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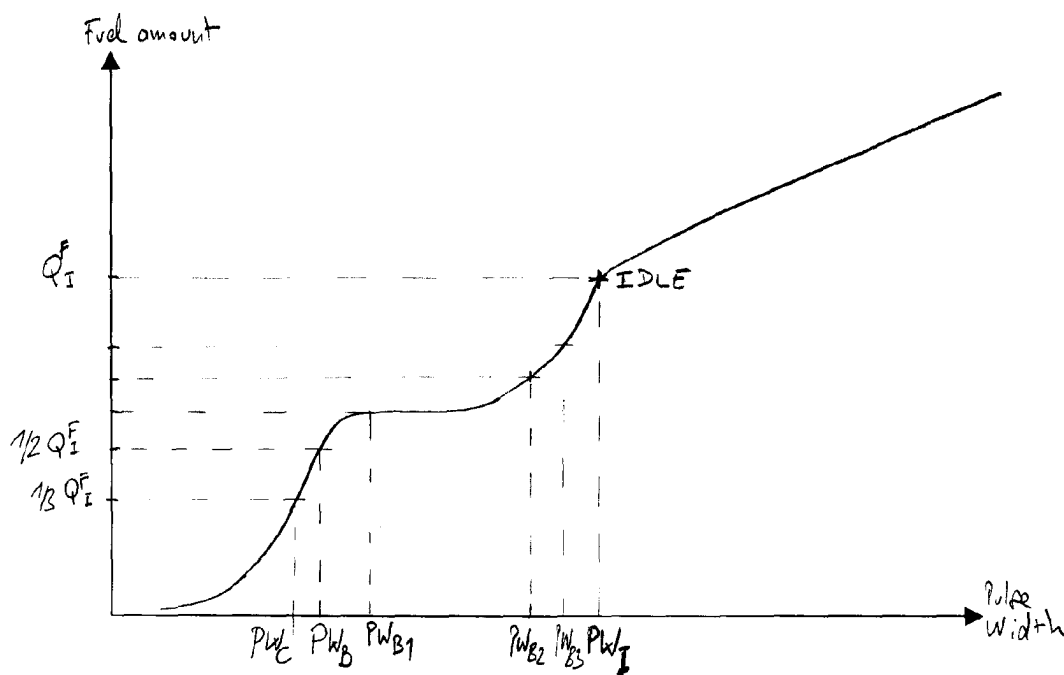
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(54) **Method for controlling an internal combustion engine**

(57) A method of operating an internal combustion engine with a direct injection system controlled by an engine control unit (ECU) is described. The ECU comprises a flow curve table storing data indicative of fuel quantities vs. injector pulse widths. The method comprises an injector learning event during which actual fuel values related to a fuel injector are determined, said injector

learning event being enabled during an idle or deceleration condition of said engine and comprising the steps of:  
operating the engine into a homogeneous combustion mode; and  
concurrently degrading the combustion and/or splitting the injection pulses while monitoring the combustion performance to determine learned fuel data.



**FIG.2**

## Description

### FIELD OF THE INVENTION

**[0001]** The present invention generally relates to the control of internal combustion engines and more specifically to the control of fuel injection in IC engines for automotive vehicles.

### BACKGROUND OF THE INVENTION

**[0002]** The contemporary design of spark ignited internal combustion engines must cope with the increasingly stringent regulations on pollutant emission. Accordingly, automotive engineers strive for designing engines with low fuel consumption and low emission of pollutants, which implies including electronic devices capable of monitoring the combustion performance and emissions in the exhaust gases.

**[0003]** The issue of fuel economy has been addressed i.a. by varying the injection schemes. Currently, direct injection engines and in particular gasoline stratified charge engines are considered to be very efficient in terms of fuel economy.

**[0004]** One requirement to reduce emissions from a spark ignited internal combustion engine is an accurate control of the combustion air/fuel ratio. This is usually done by metering a precisely controlled amount of fuel based on a measured or inferred air charge mass inducted into the engine; many control schemes are known in the art to control the air/fuel ratio. It is e.g. customary to install an oxygen sensor in the engine exhaust line pipe and to use the sensor output as a feedback signal for closed loop fuel control.

