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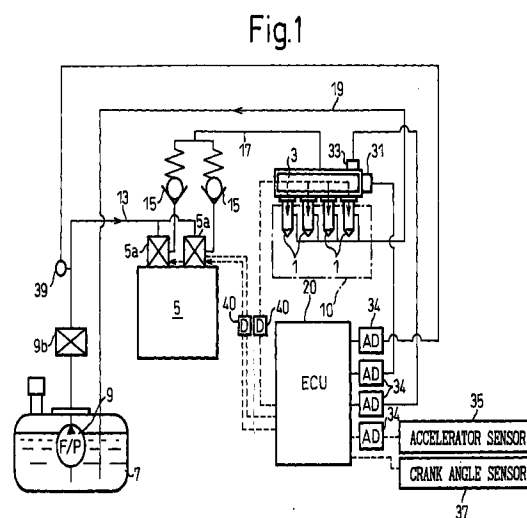
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(54) A fuel injection system for an internal combustion engine

(57) In the fuel injection system, fuel is supplied to a common rail from a high pressure fuel pump, and injected into the cylinders of an engine, from the common rail, via fuel injection valves. An electronic control unit (ECU) of the engine controls the pressure in the common rail at a value determined by the operating conditions of the engine. The ECU further detects the pressure and the temperature of the fuel in the common rail, and determines the bulk modulus of elasticity of the fuel based on the pressure and the temperature of the fuel. The ECU calculates an estimated value of the pressure change in the common rail during the fuel injection period using the determined bulk modulus. If the difference between the estimated value of the pressure change and the pressure change actually measured during the fuel injection period is large, the ECU determines that the fuel injection system has failed. Since the estimated value of the pressure change is calculated based on the bulk modulus of elasticity which is determined in accordance with the actual pressure and temperature of the fuel, the accurate estimated value is obtained even if the pressure and the temperature of the fuel in the common rail change over a very wide range.



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Description

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a fuel injection system for an internal combustion engine and, particularly, to a fuel injection system including means for detecting failures of the fuel injection system.

2. Description of the Related Art

A common rail type fuel injection system for an internal combustion engine is known in the art. A common rail type fuel injection system includes a common rail which stores high pressure fuel fed from a high pressure fuel pump. Fuel injection valves of the engine are connected to the common rail and inject the high pressure fuel in the reservoir (i.e., the common rail) into the respective cylinders of the engine. Namely, the common rail acts as a reservoir which stores high pressure fuel and distributes it to the respective fuel injection valves.

Further, a common rail type fuel injection system provided with means for detecting failures of the fuel injection system, such as a leak from the common rail or a sticking of the fuel injection valve, is also known.

This kind of the common rail type fuel injection system is, for example, disclosed in Japanese Unexamined Patent Publication (Kokai) No. 8-4577.

The fuel injection system in the '577 publication is provided with a pressure sensor for detecting the pressure of the fuel in the common rail and measures the difference of the pressures in the common rail before and after the fuel injection from the fuel injection valve, i.e., the pressure drop in the common rail during the fuel injection period. Further, the system in the '577 publication is provided with failure detecting means for estimating the pressures in the common rail before and after the fuel injection based on the operating condition of the engine in order to estimate the pressure drop during the fuel injection period, and for determining that the fuel injection system has failed when the difference between the measured pressure drop and the estimated pressure drop is larger than a predetermined limit.

In the system of the '577 publication, the estimated pressure drop ΔP caused by one fuel injection is calculated by $\Delta P = (K/V) \times Q$. Where, Q is a fuel injection amount per one fuel injection determined from the operating condition (the load condition) of the engine, K is a bulk modulus of elasticity of the fuel and V is a total volume of a high pressure part of the fuel injection system including the common rail volume, the volume of a high pressure supply line to the common rail and the volume of a fuel injection line from the common rail to the fuel injection valves. In the '577 publication, constant values are used for the bulk modulus K and the volume V. Namely, it is considered that the pressure drop during the fuel injection period is equal to the pressure drop caused by the fuel flow out from the common rail. Therefore, if the amount of fuel flowing out from the common rail during the fuel injection period is the same as the fuel injection amount Q, the pressure drop during the fuel injection period must be the same as ΔP . If the estimated ΔP is different from the measured ΔP , it is considered that the amount of the fuel flow out from the common rail during the fuel injection does not agree with the calculated (i.e., target) fuel injection amount Q. For example, if the measured pressure drop ΔP is larger than the estimated pressure drop ΔP by a certain amount, since this means that the amount of the fuel flow out from the common rail is larger than the target value of the fuel injection amount, it is considered the failure of the fuel injection system such as the sticking of the fuel injection valve at the opening position has occurred.

However, in the system of the '577 publication, it is difficult to correctly determine the failure if the pressure of the fuel in the common rail changes over a very wide range.

As stated above, the '577 publication assumes that the bulk modulus of elasticity K of the fuel is constant regardless of the pressure and temperature of the fuel. However, actually the bulk modulus of elasticity K of the fuel changes in accordance with the pressure and temperature of the fuel. Therefore, in the actual system, the pressure drop during the fuel injection period takes different values according to the pressure and temperature of the fuel in the common rail even if the fuel injection amount is the same. For example, since the bulk modulus of elasticity K of fuel becomes larger as the pressure increases, the measured pressure drop ΔP increases as the pressure in the common rail increases even if the fuel injection amount is the same. Therefore, if a constant value of the bulk modulus of elasticity K is used for estimating the pressure drop ΔP , it is difficult to determine the failure of the fuel injection system correctly if the pressure in the common rail changes over a wide range.

Further, in a common rail type fuel injection system of a certain type, the pressure of the fuel in the common rail varies in a very wide range in order to control both the fuel injection amount and the rate of injection in accordance with the operating condition of the engine. For example, in some common rail type fuel injection system, the pressure in the common rail is changed from 10 Mpa to 150 Mpa. In such a common rail type fuel injection system, since the change in the bulk modulus of elasticity is very large, the determination of the failure using the method in the '577 publication is not possible if a constant value is used for the bulk modulus of elasticity.

SUMMARY OF THE INVENTION

In view of the problems in the related art as set forth above, the object of the present invention is to provide means for correctly determining a failure of the fuel injection system even if the pressure of the fuel varies in a very wide range.

