution, which provides for deactivating the discharge stroke following the fuel injection, this side effect is positively solved.

According to an aspect of the method, the calculation of the pressure drop value may include the steps of:

- measuring a first value of a fuel rail pressure before the start of said fuel injection,
- measuring a second value the fuel rail pressure after the end of said fuel injection,
- calculating the pressure drop value as a difference between the first and the second measured value of the fuel rail pressure.

This aspect provides a very simple and reliable way to calculate the pressure drop caused by the fuel injection.

According to another aspect of the method, the measurement of the first and the second value of the fuel rail pressure may comprise the steps of,

- sampling a signal representative of the fuel rail pressure,
- filtering the signal to obtain a filtered signal,
- measuring a first value of the filtered signal before the start of said fuel injection,
- measuring a second value of the filtered signal after the end of said fuel injection,
- calculating the first value and the second value of the fuel rail pressure on the basis of the first and the second value of the filtered signal respectively.

With the filtering phase, it is possible to remove the noises that can affect the pressure signal, thereby increasing the accuracy of the measurement of the first value and the second value of the fuel rail pressure.

An aspect of the method particularly provides that the filtering of the signal may be performed with a SINC filter, for example a SINC filter tuned on a dominant frequency of a pressure oscillation in the fuel rail.

In this way the filtering of the pressure signal can be very effective and thus lead to reliable values of the fuel rail pressure.

According to another aspect of the method, the calculation of the pressure drop value may include the steps of:

- sampling a signal representative of the fuel rail pressure during the fuel injection,
- using the pressure signal as input of a first integral transform yielding as output a value of a first function having as variables a fuel rail pressure drop caused by the

fuel injection and a timing parameter indicative of an instant when the fuel injection started,

- using the pressure signal as input of a second integral transform yielding as output a value of a second function having as variables the fuel rail pressure drop caused by the fuel injection and the timing parameter indicative of the instant when the fuel injection started,
- using the value of the first function and the value of the second function to calculate the value of the fuel rail pressure drop.

This solution provides an alternative but still reliable and effective strategy for determining the fuel quantity that is actually injected during a fuel injection. This peculiar strategy has also the effect of allowing the calculation of the instant when the fuel injection actually started, i.e. the so-called start of Injection (SOI). Moreover, this strategy is basically unaffected by the noises on the pressure signal, so that the filtration of such signal is not strictly required and the computation effort for carrying out the strategy can be positively reduced.

According to another aspect of the proposed solution, the method may comprise the step of activating a number of (i.e. one or more) discharge strokes following the deactivated one by allowing each one of them to deliver fuel into the fuel rail.

This aspect has the effect of increasing the fuel rail pressure after that the discharge stroke of the fuel pump has been deactivated (and before that another discharge stroke is deactivated to repeat the calculation of the fuel injected quantity if needed), thereby preventing the fuel rail pressure from becoming too low.

In this regard, an aspect of the method may provide that the number of activated pump strokes is equal to the number of fuel injectors.

In this way, it is possible to calculate in sequence the quantity of fuel actually injected during fuel injections performed by different fuel injectors.

Moreover, this solution guarantees that the deactivation of the discharge stroke of the fuel pump has not the same periodicity of the engine cycle, thereby preventing resonance effects on the engine torque.

Another aspect of the method may provide that the activation of each discharge strokes includes the step of delivering into the fuel rail a volume of fuel having a value Q* according to the following equation:

$$Q^* = \frac{n}{n-1} \cdot Q$$

wherein n is the number of fuel injectors and Q is a value of a fuel volume that would have been delivered if all the discharge strokes had been activated.

This aspect guarantees that the fuel rail is supplied with the fuel quantity necessary to compensate for all the fuel injections performed during an engine cycle, notwithstanding one of the discharge strokes has been deactivated.

According to the present disclosure, the method can be carried out with the help of a computer program comprising a program-code for carrying out all the steps of the method described above, and in the form of a computer program product comprising the computer program. The method can be also embodied as an electromagnetic signal, said signal being modulated to carry a sequence of data bits which represent a computer program to carry out all steps of the method.

Another embodiment of the invention provides an internal combustion engine comprising a fuel rail in fluid communication with a number of (i.e. one or more) fuel injectors and with a fuel pump configured to perform a discharge stroke after each fuel injection performed by the fuel injectors, and an electronic control unit configured to:

- operate a fuel injector to perform a fuel injection,
- deactivate the first discharge stroke of the fuel pump following a start of the fuel injection, thereby by preventing said discharge stroke from delivering fuel into the fuel rail,
- calculate a value of a pressure drop caused into the fuel rail by the fuel injection,
- calculate a value of a fuel quantity injected by said fuel injection on the basis of the calculated value of the pressure drop.

This solution achieves essentially the same effects of the method described above, in particular that of providing a reliable value of the fuel injected quantity under every engine operating conditions and even when the engine is operating at high engine speed and high load (i.e. high injected fuel quantity).

According to an aspect of the engine, the electronic control unit may be configured to calculate of the pressure drop value with the steps of:

- measuring a first value of a fuel rail pressure before the start of said fuel injection,
- measuring a second value the fuel rail pressure after the end of said fuel injection,

- calculating the pressure drop value as a difference between the first and the second measured value of the fuel rail pressure.

This aspect provides a very simple and reliable way to calculate the pressure drop caused by the fuel injection.

According to another aspect of the engine, the electronic control unit may be configured to measure the first and the second value of the fuel rail pressure with the steps of,

- sampling a signal representative of the fuel rail pressure,
- filtering the signal to obtain a filtered signal,
- measuring a first value of the filtered signal before the start of said fuel injection,
- measuring a second value of the filtered signal after the end of said fuel injection,
- calculating the first value and the second value of the fuel rail pressure on the basis of the first and the second value of the filtered signal respectively.

With the filtering phase, it is possible to remove the noises that can affect the pressure signal, thereby increasing the accuracy of the measurement of the first value and the second value of the fuel rail pressure.

An aspect of the engine particularly provides that the electronic control unit may be configured to filter the signal with a SINC filter, for example a SINC filter tuned on a dominant frequency of a pressure oscillation in the fuel rail.