**[0005]** US 6,382,198 describes a direct injection engine with an enhanced fuel control using a single oxygen sensor as combustion performance indicator. The Engine Control Module (ECM) is capable of determining the actual air/fuel ratio corresponding to each individual cylinder from the combined flow of exhaust gases; this function is known as ICFC (Individual Cylinder Fuel Control). Conventionally, the ECM develops a fuel command pulse width for each of the injectors that corresponds to the driver's requested torque. For this purpose, a lookup table is used that stores fuel amounts in function of e.g. engine speed, manifold air pressure, and other parameters. The ECM also uses a table storing closed-loop fuelling corrections, which is known as block learning memory (BLM). As it is known in the art, the BLM table entries are determined based on the oxygen sensor response, which when adequately filtered, provides a measure of the deviation of the average engine air/fuel ratio from stoichiometry (average here means for a bank, i.e. a set of cylinders connected to the same exhaust manifold). The values from the base table and BLM are used to determine a global fuel amount. Additionally, the ICFC module determines, also based on the oxygen sensor response, a cylinder specific fuel error that is used to develop indi-

vidual cylinder correction factors applied to the global fuel amount. This final fuel amount is then converted into a pulse width command, which typically involves a lookup table storing fuel amounts vs. pulse widths.

**[0006]** This control strategy is already quite sophisticated and does indeed allow an enhanced control of fuel injection. A problem that has however arisen in the last years in injection control is that advanced, complex fuel injectors, in particular those used for stratified charge engines, do not have easily predictable flow performances, which results into significant performance deviation or variability between injectors of a same design.

### OBJECT OF THE INVENTION

**[0007]** It would be desirable to be able to assess fuelling errors due to the variability of flow performance of fuel injectors, in particular for modern actuator designs, so as to be able to take corrective actions.

**[0008]** This object is achieved by a method as claimed in claim 1.

### SUMMARY OF THE INVENTION

**[0009]** While the monitoring of fuel performance and the determination of fuel errors, even at the individual cylinder level, has existed for years, the behaviour of modern fuel injectors has increased the need to be able to more accurately determine injector related fuel errors in the context of modern injectors so as to be able to deliver more accurate fuel amounts, in particular for GDI spray guided combustion.

**[0010]** From this observation, the present inventors have developed a non-intrusive method of assessing fuel errors that is particularly adapted for spray guided engines and allows learning actual fuelling data that may serve for subsequent corrective actions. Indeed, the injection parameters are particularly critical in such engines that require precisely timed and measured injection pulses; otherwise the fuel does not burn, or only partially. And this is particularly critical with recent fuel injectors developed for spray guided/stratified charge engines that suffer from a sensible variability of flow performance. The present method may however be used with any GDI engine operable in homogeneous combustion.

**[0011]** According to the present invention, there is proposed an injector learning event for an engine with a direct injection system, during which actual fuelling data related to a fuel injector are determined, wherein this injector learning event may only be enabled during an idle or deceleration condition of the engine. The injector learning event comprises the steps of:

- operating the engine into a homogeneous combustion mode; and
- concurrently degrading the combustion and/or performing split injection while monitoring the combus-

tion performance to determine the learned fuel data. The learned fuel data may typically be actually injected fuel amounts and/or fuel errors.

**[0012]** Preferably, the degradation of combustion and split injection are performed at constant torque; operating at a constant operating point improves the reliability of the method and makes it transparent to the driver.

**[0013]** These learned fuel data may then be stored, and used to take corrective actions regarding the pulse width command. Preferably, the so-determined learned fuel data are used to update the flow curve table(s) that is/are stored in the Engine Control Unit and that store data indicative of fuel quantities (e.g. in mg) vs. injector pulse widths (i.e. injector opening time, e.g. in ms).

**[0014]** The need for such method is, as already explained, due to the fact that modern fuel injectors typically have varying flow performances (due to manufacturing tolerances and/or ageing) and that it is desirable to be able to assess and quantify the corresponding fuel errors. Moreover, modern combustion engines are already provided with numerous functionalities to check the quality of the combustion and the operating status of engine components.

**[0015]** In a conventional engine, when fuelling errors are detected e.g. by the oxygen sensor, and that the ECU has checked that the engine operating conditions are adequate for a proper sensor reading, that the conventional fuel error correction schemes have been implemented (e.g. BLM, ICFC), that no hardware failure is detected (e.g. inoperative actuator, misfires, throttling problems, malfunction of the Exhaust Gas Recirculation valve) and that the inducted air mass is correct (as e.g. assumed when the MAF matches the air mass estimated by the ECU), then it can reasonably be concluded that persistent problems of combustion performance are related to the fuel injector operation, i.e. fuel is injected in excess or insufficient quantity by the injector. And the injection of an excessive or insufficient fuel mass is attributed to an error in the flow curve table. In other words, the pulse width command did not inject the expected fuel mass, and the monitoring of the combustion performance permits determining the actually injected fuel amount.