This object is achieved by a fuel injection system for an internal combustion engine, which includes, a reservoir for storing pressurized fuel, a fuel injection valve connected to the reservoir and injecting fuel in the reservoir into an internal combustion engine at a predetermined timing, a fuel pump for feeding pressurized fuel to the reservoir at a predetermined timing in order to maintain the pressure of the fuel in the reservoir at a predetermined value, pressure detecting means for detecting the pressure of the fuel in the reservoir, bulk modulus detecting means for detecting a bulk modulus of elasticity of the fuel in the reservoir, and failure determining means for determining whether the fuel injection system of the engine has failed based on the bulk modulus detected by the bulk modulus detecting means and the change in the pressure of the fuel in the reservoir during the operation of the engine.

According to the present invention, the bulk modulus detecting means detects the bulk modulus of elasticity of the fuel in the reservoir, and this detected bulk modulus is used for determining whether the fuel injection system has failed.

The bulk modulus detecting means in this invention may detect the bulk modulus of elasticity indirectly based on the pressure or the temperature (or the both) of the fuel in the reservoir. The failure detecting means in this invention may determine the failure of the fuel injection system, for example, by comparing the pressure change in the reservoir during the fuel injection period or the fuel feed period with the measured pressure change in the reservoir. Since the bulk modulus of elasticity used for the determination of the failure is suitably changed in accordance with the actual pressure and temperature of the fuel in the reservoir, the failure of the system can be correctly determined even if the pressure and temperature of the fuel in the reservoir change in a very wide range.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be better understood from the description as set forth hereinafter, with reference to the accompanying drawings in which:

Fig. 1 schematically illustrates the general configuration of an embodiment of the present invention when it is applied to an automobile engine;

Fig. 2 schematically illustrates the method for detecting the failure of the fuel injection system according to the present invention;

Fig. 3 is a chart showing a typical change in the bulk modulus of elasticity of fuel according to the changes in the pressure and temperature thereof; and

Figs. 4 through 10 are flowcharts explaining various embodiments of the failure detecting operation according to the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Hereinafter, embodiments of the present invention will be explained in detail with reference to the accompanying drawings.

Fig. 1 shows a general configuration of an embodiment of the fuel injection system of the present invention when it is applied to a diesel automobile engine.

In Fig. 1, reference numeral 10 designates an internal combustion engine (in this embodiment, a four-cylinder four-cycle diesel engine). Numeral 1 designates fuel injection valves which inject fuel into the respective cylinders of the engine 10 and 3 designates a common rail (a reservoir) to which the fuel injection valves 1 are connected. As explained later, the common rail 3 stores the pressurized fuel fed from a high pressure fuel pump 5 and distributes it to the respective fuel injection valves 1.

In Fig. 1, numeral 7 represents a fuel tank which stores fuel (in this embodiment, diesel fuel) for the engine, and 9 represents a low pressure feed pump which supply the fuel in the fuel tank 7 to the high pressure fuel pump 5. In this embodiment, a fuel filter 9b is disposed on the fuel supply line 13 from the low pressure feed pump 9 to the high pressure fuel pump 5. During the operation of the engine 10, the fuel in the tank 7 is pressurized to a constant pressure by the feed pump 9 and filtered by the fuel filter 9b to eliminate foreign matter and water in the fuel and it is supplied to the high pressure fuel pump 5 via the supply line 13. Fuel is further pressurized by the high pressure fuel pump 5 and fed to the common rail 3 through a check valve 15 and a high pressure line 17. From the common rail 3, fuel is injected into the respective cylinders through the respective fuel injection valves.

Numeral 19 in Fig. 1 shows a fuel return line for returning the fuel from the fuel injection valves 1 to the fuel tank 7. The return fuel from the fuel injection valve will be explained later in detail.

In this embodiment, an electronic control unit (ECU) 20 is provided for controlling the engine 10. The ECU 20 may

be constructed as a microcomputer of a known type including a read-only memory (ROM), a random-access memory (RAM), a microprocessor (CPU) and input/output ports all connected to each other by a bi-directional bus. Further, ECU 20 is provided with a backup RAM capable of maintaining the contents or its memory even if a main switch of the engine is turned off. As explained later, the ECU 20 performs a fuel pressure control which adjusts the fuel pressure in the common rail in accordance with the engine load and speed by controlling the operation of the intake control valve 5a of the high pressure fuel pump 5. Further, the ECU 20 performs a fuel injection control which controls the fuel injection amount by adjusting the opening period of the fuel injection valve 1.

As explained later, the ECU 20 in this embodiment functions as failure determining means for determining whether the fuel injection system, including the fuel pump 5, the common rail 3 and fuel injection valves 1 etc., has failed.

In order to perform these controls, voltage signals corresponding to the pressure and the temperature of the fuel in the common rail 3 are supplied to the input port of the ECU 20 from a fuel pressure sensor 31 and a fuel temperature sensor 33 each disposed on the common rail 3 via an AD converter 34. An accelerator signal which represents the amount of depression of an accelerator pedal, by the operator of the automobile, is also supplied to the input port of the ECU 20 via the AD converter 34 from an accelerator sensor 35 disposed near the accelerator pedal (not shown). Further, in this embodiment, a fuel supply pressure sensor 39 is disposed on the fuel supply line 13 between the fuel filter 9b and the high pressure fuel pump 5, and a voltage signal corresponding to the fuel supply pressure to the fuel pump 5 is supplied from the sensor 39 to the input port of the ECU 20 via the AD converter 34. Crank angle signals are supplied from a crank angle sensor 37 to the input port of the ECU 20. In this embodiment, the crank angle sensor 37 is actually composed of two sensors. One is a reference position sensor which is disposed near a camshaft of the engine and generates a reference pulse signal when the crankshaft reaches a reference rotating position (for example, when the first cylinder of the engine 10 reaches the top dead center of the compression stroke), and another is a rotation angle sensor which generates a rotating pulse signal at a predetermined angle of rotation of the crankshaft. These crank angle signals, i.e., the reference pulse signal and the rotating pulse signal are also supplied to the input port of the ECU 20.