In this way the filtering of the pressure signal can be very effective and thus lead to reliable values of the fuel rail pressure.

According to another aspect of the engine, the electronic control unit may calculate the pressure drop value with the steps of:

- sampling a signal representative of the fuel rail pressure during the fuel injection,
- using the pressure signal as input of a first integral transform yielding as output a value of a first function having as variables a fuel rail pressure drop caused by the fuel injection and a timing parameter indicative of an instant when the fuel injection started,
- using the pressure signal as input of a second integral transform yielding as output a value of a second function having as variables the fuel rail pressure drop caused by the fuel injection and the timing parameter indicative of the instant when the fuel injection started,
- using the value of the first function and the value of the second function to calcu-

late the value of the fuel rail pressure drop.

This solution provides an alternative but still reliable and effective strategy for determining the fuel quantity that is actually injected during a fuel injection. This peculiar strategy has also the effect of allowing the calculation of the instant when the fuel injection actually started, i.e. the so-called start of Injection (SOI). Moreover, this strategy is basically unaffected by the noises on the pressure signal, so that the filtration of such signal is not strictly required and the computation effort for carrying out the strategy can be positively reduced.

According to another aspect of the engine, the electronic control unit may be configured for activating a number of (i.e. one or more) discharge strokes following the deactivated one by allowing each one of them to deliver fuel into the fuel rail.

This aspect has the effect of increasing the fuel rail pressure after that the discharge stroke of the fuel pump has been deactivated (and before that another discharge stroke is deactivated to repeat the calculation of the fuel injected quantity if needed), thereby preventing the fuel rail pressure from becoming too low.

In this regard, an aspect of the engine may provide that the number of activated pump strokes is equal to the number of fuel injectors.

In this way, it is possible to calculate in sequence the quantity of fuel actually injected during fuel injections performed by different fuel injectors.

Moreover, this solution guarantees that the deactivation of the discharge stroke of the fuel pump has not the same periodicity of the engine cycle, thereby preventing resonance effects on the engine torque.

Another aspect of the engine may provide that the electronic control unit is configured to activate each discharge strokes with the step of delivering into the fuel rail a volume of fuel having a value Q* according to the following equation:

$$Q^* = \frac{n}{n-1} \cdot Q$$

wherein n is the number of fuel injectors and Q is a value of a fuel volume that would have been delivered if all the discharge strokes had been activated.

This aspect guarantees that the fuel rail is supplied with the fuel quantity necessary to compensate for all the fuel injections performed during an engine cycle, notwithstanding one of the discharge strokes has been deactivated.

Still another embodiment of the invention provides an automotive system comprising an internal combustion engine having a fuel rail in fluid communication with a number of (i.e. one or more) fuel injectors and with a fuel pump configured to perform a discharge stroke after each fuel injection performed by the fuel injectors, and:

- means for operating a fuel injector to perform a fuel injection,
- means for deactivating the first discharge stroke of the fuel pump following a start of the fuel injection, thereby by preventing said discharge stroke from delivering fuel into the fuel rail,
- means for calculating a value of a pressure drop caused into the fuel rail by the fuel injection,
- means for calculating a value of a fuel quantity injected by said fuel injection on the basis of the calculated value of the pressure drop.

This solution achieves essentially the same effects of the method described above, in particular that of providing a reliable prediction of the real exhaust gas temperature without delay.

According to an aspect of the apparatus, the means for calculating the pressure drop value may include:

- means for measuring a first value of a fuel rail pressure before the start of said fuel injection,
- means for measuring a second value the fuel rail pressure after the end of said fuel injection,
- means for calculating the pressure drop value as a difference between the first and the second measured value of the fuel rail pressure.

This aspect provides a very simple and reliable way to calculate the pressure drop caused by the fuel injection.

According to another aspect of the apparatus, the means for measuring the first and the second value of the fuel rail pressure may comprise:

- means for sampling a signal representative of the fuel rail pressure,
- means for filtering the signal to obtain a filtered signal,
- means for measuring a first value of the filtered signal before the start of said fuel injection,
- means for measuring a second value of the filtered signal after the end of said fuel injection,

- means for calculating the first value and the second value of the fuel rail pressure on the basis of the first and the second value of the filtered signal respectively.

With the filtering phase, it is possible to remove the noises that can affect the pressure signal, thereby increasing the accuracy of the measurement of the first value and the second value of the fuel rail pressure.

An aspect of the apparatus particularly provides that the means for filtering the signal may include a SINC filter, for example a SINC filter tuned on a dominant frequency of a pressure oscillation in the fuel rail.

In this way the filtering of the pressure signal can be very effective and thus lead to reliable values of the fuel rail pressure.

According to another aspect of the method, the means for calculating the pressure drop value may include:

- means for sampling a signal representative of the fuel rail pressure during the fuel injection,
- means for using the pressure signal as input of a first integral transform yielding as output a value of a first function having as variables a fuel rail pressure drop caused by the fuel injection and a timing parameter indicative of an instant when the fuel injection started,
- means for using the pressure signal as input of a second integral transform yielding as output a value of a second function having as variables the fuel rail pressure drop caused by the fuel injection and the timing parameter indicative of the instant when the fuel injection started,
- means for using the value of the first function and the value of the second function to calculate the value of the fuel rail pressure drop.

This solution provides an alternative but still reliable and effective strategy for determining the fuel quantity that is actually injected during a fuel injection. This peculiar strategy has also the effect of allowing the calculation of the instant when the fuel injection actually started, i.e. the so-called start of Injection (SOI). Moreover, this strategy is basically unaffected by the noises on the pressure signal, so that the filtration of such signal is not strictly required and the computation effort for carrying out the strategy can be positively reduced.

According to another aspect of the proposed solution, the apparatus may comprise means for activating a number of (i.e. one or more) discharge strokes following the deactivated one by allowing each one of them to deliver fuel into the fuel rail.

This aspect has the effect of increasing the fuel rail pressure after that the discharge stroke of the fuel pump has been deactivated (and before that another discharge stroke is deactivated to repeat the calculation of the fuel injected quantity if needed), thereby preventing the fuel rail pressure from becoming too low.

In this regard, an aspect of the apparatus may provide that the number of activated pump strokes is equal to the number of fuel injectors.