**[0016]** Preferably, the determined learned fuel data, which hence typically correspond to learned fuel errors or amounts, are first stored and will subsequently be filtered to ensure that a general trend is observed in the learned values and/or that they are statistically relevant, before they are actually used for corrective actions on the pulse width commands, in particular for correcting the flow curve tables.

**[0017]** Monitoring of the combustion performance is made to determine actual fuelling values in order to have knowledge of actually injected values that can be compared to the desired, set fuel amounts. As mentioned, in the present method the learned fuelling data may be the actually injected fuel amount or a deviation from the set value, referred to as fuel error. Any appropriate way of

monitoring combustion allowing determining such values may be used; typically the combustion monitoring may be based on an oxygen sensor.

**[0018]** Other variants of the present method are recited in the appended dependent claims.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0019]** The present invention will now be described, by way of example, with reference to the accompanying drawings, in which:

FIG. 1: is a schematic diagram of an internal combustion engine with an exhaust line and engine control unit;

FIG. 2: is graph of a fuel injector flow curve on which fuel amounts determined according to the present learning method are represented;

FIG. 3: is a timing chart showing three injection patterns used in the present injector learning method (additional fuel injection in retarded mode is illustrated by the dark grey rectangles).

## DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

**[0020]** Referring to Fig.1, reference sign 10 generally designates an automotive four-cylinder internal combustion engine. The engine receives intake air through an intake passage 12 that is variably restricted by a moveable throttle valve 14. Downstream of the throttle valve 14, intake air flows through an airflow meter 15 and enters an intake manifold 16 for distribution to the individual engine cylinders 18 in bank 20, via a plurality of intake runners. A fuel injector 22 is associated with each cylinder 18 and arranged for direct fuel injection so as to deliver a predetermined, metered quantity of fuel directly into the individual cylinders 18. The combustion products from each cylinder 18 are exhausted into the exhaust line 24 via a manifold continuing into an exhaust pipe 2 that comprises a catalytic converter 28 for emission control purposes. Reference sign 31 indicates an oxygen sensor providing an oxygen sensor signal to the ECU, the oxygen sensor signal being used for combustion performance monitoring, namely through the control of air/fuel ratio.

**[0021]** A fuel control module 30, part of a microprocessor-based engine control unit, designated ECU, electrically activates the fuel injectors 22. Specifically, the ECU determines a fuel command pulse width, or injector on-time, for each engine cylinder and provides the pulse width commands to the fuel control module 30, which then activates the injectors accordingly. For this purpose, the fuel control module of the ECU comprises a flow curve table 34 storing fuel amounts vs. pulse widths.

**[0022]** In overall, the fuel amounts are determined in response to a number of inputs including: driver torque demand, manifold absolute pressure signal (MAP), intake air flow rate (MAF), engine speed (RPM) signal, and oxygen sensor signal.

**[0023]** In practice, the ECU determines an operational fuel amount required to reach the required and/or desired torque, typically depending on driver torque request, engine speed, manifold air pressure etc. This operational fuel amount, for each cylinder, is converted into a corresponding injector pulse width using the flow curve table 34. And the injectors 22 are operated by the fuel control module 30 to activate them for an on-time corresponding to the supplied injector pulse width command.

**[0024]** As it is known in the art, for an enhanced control of the injected fuel quantities, the ECU may use various functionalities to control the performance of the combustion. The ECU may e.g. include a block learning memory BLM, which is a table that stores closed-loop fuelling corrections. As it is known in the art, BLM table entries are determined based on the oxygen sensor input, which when adequately filtered provides a measure of the deviation of the average (whole bank) engine air/fuel ratio from stoichiometry. The operational fuel amount can then be computed as the sum of a base fuel amount (determined from a base fuel table in function of torque demand, RPM, MAP and other signals) and the learned corrections from the BLM.

**[0025]** A further possible ECU functionality for determining fuel errors is the ICFC scheme that is responsive to  $O_2$ , MAP and RPM input signals and develops correction factors per cylinder so that the operational fuel amount may correspond to the sum of the base fuel scheduled plus the BLM correction, to which the ICFC correction factor is applied.