The output port of the ECU 20 is connected to the fuel injection valves 1 and a solenoid actuator of the intake control valve 5a of the high pressure fuel pump 5 via respective drive circuits 40 and controls the operation of the fuel injection valve 1 and the fuel feed amount from the high pressure fuel pump 5 to the common rail 3, respectively.

The high pressure fuel pump 5 in this embodiment is a piston type pump having two cylinders. The pistons of the pump 5 are driven by cams formed on the driving shaft and reciprocate in the respective cylinders. Intake control valves 5a which are opened and closed by the respective solenoid actuator are disposed at the intake ports of the respective cylinders. The driving shaft of the pump 5 in this embodiment is driven by the crankshaft of the engine 10 and rotates synchronously with the crankshaft at the one-half speed thereof. Further, each of the cams formed on the driving shaft has two cam lift portions, whereby the respective cylinders of the pump 5 discharge fuel once per one revolution of the crankshaft. Thus, the pump 5, as a whole, discharges 4 times per two revolution of the crankshaft. Namely, since a four-cylinder four-cycle diesel engine is used in this embodiment, the pump 5 is capable of feeding fuel to the common rail 3 at the timing synchronous with the strokes of the cylinders of the engine. For example, the pump 5 in this embodiment feeds fuel to the common rail at the timing immediately after the fuel injection of the respective cylinders.

Further, the ECU 20 controls the amount of fuel fed to the common rail 3 by changing the timing where the intake control valve 5a closes during the discharge stroke of the pump cylinders. More specifically, the ECU 20 keeps the intake control valve 5a open by de-energizing the solenoid actuator during the inlet stroke and a part of the discharge stroke of the pump cylinder. When the intake control valve 5a is kept open, the fuel in the pump cylinder flows back to the fuel tank through the intake control valve during the discharge stroke, and the fuel in the pump cylinder is not fed to the common rail 3. When a predetermined time has lapsed from the beginning of the discharge stroke, the ECU 20 closes the intake control valve 5a by energizing the solenoid actuator. By doing so, the fuel trapped in the pump cylinder is pressurized by the piston and, when the pressure in the cylinder exceeds the pressure in the common rail 3, the pressurized fuel in the cylinder pushes open the check valve 15 and flows into the high pressure line 17. Namely, when the intake valve 5a is closed during the discharge stroke of the pump cylinder, fuel is fed to the common rail 3. Once the intake valve 5a is closed, the valve 5a is kept at the closed position during the discharge stroke by the fuel pressure regardless of the actuation of the solenoid actuator. Therefore, the amount of the fuel fed to the common rail 3 is determined by the timing at which the intake control valve closes. The ECU 20 in this embodiment controls the fuel feed amount to the common rail 3 by changing the timing for energizing the solenoid actuator of the intake control valve 5a.

In this embodiment, the ECU 20 determines a target value of the common rail pressure based on the engine load and speed. The relationships between the target value of the common rail pressure and the engine load and speed are determined in advance, and stored in the ROM of the ECU 20. Further, the ECU 20 controls the fuel feed amount of the high pressure fuel pump 5 so that the common rail pressure detected by the sensor 31 is kept at the target value. The ECU 20 further calculates the fuel injection amount from the engine load and speed using a predetermined relationship, and controls the opening period of the fuel injection valves to inject the calculated amount of fuel from the fuel injection valves.

As explained above, the ECU 20 in this embodiment adjusts the rate of injection of the fuel injection valves 1 in accordance with the operating condition of the engine by changing the common rail pressure, and adjusting the fuel injection amount in accordance with the operating condition of the engine by changing the common rail pressure and opening period of the fuel injection valve. Therefore, the common rail pressure in this embodiment changes in accordance with the operating condition in a very wide range (for example, from about 10 Mpa to about 150 Mpa).

Next, the method for detecting the failure of the fuel injection system used in this embodiment is explained.

In this embodiment, the failure of the fuel injection system is determined based on at least one of the changes in the common rail pressure during the fuel injection period and the fuel feed period.

Fig. 2 schematically illustrates the change in the fuel pressure in the common rail 3 during one cycle composed of the fuel injection and the fuel feed.

In Fig. 2, the period PD represents a period in which fuel injection is performed by one of the fuel injection valves, and the period PU represents a period in which the fuel feed is performed by the fuel pump 5 after each fuel injection. As shown in Fig. 2, the fuel injection from the fuel injection valves 1 and the fuel feed from the fuel pump 5 is performed at different timing so that the fuel injection period PD and the fuel feed period PU do not overlap each other. In Fig. 2, PC1₀ represents the pressure in the common rail 3 immediately before the fuel injection (PD) starts, PC2 represents the pressure in the common rail after the fuel injection is completed and before the fuel feed (PU) starts. PC1₁ represents the pressure in the common rail after the fuel feed is completed and before the next fuel injection starts. In this embodiment, the change in the common rail pressure before and after the fuel injection (i.e., the change in the pressure during the fuel injection period PD), or the change in the common rail pressure before and after the fuel feed (i.e., the change in the pressure during the fuel feed period PU), or both, are calculated based on the PC1₀, PC2 and PC1₁ measured by the fuel pressure sensor 31 by the following formulas.

$$DPC12 = PC2 - PC1_0$$

$$DPC21 = PC1_1 - PC2$$

Where, DPC12 is the change in the pressure during the fuel injection period PD, and DPC21 is the change in the pressure during the fuel feed period PU. This embodiment further calculates the estimated value DPD of the pressure change during the fuel injection period PD based on the target value of the fuel injection amount, and the estimated value DPU of the pressure change during the fuel feed period PU based on the target value of the fuel feed amount, respectively. By comparing the values DPC12 with DPD, or DPC21 with DPU, it is determined whether the fuel injection system has failed.

The estimated values of the pressure changes DPD and DPU are calculated by the methods explained below.