In this way, it is possible to calculate in sequence the quantity of fuel actually injected during fuel injections performed by different fuel injectors.

Moreover, this solution guarantees that the deactivation of the discharge stroke of the fuel pump has not the same periodicity of the engine cycle, thereby preventing resonance effects on the engine torque.

Another aspect of the apparatus may provide that the means for activating each discharge strokes includes means for delivering into the fuel rail a volume of fuel having a value Q* according to the following equation:

$$Q^* = \frac{n}{n-1} \cdot Q$$

wherein n is the number of fuel injectors and Q is a value of a fuel volume that would have been delivered if all the discharge strokes had been activated.

This aspect guarantees that the fuel rail is supplied with the fuel quantity necessary to compensate for all the fuel injections performed during an engine cycle, notwithstanding one of the discharge strokes has been deactivated.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will now be described, by way of example, with reference to the accompanying drawings.

Figure 1 schematically shows an automotive system.

Figure 2 shows an internal combustion engine of the automotive system according to the section A-A of figure 1.

Figure 3 is a schematic representation of a cross-section of the high pressure fuel pump of the automotive system of figure 1.

Figure 4 is a diagram that represents the variation of the fuel rail pressure (curve A) and the fuel injected quantity (curve B) over the crankshaft angular position during the operation of the internal combustion engine of figure 2.

Figure 5 shows in greater details a portion of the curve A shown in figure 4.

Figure 6 is a flowchart that represents a method of determining the actual fuel quantity that is injected by a fuel injector.

Figure 7 is a flowchart that represents the variation of the fuel rail pressure (curve A) and the fuel injected quantity (curve B) over the crankshaft angular position during the repetition of the method of figure 6.

DETAILED DESCRIPTION

Some embodiments may include an automotive system 100 (e.g. a motor vehicle), as shown in figures 1 and 2, that includes an internal combustion engine (ICE) 110 having an engine block 120 defining at least one cylinder 125 having a piston 140 coupled to rotate a crankshaft 145. A cylinder head 130 cooperates with the piston 140 to define a combustion chamber 150. A fuel and air mixture (not shown) is disposed in the combustion chamber 150 and ignited, resulting in hot expanding exhaust gasses causing reciprocal movement of the piston 140. The fuel is provided by at least one fuel injector 160 per combustion chamber 150 and the air through at least one intake port 210. The fuel is provided at high pressure to the fuel injector 160 from a fuel rail 170 in fluid communication with a high pressure fuel pump 180 that increase the pressure of the fuel received from a fuel source 190.

Each of the cylinders 125 has at least two valves 215, actuated by a camshaft 135 rotating in time with the crankshaft 145. The valves 215 selectively allow air into the combustion chamber 150 from the port 210 and alternately allow exhaust gases to exit through a port 220. In some examples, a cam phaser 155 may selectively vary the timing between the camshaft 135 and the crankshaft 145.

The air may be distributed to the air intake port(s) 210 through an intake manifold 200. An air intake duct 205 may provide air from the ambient environment to the intake manifold 200. In other embodiments, a throttle body 330 may be provided to regulate the flow of air into the manifold 200. In still other embodiments, a forced air system such as a turbocharger 230, having a compressor 240 rotationally coupled to a turbine 250, may be provided. Rotation of the compressor 240 increases the pressure and temperature of the air in the duct 205 and manifold 200. An intercooler 260 disposed in the duct 205 may reduce the temperature of the air. The turbine 250 rotates by receiving exhaust gases from an exhaust manifold 225 that directs exhaust gases from the exhaust ports 220 and through a series of vanes prior to expansion through the turbine 250. The exhaust gases exit the turbine 250 and are directed into an exhaust system 270. This example shows a variable geometry turbine (VGT) with a VGT actuator 290 arranged to move the vanes to alter the flow of the exhaust gases through the turbine 250. In other embodiments, the turbocharger 230 may be fixed geometry and/or include a waste gate.

The exhaust system 270 may include an exhaust pipe 275 having one or more exhaust aftertreatment devices 280. The aftertreatment devices may be any device configured to change the composition of the exhaust gases. Some examples of aftertreatment devices 280 include, but are not limited to, catalytic converters (two and three way), oxidation catalysts, lean NO_x traps, hydrocarbon adsorbers, selective catalytic reduction (SCR) systems, and particulate filters. Other embodiments may include an exhaust gas recirculation (EGR) system 300 coupled between the exhaust manifold 225 and the intake manifold 200. The EGR system 300 may include an EGR cooler 310 to reduce the temperature of the exhaust gases in the EGR system 300. An EGR valve 320 regulates a flow of exhaust gases in the EGR system 300.

The automotive system 100 may further include an electronic control unit (ECU) 450 in communication with one or more sensors and/or devices associated with the ICE 110. The ECU 450 may receive input signals from various sensors configured to generate the signals in proportion to various physical parameters associated with the ICE 110. The sensors include, but are not limited to, a mass airflow and temperature sensor 340, a manifold pressure and temperature sensor 350, a combustion pressure sensor 360, coolant and oil temperature and level sensors 380, a fuel rail pressure sensor 400, a cam position sensor 410, a crank position sensor 420, exhaust pressure and temperature sensors 430, an EGR temperature sensor 440, and an accelerator pedal position sensor 445. Furthermore, the ECU 450 may generate output signals to various control devices that are arranged to control the operation of the ICE 110, including, but not limited to, the fuel injectors 160, the throttle body 330, the EGR Valve 320, the VGT actuator 290 and the cam phaser 155. Note, dashed lines are used to indicate communication between the ECU 450 and the various sensors and devices, but some are omitted for clarity.

Turning now to the ECU 450, this apparatus may include a digital central processing unit (CPU) in communication with a memory system and an interface bus. The CPU is configured to execute instructions stored as a program in the memory system 460, and send and receive signals to/from the interface bus. The memory system 460 may include various storage types including optical storage, magnetic storage, solid state storage, and other non-volatile memory. The interface bus may be configured to send, receive, and modulate analog and/or digital signals to/from the various sensors and control devices. The program may embody the methods disclosed herein, allowing the CPU to carryout out the steps of such methods and control the ICE 110.