**[0026]** However, it is known that modern fuel injectors, and especially those manufactured for DIG and stratified charge engines, suffer from a relatively high variability of flow performance, in particular for low pulse end. Hence, the combustion performance is significantly affected by the difficultly predictable flow performance of modern fuel injectors, in particular those developed for DIG engines (in the area of application at small fuel mass delivery).

**[0027]** To address this problem, it shall be appreciated that an injector learning scheme is implemented in the ECU, which can be enabled during an idle condition or a deceleration condition of the engine. The learning scheme implies operating the engine into a homogeneous combustion mode (i.e. fuel injection takes place during the intake stroke) and concurrently degrading the combustion efficiency and/or splitting the injection pulses. While doing this, combustion performance (individual Imep via ICIE) & the exhaust individual airfuel (ICFC) are monitored to determine learned fuel data. These learned fuel data are representative of the actually injected fuel amount and may thus be expressed as fuel errors per cylinder, i.e. a deviation of a desired fuel amount from an actual fuel amount, or directly as the actually injected fuel

amount. And the learned fuel data can be used to take corrective actions on the fuel injection, in particular to correct injector pulse width commands.

**[0028]** The idea underlying this learning scheme is to explore the actual flow performance (i.e. flow vs. pulse width) of the fuel injector at a time where it does not affect the car's driveability. This is done by varying the injection scheme and playing on the number of injection pulses within a cycle, the amount of injected fuel, and thus the spark timing. This is only possible in a homogeneous combustion mode, which is barely sensible to such actions.

**[0029]** In this connection, one may note that an intrusive modification of the injected fuel amounts and spark timing when operating in stratified combustion mode is not possible, since the injection schemes are too precise and critical.

**[0030]** It will be understood that the degrading of the combustion and split mode are carried out as compared to the otherwise normal combustion control. When entering injector learning event, the injected fuel quantity will not be as optimal as the conventionally determined operational fuel amount (as explained above) since the combustion will normally first be degraded (addition of fuel and retarded ignition) and the degradation will even increase.

**[0031]** When the engine is idling, it has the advantage of being at a stable operating point. There is no change of operating point and modifications of the injection scheme are not directly felt by the driver. In addition, the engine operation is not influenced by the powertrain. Also, the degradation of combustion and split injection performed during the learning mode are advantageously controlled to maintain a constant torque.

**[0032]** The possibility of exploring an injector's flow performance using the present method will now be explained with reference to Figs. 2 and 3. Fig.2 shows a typical injector flow curve (the flow or fuel quantity delivered by the injector being plotted vs. pulse width). Such a flow curve is stored in the ECU for injector control, however it is discretized in the flow curve table 34, as it is known by those skilled in the art. This flow curve indicates the pulse width PW required to inject a fuel quantity  $Q^F$ . The fuel quantity to be injected when running at idle is  $Q^F_I$  and requires according to the flow curve an injector on-time  $PW_I$ . While this curve may initially more or less correspond to the actual flow performance of the injector, in practice deviations from this initial flow curve occur, at least due to ageing. The most difficult part of the flow curve to modelize for modern injectors is the lower part, typically below idle. And this is actually the region that is mainly exploited for stratified charge operation, a combustion mode requiring an accurate metering of small fuel quantities.

**[0033]** According to a preferred variant of the present method, the exploration of the injector-specific flow performance is carried out as follows. Starting from the IDLE point ( $PW_I$ ,  $Q^F_I$ ), the combustion is first degraded, i.e. a

greater fuel amount is injected and the spark timing is retarded; this is shown in Fig.3a). The combustion is preferably progressively degraded, i.e. the fuel amount is e.g. successively increased by 20, 40 and 60%. Since combustion performance is permanently monitored during the learning scheme, a cylinder specific fuel error information is available which allows determining the actually injected fuel amount that corresponds to the pulse width command.

**[0034]** As can be understood from Fig.2, degrading the combustion efficiency from the idle point thus allows exploring the flow curve at greater fuel amounts:  $PW_{A1}$  and  $PW_{A2}$ .