The pressure change DPD during the fuel injection period is calculated by the following formula.

$$DPD = -(K/VPC) \times QFINC$$

Where, K is the bulk modulus of elasticity of the fuel, VPC is the volume of the high pressure part of the fuel injection system including the common rail 3, and QFINC is a target value of the fuel injection amount expressed in the volume under the reference pressure (for example, 0.1 Mpa). Since the ECU 20 controls the fuel injection valves 1 so that the target fuel injection amount is injected, the amount of the fuel actually flowing out from the common rail 3 during the fuel injection period PD becomes the same as QFINC, and the estimated value DPD becomes the same as DPC12, unless failure occurs in the fuel injection valve or the common rail 3. On the other hand, if a failure, such as a fuel leak, occurs in the fuel injection valve 1 or common rail 3, the actual amount of the fuel flowing out from the common rail 3 becomes larger than QFINC. In this case, the actual change in the common rail pressure DPC12 becomes larger than the estimated value DPD. Therefore, this embodiment calculates the difference dDPD between the estimated value DPD and the actual value DPC12 (i.e., dDPD = DPC12 - DPD), and determines that the fuel injection system has failed if the value dDPD exceeds a predetermined value R1 (R1 > 0).

Similarly to the above, the estimated value DPU of the pressure change during the fuel feed period PU is calculated by the following formula.

$$DPU = (K/VPC) \times QPMD$$

QPMD is a target value for the fuel feed amount, i.e., the amount of the fuel flowing into the common rail 3 during the fuel feed period PU. Since the ECU 20 controls the intake control valve 5a of the fuel pump 5 so that the actual fuel feed amount agrees with the target value QPMD, the amount of fuel flowing into the common rail 3 becomes the same as QPMD, and the estimated value DPU becomes the same as the measured value DPC21, unless a failure occurs in the fuel pump 5 or the common rail 3. Therefore, this embodiment calculates the difference dDPU between the esti-

mated value DPU and the actual value DPC21 by $dDPU = DPU - DPC21$, and determines that the fuel injection system has failed if the dDPU is larger than a predetermined value R2 ($R2 > 0$).

As explained above, the determination of the failure based on the change in the pressure during the fuel injection period using DPD and DPC12 and the determination of the failure based on the change in the pressure during the fuel feed period using DPU and DPC21 can be performed independently of each other. However, if both of the methods are used to determine the failure, the type of the failure such as the failed portion of the fuel injection system can be identified by comparing the results of the determination by the both methods. The detail of the method for identifying the type of the failure will be explained later in detail.

When calculating DPD and DPU, it is necessary to consider the change in the bulk modulus of elasticity of fuel. The bulk modulus of elasticity of fuel changes in accordance with the pressure and the temperature. Fig. 3 shows a typical change in the bulk modulus of elasticity of fuel (diesel fuel) in accordance with the pressure and the temperature. As shown in Fig. 3, the bulk modulus of elasticity of diesel fuel increases as the pressure increases, and decreases as the temperature increases. The rate of change in the bulk modulus of elasticity associated with the changes in the pressure and the temperature is relatively small. Therefore, when the pressure and the temperature of fuel changes in a relatively narrow range, the errors in the values DPD and DPU are not large even if the bulk modulus of elasticity is assumed to be a constant. However, if the changes in the pressure and the temperature of fuel are large, particularly, in the case where the pressure of fuel changes over a very wide range such as in the present embodiment (about 10 Mpa to 150 Mpa), the change in the bulk modulus of elasticity becomes large. Therefore, if DPD and DPU are calculated based on a constant bulk modulus of elasticity, the errors in the values of DPD and DPU also become large, and the failure of the fuel injection system cannot be correctly determined.

In this embodiment, the bulk modulus of elasticity of the diesel fuel used for the engine 1 is measured in advance, under various pressure and temperature conditions within a possible range in the operation of the engine. And the measured values of the bulk modulus are stored in the ROM of the ECU 20 in the form of a numerical map using the pressure and the temperature. When calculating DPD and DPU, the ECU 20 determines the value of the bulk modulus of elasticity of the fuel in the common rail 3 from the numerical map using the fuel pressure PC and the fuel temperature THF in the common rail 3 detected by the fuel pressure sensor 31 and the fuel temperature sensor 33, and calculates DPD and DPU from the above-explained formulas using the determined value of the bulk modulus of elasticity.

Next, an embodiment of the actual failure determining operation using the bulk modulus of elasticity of the fuel determined in accordance with the pressure and the temperature of the fuel is explained with reference to Figs. 4 and 5.

Fig. 4 is a flowchart explaining an embodiment of the failure determining operation based on the change in the pressure of the fuel in the common rail 3 during the fuel injection period (DPD, DPC12). This operation is performed by a routine executed by the ECU 20 at predetermined intervals (for example, at every predetermined rotation angle of the crankshaft).

In Fig. 4, when the operation starts, the pressure PC and the temperature THF of the fuel in the common rail 3 and the crank angle CA is read from the fuel pressure sensor 31, the fuel temperature sensor 33 and the crank angle sensor 37, respectively. The ECU 20 determines whether the present crank angle CA agrees with a predetermined value CA1₀ or CA2 at steps 403 through 409 and, if CA agrees neither of CA1₀ and CA2, the operation immediately terminates after step 407. The crank angle CA1₀ corresponds to the timing immediately before the starts of the fuel injection in the respective cylinders, i.e., the sampling timing of PC1₀ in Fig. 2. The crank angle CA2 corresponds to the timing immediately before the start of the fuel feed in the respective cylinders and corresponds to the sampling timing of PC2 in Fig. 2.

If the present crank angle CA agrees with the sampling timing of PC1₀ (i.e., $CA = CA1_0$) at step 403, the ECU 20 stores the present values of the pressure PC and the temperature THF as PC1₀ and THF1, respectively (step 405) and, if the present crank angle CA agrees with the sampling timing of PC2 (i.e., $CA = CA2$) at step 407, the present value of PC is stored as PC2 at step 409. By performing steps 401 through 409, the newest values of PC1₀, THF1 and PC2 are read and stored.

At step 411, the bulk modulus of elasticity K of the fuel in the common rail 3 is determined based on the stored values of the pressure PC1₀ and the temperature THF1 of the fuel in the common rail 3. The bulk modulus K is determined from the numerical map stored in the ROM of the ECU 20 using the values of PC1₀ and THF1 as explained before. Further, at step 413, the estimated pressure change during the fuel injection period is calculated based on the bulk modulus K determined at step 411 and the fuel injection amount QFINC, by

$$DPD = -(k/VPC) \times QFINC.$$

In this embodiment, the ECU 20 calculates the fuel injection amount QFINC by a fuel injection amount calculation routine (not shown) based on the engine speed and the amount of depression of the accelerator pedal (accelerator signal).