The program stored in the memory system 460 is transmitted from outside via a cable or in a wireless fashion. Outside the automotive system 100 it is normally visible as a computer program product, which is also called computer readable medium or machine readable medium in the art, and which should be understood to be a computer program code residing on a carrier, said carrier being transitory or non-transitory in nature with the consequence that the computer program product can be regarded to be transitory or non-transitory in nature.

An example of a transitory computer program product is a signal, e.g. an electromagnetic signal such as an optical signal, which is a transitory carrier for the computer program code. Carrying such computer program code can be achieved by modulating the signal by a conventional modulation technique such as QPSK for digital data, such that binary data representing said computer program code is impressed on the transitory electromagnetic signal. Such signals are e.g. made use of when transmitting computer program code in a wireless fashion via a WiFi connection to a laptop.

In case of a non-transitory computer program product the computer program code is embodied in a tangible storage medium. The storage medium is then the non-transitory carrier mentioned above, such that the computer program code is permanently or non-permanently stored in a retrievable way in or on this storage medium. The storage medium can be of conventional type known in computer technology such as a flash memory, an Asic, a CD or the like.

Instead of an ECU 450, the automotive system 100 may have a different type of processor to provide the electronic logic, e.g. an embedded controller, an onboard computer, or any processing module that might be deployed in the vehicle.

One of the tasks of the ECU 450 is that of operating the fuel injectors 160. In this regard, each fuel injector 160 may be embodied as an electromechanical valve having a nozzle in fluid communication with the corresponding combustion chamber 150, a needle, which is normally biased by a spring in a closed position of the nozzle, and an electro-magnetic actuator (e.g. solenoid), which moves the needle towards an open position of the nozzle in response of an energizing electrical current. This energizing electrical current may be provided by the ECU 450. In this way, any time the electro-magnetic actuator is provided with the energizing electrical current (also referred as to electrical command), a direct connection is opened between the fuel rail 170 and the cylinder 125, which let a certain quantity of fuel to be injected into the combustion chamber 150, thereby performing a so-called fuel injection. The fuel quantity injected into the combustion chamber 150 by a fuel injection generally depends on the pressure of the fuel in the fuel rail 170 and on the needle displacement, which is correlated with the duration of the electrical command (i.e. the so-called energizing time ET).

During the operation of the internal combustion engine 110, the ECU 450 usually command each one of the injectors 160 to perform at least one fuel injection in the corresponding combustion chamber 150, when the piston 140 is in proximity of the Top Dead Center (TDC) position, between the compression stroke and the expansion stroke. In case of a four-stroke engine, each fuel injector 160 is thus configured to perform at least one fuel injection every two complete rotations (720°) of the crankshaft 145. In addition, the fuel injections performed by each fuel injectors 160 are generally scheduled at different times with respect to the fuel injections performed by any other fuel injectors 160. As a consequence, considering the explanatory case of a four-cylinder engine, at least one fuel injection is performed every 180° rotation of the crankshaft 145 by a different fuel injector 160 in a different combustion chamber 150.

The fuel quantity that exits the fuel rail 170 due to the fuel injections is compensated by the fuel pump 180. As shown in figure 3, the fuel pump 180 may be embodied as a volumetric pump having a cylinder 181 and a reciprocating piston 182 which is accommodated inside the cylinder 181. A cylinder head 183 cooperates with the cylinder 181 and the piston 182 to define an operating chamber 184. The operating chamber 184 is provided with a fuel inlet 185, which may be located in the cylinder head 183, and a fuel outlet 186, which may be located on the cylinder 181. The fuel inlet 185 is in fluid communication with the fuel source 190 and the fuel outlet 186 is fluid communication with the fuel rail 170. The fuel outlet 186 may be provided with an outlet valve (not shown), for example a check valve, that opens the communication with the fuel rail 170 when the pressure inside the operating chamber 184 exceeds a predetermined value.

The piston 182 moves within the cylinder 181 between a Top Dead Center (TDC) position, which corresponds to a minimum volume of the operating chamber 184, and a Bottom Dead Center (BDC) position, which corresponds to a maximum volume of the operating chamber 184. The piston 182 may be driven by the engine crankshaft 145 through a timing system, in the present example through a cam 187 rotating in time with the crankshaft 145. Due to the reciprocating movement of the piston 182, this component cyclically performs a suction stroke that fills the operating chamber 184 with the fuel coming from the fuel source 190, followed by a discharge stroke that delivers the fuel at high pressure inside the fuel rail 170. In particular, the cinematic connection between the cam 187 (or any other actuating means of the piston 182) and the crankshaft 145 is configured so that the piston 182 performs a discharge stroke after each fuel injection performed by any one of the fuel injectors 160 (e.g. any time that one of the engine pistons 140 is performing the expansion stroke). In the explanatory case of a four-stroke and four-cylinder engine, the cinematic connection is thus configured so that the piston 182 performs a discharge stroke every 180° rotation of the crankshaft 145.

A digital inlet valve 500 may cooperate with the fuel pump 180 to determine the amount of fuel which is actually admitted into the operating chamber 184 during the suction stroke of the piston 182. The digital inlet valve 500 may comprise a shutter 505 associated to the fuel inlet 185 of the high pressure pump 180. The shutter 505 may be provided with a shaft 510 which is accommodated in a valve housing 525 associated to the cylinder head 183. The valve housing 525 may be provided with a conduit 565 configured to fluidly connect the fuel inlet 185 with the fuel source 190. The shutter 505 can axially translate between a closed position, where it closes the fuel inlet 185, thereby preventing the fuel from flowing into the operating chamber 184, and an open position, wherein it is spaced apart from and opens the inlet conduit 185, thereby letting the fuel flow into the operating chamber 184.

The axial translation of the shutter 505, from the closed to the open position, may be operated by means of a linear electromagnetic actuator 530, also known as linear solenoid, in contrast with the action of a compression spring 535 that acts on the shaft 510 to bias the shutter 505 towards the open position. The linear electromagnetic actuator 530 is accommodated inside the valve housing 525 and comprises a coil winding that can translate the shaft 510 in contrast to the action of the compression spring 535, thereby moving the shutter 505 in the closed position.