**[0035]** Exploration of the flow curve below the IDLE point is then carried out by splitting the injection pulses, first into two pulses of same width to deliver a fuel amount equal to that of idle. Accordingly, the two pulses of Fig. 3b) have a width  $PW_B$  (corresponding to  $\frac{1}{2} Q^F_I$ ). From the combustion monitoring strategy corresponding fuel errors are obtained, that are represented in Fig.2 in absolute values. Next, the two pulses are progressively degraded (indicated by the dark grey fuel additions in Fig. 3b), and the pulse width is thus increased and the spark timing retarded. This allows exploring a part of the curve between the  $PW_B$  and  $PW_1$  points and leads to points:  $PW_{B1}$ ,  $PW_{B2}$  and  $PW_{B3}$ .

**[0036]** In a further step the fuel injection is split into three pulses (Fig.3c) to deliver a fuel amount  $Q^F_I$  which requires three equal pulses of width  $PW_C$  (corresponding to  $\frac{1}{3} Q^F_I$ ). Degrading these injection pulses allows exploring the flow curve between  $PW_C$  and  $PW_B$ .

**[0037]** Again, this exploration of the injector flow performance as described above also implies monitoring the combustion parameters, which allows determining for each pulse width  $PW$  the fuel amount that was actually injected in the engine cylinder, respectively a fuel error for a given injector pulse width command.

**[0038]** Monitoring of the fuel combustion efficiency can be carried out by any appropriate method, and preferably based on oxygen sensing, e.g. using the oxygen sensor indicated 31 in Fig.1. Preferably, the fuel error of a given cylinder is determined based on three parameters available in the ECU:

- the manifold air flow, for the accuracy of air check;
- an oxygen sensor, preferably of the so-called "wide-range air fuel sensor" (WRAF) type for individual air fuel calculation, namely using the known ICFC method;
- a crank sensor to calculate individual IMEP and ICIE, to correlate the fuel error of the oxygen sensor.

**[0039]** These are conventional approaches and need not be herein further described.

**[0040]** The determined fuel errors are then stored in a table vs. the corresponding pulse width, and can be used

to correct fuel pulse commands.

**[0041]** A table of correcting pulse width factors can e.g. be built. The pulse width command sent to the injection control module 30 may correspond to the sum of the pulse width looked-up from the flow curve table 34 and a correcting PW factor read from such table.

**[0042]** However, it is preferred that the flow curve table 34 is updated based on the learned fuel data.

**[0043]** In a preferred embodiment, the ECU stores one flow curve table per cylinder/injector. This fuel curve table is preferably specific to the fuel injector. As it is known in the art, injector specific fuel parameters can be installed at the moment of mounting the fuel injectors in the engine. In this context, it is known to store a characteristic equation (e.g. a polynomial) fitting a master flow curve representative of a population of injectors, and to install injector specific coefficients or terms at the time of mounting of the fuel injector.

**[0044]** In the present embodiment, the ECU advantageously stores a set of characteristic equations for each injector, each characteristic equation within the set fitting a respective segment of such master flow curve representative of a general population of fuel injectors. The segmentation of the master flow curve means that the master flow curve is divided into distinct portions each described by a respective fitting equation over a distinct, non overlapping, pulse width range.

**[0045]** At the moment of fuel injector installation, injector specific parameters are loaded into the ECU and the flow curve tables are recalculated using the stored characteristic equations with the injector specific parameters. Typically, the equations may be polynomials and the injector specific parameters are coefficients for the polynomials.

**[0046]** When implementing the present learning event, it is thus possible to measure fuel errors and/or actually injected fuel amounts for known, precise pulse width values. Once a certain amount of points (pulse width; actually injected value) have been acquired and are considered significant, they can be used to recalculate the coefficients of the characteristic polynomials, and the flow curve tables can be recalculated using the updated coefficients.

**[0047]** The benefit of the segmented approach is that coefficients of a given polynomial (describing only a segment of the flow curve) can be recalculated with only a few measurement points, and the corresponding section of the flow curve table can be recalculated. Hence, it is not necessary to acquire measurement values over the whole operating pulse width values to be able to properly update the flow curve table.

## Claims

1. A method of operating an internal combustion engine with a direct injection system controlled by an engine control unit (ECU), said ECU comprising a flow curve

table storing data indicative of fuel quantities vs. injector pulse widths,

**characterized in that** said method comprises an injector learning event during which actual fuel values related to a fuel injector are determined, said injector learning event being enabled during an idle or deceleration condition of said engine and comprising the steps of:

operating the engine into a homogeneous combustion mode; and  
concurrently degrading the combustion and/or splitting the injection pulses while monitoring the combustion performance to determine learned fuel data.