The actual pressure change DPC12 during the fuel injection period is calculated at step 415 using PC1₀ and PC2

by $DPC12 = PC2 - PC1_0$.

At step 417, the difference dDPD between the estimated value DPD of the pressure change during a fuel injection period and the actual value DPC12 thereof is calculated by $dDPD = DPD - DPC12$.

At step 419, the ECU 20 determines whether the difference dDPD exceeds a predetermined value R1. If $dDPD > R1$ at step 419, since this means that the amount of the fuel flowing out from the common rail 3 is larger than the normal amount (i.e., the target value of the fuel injection amount), the ECU 20 determines that the fuel injection system has failed, and sets the value of a failure flag XD to 1 at step 423. Further, if $dDPD \leq R1$ at step 419, the ECU 20 determines that the fuel injection system is normal, and sets the value of the flag XD to 0 at step 421. When the failure flag XD is set to 1, an alarm is activated by another routine (not shown) in order to notify the driver of the automobile that a failure has occurred in the fuel injection system. The result of the determination, i.e., the value of the flag XD, may be stored in the backup RAM to facilitate future inspection and maintenance.

Though the value of the bulk modulus of elasticity of the fuel is determined based on the pressure $PC1_0$ and the temperature THF1 of the fuel before the fuel injection is performed, since the change in the pressure and temperature of the fuel during the fuel injection period is relatively small, the pressure (PC2) and the temperature of the fuel after the fuel injection may be used for determining the bulk modulus. Further, the average values of the pressures and temperatures before and after the fuel injection may be used for determining the bulk modulus.

Fig. 5 shows a flowchart explaining an embodiment of the failure determining operation based on the change in the pressure of the fuel in the common rail 3 during the fuel feed period (DPU, DPC21). Similarly to the operation in Fig. 4, the operation in Fig. 5 is performed by a routine executed by the ECU 20 at a predetermined interval (for example, at every predetermined rotation angle of the crankshaft of the engine).

In this operation, the estimated value DPU of the change in the pressure of the fuel during the fuel feed period is calculated on the basis of the bulk modulus of elasticity determined in a similar manner to that in the operation in Fig. 4, and determination is carried out based on the difference dDPU between the estimated value DPU and the actual value DPC21 of the pressure change.

The respective steps in the flowchart in Fig. 5 represent similar operations as the steps in Fig. 4. Therefore, only the operations in Fig. 5 different from those in Fig. 4 are explained hereinafter. Steps 503 through 509 represent the operations for reading the pressures $PC1_1$ and PC2 (Fig. 2) and temperature THF2. CA2 in step 503 and CA1₁ in step 507 are crank angles corresponding to the timing after the fuel injection is completed and before the fuel feed starts and the timing immediately before the next fuel injection starts. Further, the bulk modulus of elasticity K of the fuel is determined in accordance with the pressure PC2 and the temperature THF2 of the fuel in the common rail 3 at the time after the fuel injection and before the fuel feed in this embodiment. However, as explained before, the pressure $PC1_1$ and the temperature THF1 of the fuel after the fuel feed is completed may be used for determining the value of the bulk modulus K.

In Fig. 5, at step 513, the ECU 20 calculates the estimated value DPU of the pressure change of the fuel in the common rail 3 by

$$DPU = (k/VPC) \times QPMD.$$

QPMD is the fuel feed amount from the fuel pump 5 calculated, by a routine not shown, based on the operating condition of the engine. Further, the actual value of the pressure change DPC21 is calculated at step 515 by $DPC21 = PC2 - PC1_1$, and the difference dDPU between the estimated value DPU and the actual value DPC21 is calculated at step 517 by $dDPU = DPU - DPC21$.

At step 519, the value of the failure flag XU similar to the flag XD in Fig. 4 is set to 1 (failed) or 0 (normal) at steps 523 or 521 based on whether the dDPU is larger than a predetermined value R2.

In the embodiments in Figs. 4 and 5, the bulk modulus of elasticity K of the fuel is determined based on both the pressure and the temperature of the fuel in the common rail 3. However, in the engine in which the change in the temperature of the fuel in the common rail 3 is small, the bulk modulus k may be determined based on only the pressure of the fuel assuming that the temperature of the fuel is constant. Similarly, in the engine in which the change in the pressure of the common rail 3 is small, the bulk modulus K may be determined based on only the temperature of the fuel assuming that the pressure of the fuel is constant.

Next, another embodiment of the calculation of the estimated pressure change DPD is explained.

Step 413 in Fig. 4 calculates the pressure change DPD during the fuel injection period by $DPD = -(k/VPC) \times QFINC$ on the assumption that the pressure change in the fuel in the common rail 3 is caused solely by the fuel flowing out from the common rail due to fuel injection. However, in the actual fuel injection system, the fuel flowing out from the common rail other than the fuel injected from the fuel injection valves exists during the fuel injection period even if the fuel injection system is normal.

For example, in some types of fuel injection valves, in which the fuel is used as hydraulic fluid to open the fuel injection valve, a certain amount of fuel is returned to the fuel tank associating with the fuel injection operation of the fuel

injection valve. More specifically, in these types of fuel injection valves, the fuel injection valve is maintained at closed position by exerting fuel pressure both on the upper side and the lower side (the fuel injection port side) of the valve element in order to cancel the force exerted on the valve element by the fuel pressure. When the fuel injection valve is to be opened, the fuel on the upper side of the valve element is relieved through the fuel return line 19 via a solenoid valve in order to reduce the force exerted on the upper side of the valve element. By reducing the pressure on the upper side of the valve element, the valve element is moved by the fuel pressure exerting on the lower side of the element against the urging force of a spring, thereby the valve element opens the fuel injection port to inject the fuel. Therefore, in this type of the fuel injection valve, fuel is returned from the common rail 3 to the fuel tank by the fuel injection operation in addition to the fuel injected through the fuel injection valve.

Further, in addition to the fuel return associating with the fuel injection operation, fuel which leaks from the clearances of the sliding parts of the fuel injection valve always exists. The fuel leaked from the sliding parts is also returned to the fuel tank 7 through the fuel return line 19.