The digital inlet valve 500 (in particular to the electromagnetic actuator 530) may be operated by the ECU 450. In particular, the operation of the digital inlet valve 500 generally provides that, during any suction stroke of the piston 182, the electromagnetic actuator 530 is not energized, so that the elastic force of compression spring 535 bias the shutter 505 in the open position. In this way, the depression generated by the piston 182 in the operating chamber 184 draws fuel from the fuel source 190 into the operating chamber 184 via the fuel inlet 185. During the following discharge stroke of the piston 182, the electromagnetic actuator 530 is energized to move the shutter 505 in the closed position. In this way, the pressure inside the operating chamber 184 increases and, when the outlet valve (not shown) opens, the fuel is discharged into the fuel rail 170. It should be observed that the shutter 505 of the digital inlet valve 500 may be closed at any time during the discharge stroke of the piston 182. If the shutter 505 is closed early (i.e. proximate to the beginning of the discharge stroke), almost all the fuel contained in the operating chamber 184 is delivered to the fuel rail 140. If conversely the shutter 505 is closed late (i.e. proximate to the end of the discharge stroke), most of the fuel contained in the operating chamber 184 is routed back to the fuel source 190 via the fuel inlet 185 and only a small quantity of fuel is discharged into the fuel rail 170. As a consequence, by regulating the instant when the shutter 505 opens, the ECU 450 is able to regulate the volume of fuel which is actually supplied into the fuel rail 170.

In view of the operation of the fuel injectors 160 and the fuel pump 180, the pressure of the fuel within the fuel rail 170 cyclically oscillates as indicated by the curve A in figure 4. In particular, any fuel injection performed by a fuel injector 160 in the corresponding combustion chamber 150 (curve B) causes the fuel rail pressure to drop from a high level to a low level. When the fuel injection ends, the fuel rail pressure becomes stable at the low level, until the fuel pump 180 performs a discharge stroke. As explained, the discharge stroke of the fuel pump 180 causes a predetermined quantity of fuel to be supplied into the fuel rail 170, so that the fuel rail pressure raises from the low level back to the high level. When the discharge stroke of the fuel pump 180 ends, the fuel rail pressure becomes stable at the high level, until another fuel injection is performed by another fuel injector 160 in another combustion chamber 150. Afterwards, the fuel rail pressure continues to oscillate in the same way.

In order to determine the quantity of fuel which is actually injected by one of the fuel injectors 160 during one fuel injection, the ECU 450 may be configured, as illustrated in figure 6, to calculate (block S100) a value of the pressure drop ΔP_{inj} caused into the fuel rail 170 by said fuel injection and then to calculate (block S105) a value q_{inj} of the fuel quantity actually injected during said fuel injection, on the basis of the calculated value of the pressure drop ΔP_{inj}.

More particularly, the fuel rail pressure drop ΔP_{inj} can be used to calculate a dynamic fuel quantity q_{inlet} that actually flows through the fuel injector 160 according to the following equation:

$$q_{inlet} = C_{hyd} \cdot \Delta P_{inj}$$

wherein C_{hyd} is the value of the hydraulic capacitance of the fuel rail 170.

The dynamic fuel quantity q_{inlet} may be the sum of two contributions, namely the fuel injected quantity q_{inj} and the dynamic leakage q_{dyn} of the fuel injector 160. The fuel injected quantity q_{inj} is the quantity of fuel that actually enters the combustion chamber 150, whereas dynamic leakage q_{dyn} is a quantity of fuel that, when the injector needle is moved in the open position, flows through a backflow outlet of the fuel injector 160 and returns into the fuel source 190. As a consequence, the dynamic fuel quantity q_{inlet} that globally flows through the fuel injector 160 during a fuel injection (in addition to the static leakage that is always present) may be considered as the sum of the fuel injected quantity q_{inj} and the dynamic leakage q_{dyn}:

$$q_{inlet} = q_{inj} + q_{dyn}$$

However, q_{inlet}, q_{inj} and q_{dyn} are parameters that depend only on the fuel pressure at the inlet of the fuel injector 160 and on the energizing time (which determines the needle lift). Therefore, knowing q_{inlet}, the fuel pressure and the energizing time used to perform the fuel injection, it is possible to determine the value q_{inj} of the fuel injected quantity as a function of q_{inlet}:

$$q_{inj} = f(\, q_{inlet})$$

Once determined, the value q_{inj} of the fuel injected quantity may be used to control the operation of the internal combustion engine 110 in many ways. For example, it can be involved in a closed-loop control strategy of the fuel injected quantity, which may provide for determining the value q_{inj} of the fuel injected quantity according to the method above, calculating a difference e between the calculated value q_{inj} and a predetermined target value q_{inj}^* of the fuel injected quantity, and then to use said difference to correct an energizing time to be applied to the fuel injector 160, in order to minimize the error. In particular, the calculated difference may be used as input of a controller, for example a proportional-integrative (PI) controller, that yields as output a correction value to be added to the energizing time, in order to obtain a corrected energizing time that is finally used to operate the fuel injector 160.

Turning now to the determination of the pressure drop ΔP_{inj} (see figure 5), this parameter may be calculated by the ECU 450 through the measurement of two values of the fuel rail pressure, namely a first value A1 and a second value A2. The first value A1 is measured before the start of the fuel injection, in particular between the end of the last discharge stroke of the fuel pump 180 and the beginning of the fuel injection, when the fuel rail pressure is stable at the high level. The second value A2 is measured after the end of the fuel injection, in particular between the end of the fuel injection and the beginning of the next discharge stroke of the fuel pump 180, when the fuel rail pressure is stable at the low level. The pressure drop ΔP_{inj} is finally calculated by the ECU 450 as the difference between the first and the second value A1 and A2.