2. The method according to claim 1, comprising developing injector pulse width corrective amounts based on said learned fuel data. 20
3. The method according to claim 1, comprising updating said flow curve table based on said learned fuel data determined during said injector learning event. 25
4. The method according to any one of the preceding claims, wherein the monitoring of the combustion performance is monitored by means of at least one oxygen sensor. 30
5. The method according to any one of the preceding claims, wherein combustion is first progressively degraded to acquire learned fuel data for greater fuel amounts; then the fuel amount corresponding to a conventionally determined fuel amount is split into equal parts to acquire corresponding learned points, and these split injections are progressively degraded. 35
6. The method according to any one of the preceding claims, wherein degrading the combustion and/or splitting the injection pulses is carried out at substantially constant torque. 40
7. The method according to any one of the preceding claims, wherein said ECU comprises one flow curve table and fuel injector per cylinder and said injector learning event is performed for each fuel injector to determine injector specific learned fuel data, and wherein the flow curve table of each fuel injector is updated based on the learned fuel data. 45
8. The method according to claim 7, wherein each flow curve table is built from a stored set of equations specific to a respective fuel injector, each equation from the set corresponding to a distinct range of pulse widths. 50
9. The method according to claim 8, wherein said equa-

tions comprise polynomials defined by stored operational coefficients, and wherein updating each flow curve table involves updating said operational coefficients for at least one equation based on said learned fuel data; and updating the entries of the flow curve table using said at least one equation based on the updated coefficients.

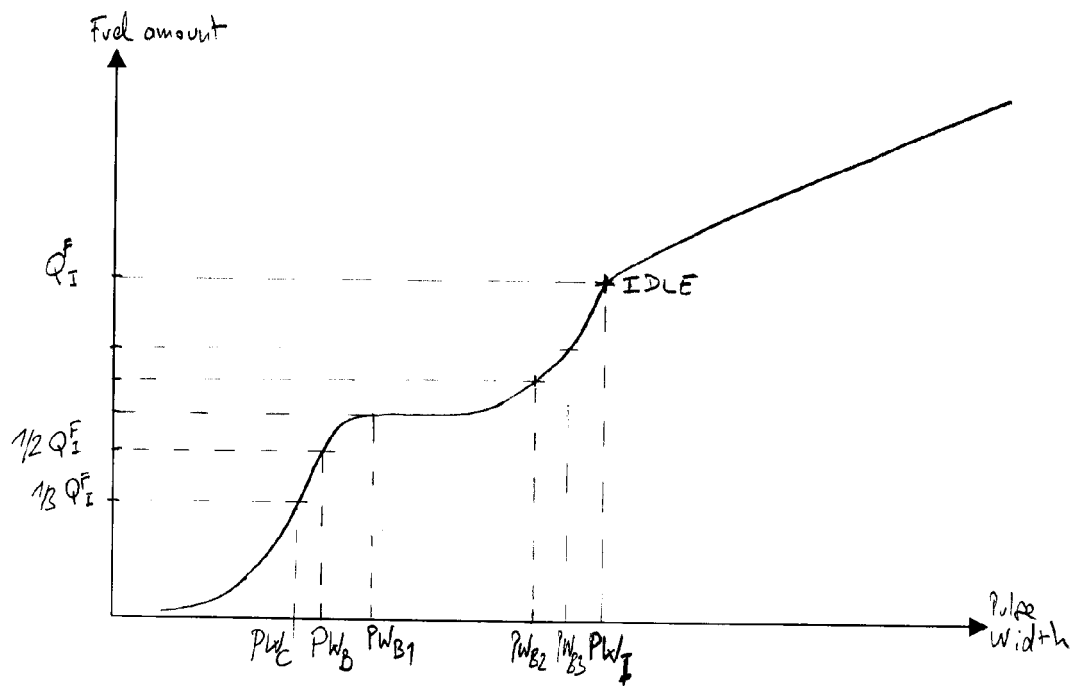
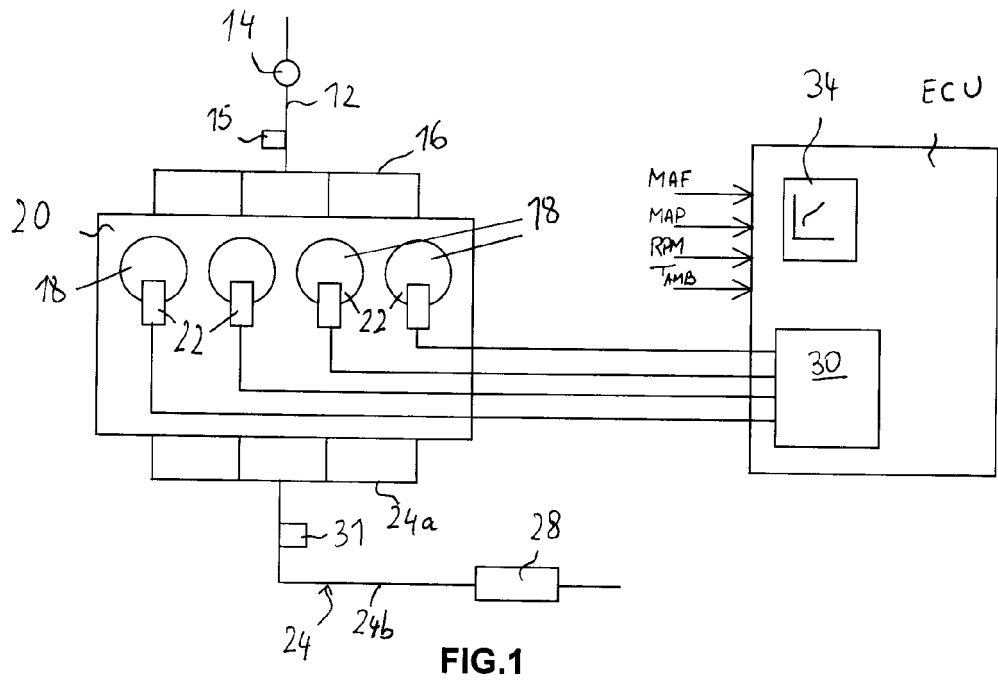