In this embodiment, the fuel return-to the fuel tank in association with the fuel injection operation is referred to as "a dynamic fuel return", and the fuel constantly returned from the common rail to the fuel tank regardless of the fuel injection operation, such as the fuel leaked from the sliding parts, is referred to as "a static fuel return".

Therefore, in the actual fuel injection system, a sum of the amount of the fuel returned to the fuel tank by the dynamic fuel return (i.e., the dynamic fuel return amount) and the amount of the fuel returned to the fuel tank by the static fuel return (i.e., the static fuel return amount) flows out from the common rail 3 in addition to the amount of the fuel injected into the cylinder. In order to calculate the estimated pressure change DPD during the fuel injection period, it is necessary to allow for the dynamic fuel return amount and the static fuel return amount in addition to the fuel injection amount QFINC.

In the embodiments explained hereinafter, the dynamic fuel return amount QILD and the static fuel return amount QILS are considered when the estimated value DPD is calculated. The dynamic fuel return amount QILD and the static fuel return amount QILS are calculated by the method explained below.

The dynamic fuel return amount QILD is the amount of the fuel returned to the fuel tank only when the fuel injection valve opens and is expressed by the amount of fuel returned to the tank by one fuel injection. The dynamic fuel return amount QILD is a function of the length of the opening period of the fuel injection valve TQFIN (i.e., the length of the period in which the solenoid valve is energized for relieving the fuel on the upper side of the valve element of the fuel injection valve) and the fuel pressure immediately before the fuel injection starts (i.e., fuel pressure PC1₀). In this embodiment, the dynamic fuel return amount is measured in advance under various conditions of the fuel pressure and the opening period of the fuel injection valve, and the measured values of the dynamic fuel return amount are stored in the ROM of the ECU 20 in the form of a numerical map based on the fuel pressure PC1₀ and the fuel injection period TQFIN. The dynamic fuel return amount QILD is determined from this numerical map using the fuel pressure PC1₀ and the fuel injection period TQFIN in the actual operation of the engine.

The static fuel return amount QILS is expressed by the total amount of the fuel leaked from the sliding parts during the period between the sampling point of PC1₀ and the sampling point of PC2 (Fig. 2). The static fuel return amount QILS is a function of the fuel pressure PC1₀, the fuel temperature THF1 (i.e., the viscosity of the fuel) and the engine speed NE (i.e., the time lapsed from the sampling point of PC1₀ to the sampling point PC2). In this embodiment, the static fuel return amount QILS is measured in advance under various conditions of the fuel pressure, the fuel temperature and the engine speed, and the values of the measured QILS are stored in the ROM of the ECU 20 in the form of a numerical map using the fuel pressure, the fuel temperature and the engine speed as the parameters. The static fuel return amount QILS is determined from this numerical map using the fuel pressure PC1₀ and the fuel temperature THF1 and the engine speed NE in the actual operation of the engine.

Fig. 6 shows a flowchart of the calculation of the estimated pressure change DPD during the fuel injection period when taking QILD and QILS into consideration. This calculation is, for example, performed by a subroutine executed at step 413 in Fig. 4.

In Fig. 6, at step 6, the opening period of the fuel injection valve (i.e., the period for energizing the solenoid valve) TQFIN calculated by another routine (not shown) by ECU 20 and the engine speed NE are read in. At step 603, the dynamic fuel return amount QILD is determined from the numerical map for QILD stored in the ROM of the ECU 20 using the fuel pressure PC1₀ stored at step 403 (Fig. 4) and TQFIN. At step 605, the static fuel return amount QILS is determined from the numerical map for QILS stored in the ROM of the ECU 20 using the fuel temperature THF1 stored at step 405 (Fig. 4), the fuel pressure PC1₀ and the engine speed NE.

At step 607, the fuel injection amount QFINC is read in, and at step 609, the pressure change during the fuel injection period DPD is calculated based on the values QFINC, QILD, QILS and the bulk modulus of elasticity K determined at step 411 in Fig. 4 by the following formula.

$$DPD = -(K/VPC) \times (QFINC + QILD + QILS)$$

(QFINC + QILD + QILS) in the above formula represents (the fuel injection amount + a sum of the amounts of fuel returned during the fuel injection period), i.e., the total amount of the fuel flowing out from the common rail during the fuel injection period. By performing the calculation of DPD in Fig. 6, the accuracy of the estimated pressure change DPD is improved and, thereby, the accuracy of the failure determination by the operation in Fig. 4 further increases.

Next, an other embodiment of the method for calculating the pressure change DPU during the fuel feed period is explained.

As explained above, the accuracy of the estimated value DPD of the pressure change during the fuel injection period can be improved by taking the amount of the fuel returned from the common rail into consideration. The accuracy of the estimated value DPU can be also improved in a similar manner. In this case, only the static fuel return amount QILS is to be considered as the amount of the fuel returned from the common rail because the fuel injection is not performed during the fuel feed period. On the other hand, the amount of the fuel leaked from the fuel pump must be considered to calculate the fuel feed amount QPMD accurately.

The fuel feed amount QPMD from the fuel pump is expressed by the following formula.

$$QPMD = QG - QD - QL$$

In the formula, QG is a geometric discharge amount of the pump which corresponds to a displacement of the pump piston during the period in which the intake control valve of the pump cylinder opens. The geometric discharge amount QG is a function of the basic timing (crank angle) TF at which the solenoid actuator of the intake control valve 5a is energized and the delay time TFD which is the difference between the basic timing TF and the timing at which the solenoid actuator is actually energized.

QD is a dead volume loss of the pump which represents the amount of the fuel remained in the pump cylinder when the pump piston reaches the top dead center. The dead volume loss QD is a function of the fuel pressure PC1₁ at the end of the fuel feed period and the bulk modulus of elasticity of the fuel. In the calculation of QD, the fuel pressure PC2 at the beginning of the fuel feed period may be used instead of PC1₁ as an approximation.

Further, QL represents the amount of the fuel leaked within the pump and is a function of the fuel pressure PC1₁ (or PC2), the fuel temperature THF2 (the viscosity of the fuel) and the pump speed (the engine speed) NE.