In this regard, the two values A1 and A2 of the fuel rail pressure may be measured by means of the fuel rail pressure sensor 400. In particular, the fuel rail pressure sensor 400 is configured to generate a “rough” electric signal indicative of the pressure within the fuel rail 170. The ECU 450 may be configured to sample the “rough” electric signal generated by the fuel rail pressure sensor 400. By way of example, the “rough” signal may be sampled in an angular domain (i.e. referred to the crankshaft angular position), in order to make it independent from the engine speed. The “rough” signal may then be filtered by the ECU 450, in order to remove pressure oscillations and other noises. By way of example, the “rough” signal generated by the fuel rail pressure sensor 400 may be filtered with a SINC filter, for example a SINC filter tuned on a dominant frequency of the pressure oscillation in the fuel rail. In greater details, the SINC filter may have the following transfer function exposed in a discrete form (according to the mathematical theory of Z transformation applied to the sampled signal):

$$SINC^N(Z) = \left[\frac{1}{OSR} \cdot \left(\frac{1 - Z^{-OSR}}{1 - Z^{-1}}\right)\right]^N$$

wherein Z is the so-called z-operator, N is the order of the filter and OSR is the so-called oversampling ratio, that is the ratio between the filter data input stream frequency and the filter data output stream frequency.

At this stage, the ECU 450 may be configured to measure two values of this filtered signal, namely a first value sampled between the end of the last discharge stroke of the high pressure pump 180 and the beginning of the fuel injection, and a second value sampled between the end of the fuel injection and the beginning of the next discharge stroke of the high pressure pump 180.

On the basis of the first value of the filtered signal, the ECU 450 may finally calculate the first value A1 of the fuel rail pressure, and analogously, on the basis of the second value of the filtered signal, the ECU 450 may finally calculate the second value A2 of the fuel rail pressure. In particular, the first and the second value A1 and A2 of the fuel rail pressure may be calculated by means of a model of the fuel rail pressure sensor 400, according to conventional approaches.

In other embodiments, the pressure drop ΔP_{inj} caused by the fuel injection may be calculated with a different strategy. As can be seen from figure 5, it is possible to determine an angular interval that contains the pressure drop ΔP_{inj} caused by the fuel injection. To this angular interval can be assigned an extension ranging from 0 to 2π, even if this angular interval does not actually correspond to a full rotation of the crankshaft 145 but to a selected portion of it.

Using the angular interval [0, 2π] as interval of integration, the alternative strategy may prescribe that the ECU 450 calculates the following integral transforms:

$$L_\alpha = \int_0^{2\pi} P(\theta) \cdot \cos(\theta)\, d(\theta)$$

$$L_\beta = \int_0^{2\pi} P(\theta) \cdot \sin(\theta)\, d(\theta)$$

wherein L_α is the value yielded by the first integral transform, L_β is the value yielded by the second integral transform, P is the fuel rail pressure as measured by the “rough” signal generated by the fuel rail pressure sensor 400, Θ is the angular position of the crankshaft 145, 0 is the predetermined starting value of the integration interval [0, 2π] in the crankshaft angular domain, 2π is the predetermined final value of the integration interval [0, 2π] in the crankshaft angular domain.

The pressure P of the fuel rail may be considered as the sum of two contributions:

$$P = P_{eq} + \delta P_{noise}$$

wherein P_{eq} represents an equivalent pressure (e.g. a mean pressure) of the fuel rail 170 and δP_{noise} represents the pressure fluctuations due to the pressure waves and electronic noise of the sensor.

As a consequence, the preceding integral transforms may be rewritten as follows:

$$L_\alpha = \int_0^{2\pi} P(\theta) \cdot \cos(\theta)\, d(\theta) = \int_0^{2\pi} [P_{eq} + \delta P_{noise}] \cdot \cos(\theta)\, d(\theta)$$

$$L_\beta = \int_0^{2\pi} P(\theta) \cdot \sin(\theta)\, d(\theta) = \int_0^{2\pi} [P_{eq} + \delta P_{noise}] \cdot \sin(\theta)\, d(\theta)$$

However, the frequency spectrum of the pressure fluctuations δP_{noise} is much higher than the frequency spectrum of the equivalent pressure P_{eq}, so that the contribution of the pressure fluctuations to the integral transform is negligible:

$$\int_0^{2\pi} \delta P_{noise} \cdot \cos(\theta)\, d(\theta) \cong \int_0^{2\pi} \delta P_{noise} \cdot \sin(\theta)\, d(\theta) \cong 0$$

As a consequence, the integral transforms may be rewritten as follows:

$$L_\alpha = \int_0^{2\pi} P(\theta) \cdot \cos(\theta)\, d(\theta) \cong \int_0^{2\pi} P_{eq} \cdot \cos(\theta)\, d(\theta) = T_\alpha(\Delta P_{inj}, \gamma_{inj}) = \Delta P_{inj} \cdot sin\gamma_{inj}$$

$$L_\beta = \int_0^{2\pi} P(\theta) \cdot \sin(\theta)\, d(\theta) \cong \int_0^{2\pi} P_{eq} \cdot \sin(\theta)\, d(\theta) = T_\beta(\Delta P_{inj}, \gamma_{inj}) = \Delta P_{inj} \cdot (1 - cos\gamma_{inj})$$

wherein ΔP_{inj} is the fuel rail pressure drop caused by the fuel injection, γ_{inj} is the angular distance of the fuel injection from the staring value 0 of the integration interval [0, 2π], T_α and T_β are two functions having as variables the fuel rail pressure drop ΔP_{inj} and the angular distance γ_{inj}.

After having calculated the values L_α and L_β, the ECU 450 may thus calculate the fuel rail pressure drop ΔP_{inj} and the angular distance γ_{inj} with the following equations:

$$\Delta P_{inj} = -\frac{L_\alpha^2 + L_\beta^2}{2L_\beta}$$

$$\gamma_{inj} = arcsin\left(-\frac{2L_\alpha L_\beta}{L_\alpha^2 + L_\beta^2}\right)$$

The angular distance γ_{inj} provides a measurement of the Start of Injection (SOI), whereas the fuel rail pressure drop ΔP_{inj} can be used to calculate the fuel quantity actually injected by the fuel injection.

In should be noted that, according to this alternative approach, there is no need of filtering the “rough” signal generated by the fuel rail pressure sensor 400, because the impact of the noises on the calculation is negligible.

Regardless from the strategy used to calculate the pressure drop ΔP_{inj}, it happens sometimes that, under certain operating conditions (especially when the engine 110 is operating at high speed and/or high load), the fuel injection actually ends after the beginning of the following discharge stroke of the fuel pump 180, with the consequence that the fuel rail 170 receives additional fuel from the fuel pump 180 while the fuel injector 160 is still open.