FIG. 2

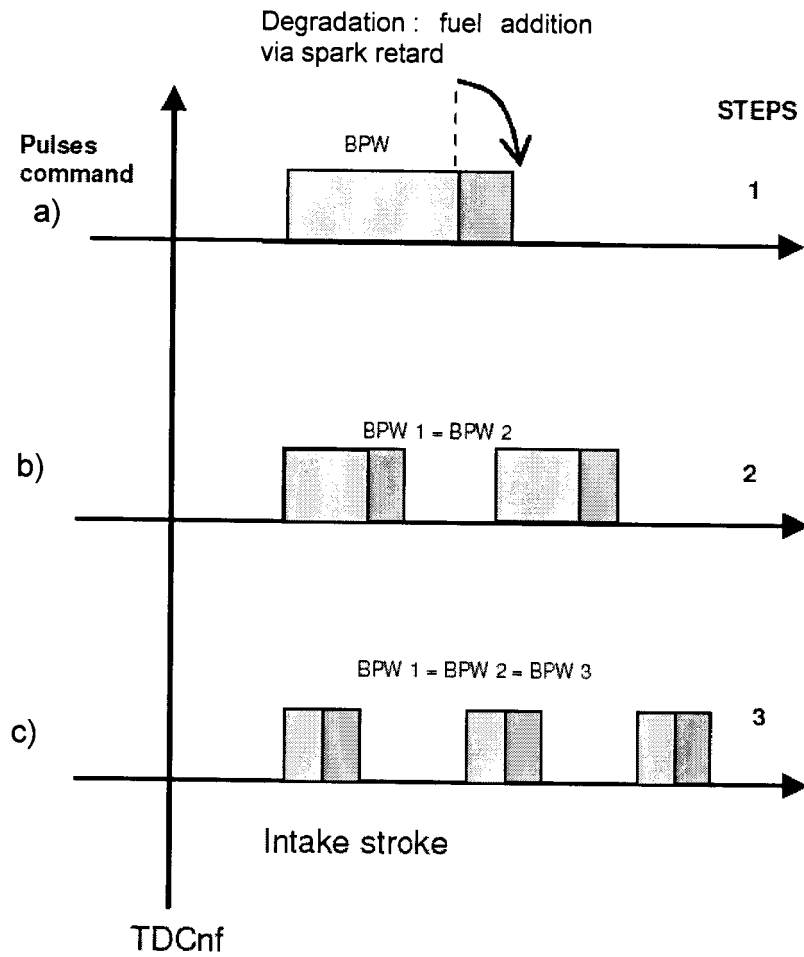


FIG.3



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Application Number  
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**ANNEX TO THE EUROPEAN SEARCH REPORT  
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EP 10 17 3579

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on  
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