QG, QD and QL are measured in advance with various conditions of the respective parameters. The measured values of QG, QD and QL are stored in the ROM of the ECU 20 in the form of numerical maps based on TF and TFD (in the case of QG), PC2 and K (in the case of QD) and PC2, THF2 and NE (in the case of QL). The values of QG, QD and QL are determined from these numerical maps using the measured values of the respective parameters during the actual operation of the engine. In this embodiment, the actual fuel feed amount QPMD is accurately calculated by using the values QG, QD and QL determined in the actual operation of the engine.

Fig. 7 is a flowchart of the calculating operation of the estimated value DPU of the pressure change during the fuel feed period using the fuel feed amount QPMD which is calculated taking the amounts QG, QD, QL into the consideration. This operation is performed by a subroutine executed at step 513 in Fig. 5.

In Fig. 7, at step 701, the basic timing TF for energizing the solenoid actuator of the intake control valve 5a, the delay time TFD and the engine speed NE are read in. The basic timing TF and the delay time TFD are calculated in the pump control operation (not shown) performed by the ECU 20 based on the operating condition of the engine.

At step 703, the static fuel return amount QILS is determined from the numerical map for QILS using the fuel pressure PC2 and the fuel temperature THF2 stored at step 505 in Fig. 5 and the engine speed NE. Further, the geometric discharge amount QG is determined from TF and TFD at step 705 based on the numerical map for QG stored in the ROM of the ECU 20. At step 707, the dead volume loss QD is determined from the fuel pressure PC2 and the bulk modulus of elasticity K of the fuel calculated at step 511 in Fig. 5 based on the numerical map for QD. The internal leak of the pump QL is determined at step 709 from the fuel pressure PC2, the fuel temperature THF2 and the engine speed NE based on the numerical map for QL.

The accurate fuel feed amount QPMD is calculated at step 711 by $QPMD = QG - QD - QL$ using the values of QG, QD and QL calculated at the previous steps.

The pressure change DPU in the fuel during the fuel feed period is calculated using the bulk modulus of elasticity K determined at step 511 in Fig. 5 and the static fuel return amount QILS and the actual fuel feed amount QPMD by the following formula.

$$DPU = (K/VPC) \times (QPMD - QILS)$$

QPMD in the formula represents the amount of the fuel flowing into the common rail during the fuel feed period, and QILS represents the amount of the fuel flowing out from the common rail during the fuel feed period. By calculating DPU in the manner explained above, the accuracy of the estimated pressure change DPU is improved and, thereby, the failure of the fuel injection system can be determined more accurately.

Next, another embodiment for the determining operation of the static fuel return amount QILS is explained.

In the embodiments in Figs. 6 and 7, the static fuel return amount QILS is determined from the numerical map based on the fuel pressure, the fuel temperature and the engine speed. Therefore, if the values of the fuel pressure, the fuel temperature and the engine speed are the same, the value of the static fuel return amount QILS always becomes the same regardless of the condition of the fuel injection valves. However, the static fuel return amount is, as explained before, the amount of the fuel leaks from the clearances of the sliding parts of the fuel injection valves. Since the clearances of the sliding parts of the fuel injection valves change in accordance with the operation hours of the engine, the static fuel return amount also changes in accordance with the operation hours even if the operating conditions are the same. Therefore, if the static fuel return amount QILS is determined from the numerical map stored in the ROM in advance, the changes in the static fuel return amount is not incorporated into the determined QILS and, thereby, the accuracy of the evaluated values DPD and DPU become low. In the embodiment explained hereinafter, the ECU 20 measures the actual values of QILS during the operation of the engine and learns the change in the QILS based on the measured values. Further, the ECU 20 uses the learned result when it determines the static fuel return amount QILS in order to increase the accuracy of the QILS. According to this embodiment, the actual changes in the static fuel return amount are incorporated into the calculated value of QILS and accuracy of the determination of the failure is increased.

Fig. 8 is a flowchart showing the learning operation of the static fuel return amount QILS according to this embodiment. This operation is performed by a routine executed by the ECU 20 at predetermined intervals.

In this operation, the pressure change in the common rail is measured during the period in which neither the fuel injection nor the fuel feed is performed, and the static fuel return amount QILS is calculated based on the measured pressure change. When neither of the fuel injection and the fuel feed is performed, the change in the pressure in the common rail depends solely on the static fuel return amount. Therefore, assuming that the length of the period is ΔT , and the total static fuel return amount during the period ΔT is QILS, the pressure change (the pressure drop) in the common rail during this period is expressed by the following formula.

$$\Delta P = -(K/VPC) \times QILS$$

Further, since the total amount of the static fuel return amount during the period ΔT is a function of the fuel pressure PC in the common rail and the fuel temperature (the viscosity of the fuel), the total amount QILS of the static fuel return amount in this period is expressed by a linear function of the pressure PC in the common rail, if the temperature of the fuel in this period is constant. In this case, QILS is, for example, expressed by the following formula.

$$QILS = \Delta T \times (a + b \times PC)$$

In the above formula, a and b are constants. Therefore, when the fuel temperature is constant, the pressure change ΔP during the period ΔT in which both the fuel injection and the fuel feed do not occur is expressed by the following formula.

$$\Delta P = -(K/VPC) \times \Delta T \times (a + b \times PC)$$

This means that if ΔP during the period ΔT (in which the fuel injection and the fuel feed do not occur and the fuel temperature is maintained at the same) is measured, the constants a and b, under that temperature condition, are easily obtained by solving simultaneous equations. In this embodiment, the ECU 20 measures the ΔP periodically in the respective fuel temperature range during the operation of the engine and calculates the values of the constants a and b in the respective fuel temperature range. The ECU 20 further stores the values of a and b in the respective temperature range in the backup RAM and calculates the static fuel return amount QILS using the values of the constants a and b stored in the backup RAM in accordance with the fuel temperature. Thus, the learning of the changes in the static fuel return amount is performed.

In the operation in Fig. 8, ΔP is calculated based on $DPC12 (= PC2 - PC1_0)$. In the normal engine operation, the fuel injection occurs in the period between the sampling points of $PC1_0$ and $PC2$ (Fig. 2), and the fuel feed does not occur in this period. Therefore, in the fuel cut operation of the engine in which the fuel injection is not performed, both the fuel feed and the fuel injection do not occur during the period between the sampling points of $PC1_0$ and $PC2$. Therefore, the value of $DPC12$ during the fuel cut operation can be used for ΔP when calculating the values of the constants a and b.