Hence, the fuel rail pressure starts to raise towards the high level before having reached the low level (see curve A of fig. 7) and it becomes impossible (or at least very difficult) to determine the real pressure drop ΔP_{inj} caused by the fuel injection.

As indicated in figure 6, in order to solve this drawback, the ECU 450 may be configured to deactivate (block S110) the discharge stroke of the high pressure pump 180 that immediately follows the fuel injection for which the pressure drop ΔP_{inj} has to be determined.

Summarizing, the ECU 450 may be configured to operate the fuel injector 160 to perform the fuel injection, to deactivate the first discharge stroke of the high pressure pump 180 that follows the start of said injection, to calculate the value ΔP_{inj} of the pressure drop caused by the last fuel injection started before the deactivated discharge stroke, and finally to calculate the value of the fuel quantity injected by said fuel injection on the basis of said calculated value ΔP_{inj} of the pressure drop (e.g. according to one of the strategies described above).

By deactivation of the discharge stroke of fuel pump 180 is generally meant the step of preventing the discharge stroke from delivering fuel into the fuel rail 170. The ECU 450 may operate such deactivation by means of the digital inlet valve 500. In particular, the ECU 450 may operate the electromagnetic actuator 530 of the digital inlet valve so that the shutter 505 remains open during the entire discharge stroke of the piston 182. In this way, all the fuel contained in the operating chamber 184 is delivered back into the fuel source 190 and no fuel is actually supplied into the fuel rail 170.

Thanks to the deactivation of the discharge stroke of the fuel pump 180, the fuel rail pressure is not increased after the fuel injection (see the portion of the curve A of figure 7 within the ellipses) and it is thus possible to reliably use the strategies described above, in order to determine the pressure drop ΔP_{inj} caused by said fuel injection and the fuel quantity q_{inj} actually injected.

This method of calculating the fuel quantity q_{inj} actually injected during a fuel injection, which involves the deactivation of the following discharge stroke of the high pressure pump 180, may be repeated more than once either for the same fuel injector 160 or for other fuel injectors 160 of the internal combustion engine 110.

In the first case, the ECU 450 may be configured to calculate an average value of all the calculated values q_{inj} of the fuel quantity injected by the same fuel injector 160, in order to achieve a more robust indication of the behavior of such fuel injector 160. In the second case, the ECU 450 gets an indication of the behavior of all the fuel injectors 160 of the internal combustion engine 110.

In any case, the deactivation of the discharge stroke of the high pressure fuel pump has the effect that the pressure level inside the fuel rail 140 tends to fall below the low level (see the portion of the curve A of figure 7 within the ellipses), because the fuel injected during the fuel injection is not compensated by the following discharge stroke of the fuel pump 180.

For this reason, some embodiments provides the ECU 450 for “activating” a number of (i.e. one or more) discharge strokes of high pressure fuel pump 180 after the deactivated one, thereby allowing each one of said “activated” discharge strokes to actually deliver fuel into the fuel rail 170.

In other words, these embodiments prescribe that the deactivation of the discharge stroke of the high pressure fuel pump 180 (and thus the calculation of the pressure drop ΔP_{inj} and of the fuel quantity q_{inj}) may be repeated by the ECU 450 only after that, in the interim period, a certain number of discharge strokes of the high pressure fuel pump 180 have been executed to actually deliver fuel inside the fuel rail 170.

In this regard, the number of such activated compression strokes may equal to the number of fuel injectors 160 of the internal combustion engine 110. In the explanatory example of a four-injector engine, any deactivation of the discharge stroke of the high pressure fuel pump 180 may be followed by four “activated” discharge stroke of the high pressure fuel pump 180, before being repeated.

This solution implies that any deactivation of the discharge stroke of the high pressure fuel pump 180 is correlated to a fuel injection performed by a different fuel injector 160, so that the ECU 450 is able to calculate in sequence the quantity q_{inj} of fuel actually injected by all the fuel injectors 160 of the internal combustion engine 110. Moreover, this solution guarantees that the deactivations of the discharge stroke of the fuel pump 180 have not the same periodicity of the engine cycle, thereby preventing resonance effects on the engine torque.

In this context, the ECU 450 may be configured to operate each “activated” discharge strokes (in the interim period between two consecutive deactivation) in order to deliver into the fuel rail 170 a volume of fuel having a value Q according to the following equation:

$$Q^* = \frac{n}{n-1} \cdot Q$$

wherein n is the number of fuel injectors 160 and Q is a value of a fuel volume that would have been delivered during the normal operation of the fuel pump 180, namely if all the discharge strokes of the fuel pump 180 had been activated.

In this way, each one of the “activated” discharge strokes of the fuel pump 180 delivers more fuel than normally prescribed, thereby guaranteeing that the overall quantity of fuel supplied into the fuel rail 170 during an engine cycle is sufficient for compensating the fuel injections performed by all the fuel injectors 160, notwithstanding one of the discharge strokes of the fuel pump 180 has been deactivated.

While at least one exemplary embodiment has been presented in the foregoing summary and detailed description, it should be appreciated that a vast number of variations exist. It should also be appreciated that the exemplary embodiment or exemplary embodiments are only examples, and are not intended to limit the scope, applicability, or configuration in any way. Rather, the foregoing summary and detailed description will provide those skilled in the art with a convenient road map for implementing at least one exemplary embodiment, it being understood that various changes may be made in the function and arrangement of elements described in an exemplary embodiment without departing from the scope as set forth in the appended claims and their legal equivalents.

REFERENCES

100	automotive system
110	internal combustion engine
120	engine block
125	cylinder
130	cylinder head
135	camshaft
140	piston
145	crankshaft
150	combustion chamber
155	cam phaser
160	fuel injector
170	fuel rail
180	fuel pump
181	cylinder
182	piston
183	cylinder head
184	operating chamber
185	inlet
186	outlet
187	cam
190	fuel source
200	intake manifold
205	air intake duct
210	intake port
215	valves
220	exhaust port
225	exhaust manifold
230	turbocharger
240	compressor
250	turbine

260	intercooler
270	exhaust system
275	exhaust pipe
280	aftertreatment devices
290	VGT actuator
300	exhaust gas recirculation system
310	EGR cooler
320	EGR valve
330	throttle body
340	mass airflow and temperature sensor
350	manifold pressure and temperature sensor
360	combustion pressure sensor
380	coolant and oil temperature and level sensors
400	fuel rail pressure sensor
410	cam position sensor
420	crank position sensor
430	exhaust pressure and temperature sensors
440	EGR temperature sensor
445	accelerator pedal position sensor
450	ECU
460	memory system
500	digital inlet valve
505	shutter
510	shaft
525	valve housing
530	electromagnetic actuator
535	compression spring
565	conduit
S100	block
S105	block
S110	block
A	curve

B	curve
A1	first point
A2	second point

5

CLAIMS

1. A method of operating an internal combustion engine (110), wherein the internal combustion engine (110) comprises a fuel rail (170) in fluid communication with a number of fuel injectors (160) and with a fuel pump (180) configured to perform a discharge stroke after each fuel injection performed by the fuel injectors (160), and wherein the method comprises the steps of:

- operating a fuel injector (160) to perform a fuel injection,
- deactivating a first discharge stroke of the fuel pump (180) following a start of the fuel injection by preventing said discharge stroke from delivering fuel into the fuel rail (170),
- calculating a value of a pressure drop caused into the fuel rail (170) by the fuel injection,
- calculating a value of a fuel quantity injected by said fuel injection on the basis of the calculated value of the pressure drop.

2. A method according to claim 1, wherein the calculation of the pressure drop value includes the steps of:

- measuring a first value of a fuel rail pressure before the start of said fuel injection,
- measuring a second value of the fuel rail pressure after the end of said fuel injection,
- calculating the pressure drop value as a difference between the first and the second measured values of the fuel rail pressure.

3. A method according to claim 2, wherein the measurement of the first and the second value of the fuel rail pressure comprises the steps of,

- sampling a signal representative of the fuel rail pressure,
- filtering the signal to obtain a filtered signal,
- measuring a first value of the filtered signal before the start of said fuel injection,
- measuring a second value of the filtered signal after the end of said fuel injection,
- calculating the first value and the second value of the fuel rail pressure on the basis of the first and the second value of the filtered signal respectively.

4. A method according to claim 3, wherein the filtering of the signal is performed with a SINC filter.

5. A method according to claim 4, wherein the SINC filter is tuned on a dominant frequency of a pressure oscillation in the fuel rail (170).

6. A method according to claim 1, wherein the calculation of the pressure drop value includes the steps of:

- sampling a signal representative of the fuel rail pressure during the fuel injection,
- using the pressure signal as input of a first integral transform yielding as output a value of a first function having as variables a fuel rail pressure drop caused by the fuel injection and a timing parameter indicative of an instant when the fuel injection started,
- using the pressure signal as input of a second integral transform yielding as output a value of a second function having as variables the fuel rail pressure drop caused by the fuel injection and the timing parameter indicative of the instant when the fuel injection started,
- using the value of the first function and the value of the second function to calculate the value of the fuel rail pressure drop.

7. A method according to any of the preceding claims, comprising the step of activating a number of discharge strokes following the deactivated one by allowing each one of them to deliver fuel into the fuel rail (170).

8. A method according to claim 7, wherein the number of activated pump strokes is equal to the number of fuel injectors (160).

9. A method according to claim 8, wherein the activation of each discharge strokes includes the step of delivering into the fuel rail (170) a volume of fuel having a value Q* according to the following equation:

$$Q^* = \frac{n}{n-1} \cdot Q$$

wherein n is the number of fuel injectors (160) and Q is a value of a fuel volume that would have been delivered if all the discharge strokes had been activated.

10. A method according to any preceding claim, wherein the internal combustion engine comprises a cylinder (181), a reciprocating piston (182) which is accommodated inside the cylinder (181), an operating chamber (184) and an inlet valve (505), wherein reciprocating movement of the piston (182) performs a suction stroke that fills the operating chamber (184) with fuel coming from a fuel source (190), followed by a discharge stroke that delivers fuel to the fuel rail (170), wherein the inlet valve (505) controls admission of fuel into the operating chamber (184), and wherein deactivating the first discharge stroke is performed by keeping the inlet valve open during the discharge stroke of the piston.

11. A computer program comprising a program-code for carrying out the method according to any of the preceding claims.

12. A computer program product comprising the computer program according to claim 11.

13. An electromagnetic signal modulated to carry a sequence of data bits which represent a computer program according to claim 11.

14. An internal combustion engine (110) comprising a fuel rail (170) in fluid communication with a number of fuel injectors (160) and with a fuel pump (180) configured to perform a discharge stroke after each fuel injection performed by the fuel injectors (160), and an electronic control (450) unit configured to:

- deactivate a discharge stroke of the fuel pump (180) by preventing said discharge stroke from delivering fuel into the fuel rail (170),
- calculate a value of a pressure drop caused into the fuel rail (170) by a last fuel injection started before the deactivated discharge stroke,
- calculate a value of a fuel quantity injected by said fuel injection on the basis of the calculated value of the pressure drop.

Intellectual
Property
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Application No: GB1612146.9 **Examiner:** Mr Alastair Kelly
Claims searched: 1-14 **Date of search:** 27 January 2017

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
X	1-14	US2012/118053 A1 [SERRA] See abstract and figures and note paragprah [0012]
X	1-14	US2012/123703 A1 [SERRA] See abstract and figures and note paragprah [0011]
X	1-14	US2010/147058 A1 [CINPINSKI] See abstract and figures and note paragraph [0014]
X	1-14	US2010/199951 A1 [CINPINSKI] See abstract and figures and note paragraph [0032] - [0033]

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^X :

Worldwide search of patent documents classified in the following areas of the IPC

F02D

The following online and other databases have been used in the preparation of this search report

EPODOC, WPI

International Classification:

Subclass	Subgroup	Valid From
F02D	0041/40	01/01/2006
F02D	0041/02	01/01/2006
F02D	0041/30	01/01/2006
F02D	0041/38	01/01/2006