In Fig. 8, it is determined whether the value of a flag FC is set at 1 at step 801. FC is a flag set by a fuel cut operation routine (not shown) performed by ECU 20, and $FC = 1$ means that the fuel cut operation is being performed at present. If the fuel cut operation is not being performed ($FC \neq 1$) at step 801, the ECU 20 terminates the operation without calculating the values of the constants a and b.

If $FC = 1$ at step 801, i.e., if the fuel cut operation is being performed, the ECU 20 read the present values of the

fuel pressure PC, the fuel temperature THF, the crank angle CA and the engine speed NE at step 803.

At steps 805 through 811, the ECU 20 measures the values of the pressure PC1₀ and the temperature THF1 and the pressure PC2 (Fig. 2). At step 813, the bulk modulus of elasticity K of the fuel is determined in accordance with the pressure PC1₀ and the temperature THF1. Steps 803 through 813 are the operations substantially the same as steps 401 through 411 in Fig. 4.

At step 815, the measured value of the pressure change DPC is calculated by $DPC = PC2 - PC1_0$. Since this operation is performed during the fuel cut operation, the measured value DPC represents the pressure change in the common rail when the fuel injection and the fuel feed are not performed.

The constants a and b used for calculating the static fuel return amount QILS are calculated at step 817 using the values of DPC. As explained before, the pressure change in the common rail during the period in which the fuel injection and the fuel feed are not performed is expressed by the following formula.

$$DPC = -(K/VPC) \times \Delta T \times (a + b \times PC1_0).$$

ΔT is an interval between the sampling points of PC1₀ and PC2 and $\Delta T \times (a + b \times PC1_0)$ corresponds to the static fuel return amount QILS. At step 817, the values of the constants a and b are obtained by solving the following simultaneous equations using the values of DPC measured in two successive execution of the operation.

$$DPC = -(K/VPC) \times \Delta T \times (a + b \times PC1_0)$$

$$DPC_{(i-1)} = -(K_{(i-1)}/VPC) \times \Delta T_{(i-1)} \times (a + b \times PC1_{0(i-1)})$$

The values with suffix (i-1) are the values measured or calculated when the operation is last performed. By solving the above-noted simultaneous equations, the values of the constants a and b are obtained.

The ECU 20 stores the set of the calculated values of the constants a, b and the fuel temperature THF1 in the backup RAM at step 819 and renews the values of DPC_(i-1), K_(i-1), $\Delta T_{(i-1)}$, PC1_{0(i-1)} at step 821 in order to prepare for the next execution of the operation.

By performing the operation in Fig. 8, the values of the constants a and b associated with the respective fuel temperature are stored in the backup RAM of the ECU 20. When the fuel cut operation is performed, the values of a and b associated with the fuel temperature during the fuel cut operation are recalculated and the values already stored in the backup RAM are replaced with the re-calculated values. Thus, the values of the constants a and b stored in the backup RAM always correspond to the change in the clearances of the sliding parts.

In this embodiment, the ECU 20 performs the failure determining operation the same as Fig. 6 or Fig. 7. But, at steps 605 and 703, the static fuel return amount QILS is calculated using the values of the constants a and b stored in the backup RAM. More specifically, the ECU 20 reads from the backup RAM the values of a and b corresponding to the present fuel temperature, and calculates QILS by the following formula using the fuel pressure PC and the engine speed NE (i.e., the time ΔT).

$$QILS = \Delta T \times (a + b \times PC)$$

The ECU 20 calculates the estimated values DPD and DPU of the pressure change in the common rail using the calculated value of QILS. Therefore, the calculated values DPD and DPU always correspond to the changes in the conditions of the engine and the fuel injection valves, and the failure of the fuel injection system can be determined more accurately using these values of DPD and DPU.

Next, another embodiment of the present invention is explained.

In the previous embodiments, either of two types of the failure determining operation, i.e., the determining operation based on the pressure change in the common rail during the fuel injection period (DPD, DPC12) and the determining operation based on the pressure change in the common rail during the fuel feed period (DPU, DPC21) is used. These determining operations may be used separately as explained in the previous embodiments. However, if both of the determining operations are performed at the same time, it becomes possible to determine the types of the failure or identify the failed parts in the fuel injection system.

For example, if it is determined that the system has failed by the determining operation based on the pressure change during the fuel feed period (DPU, DPC21) though it is determined that the system is normal by the determining operation based on the pressure change during the fuel injection period (DPD, DPC12), it is considered that the failure occurs at somewhere upstream of the common rail 3 in the fuel injection system (for example, the leak in the portion upstream of the check valve 15, or the shortage of the fuel supplied to the fuel pump). Conversely, if it is determined that the system has failed by the determining operation based on the pressure change during the fuel injection period (DPD, DPC12) though it is determined that the system is normal by the determining operation based on the pressure

change during the fuel feed period (DPU, DPC21), it is considered that the actual amount of the fuel injection from the fuel injection valves has become excessively large.

When the result of the determination based on the pressure change during the fuel injection period (DPD, DPC12) is expressed by the value of the flag XD (Fig. 4) and the result of the determination based on the pressure change during the fuel feed period (DPU, DPC21) is expressed by the value of the flag XU (Fig. 5), the types of the failure in the fuel injection system are determined by the values of the flags XD, XU as shown below.

(A) When XU = 1 (failed) and:

(1) XD = 1 (failed);

The leakage from the high pressure line 17 or from the common rail 3, or the sticking of the fuel injection valve at the opening position, etc.

(2) XD = 0 (normal);

The leakage from the fuel system upstream of the pump check valve 15, or the shortage of the fuel supplied to the fuel pump 5, etc.

(B) When XU = 0 (normal) and:

(3) XD = 1 (failed);

Fuel injection amount is excessively large.

(4) XD = 0 (normal);

Fuel injection system is normal.

In the embodiments explained hereinafter, the ECU 20 performs both the determination based on the pressure change during the fuel injection period (Fig. 4) and the determination based on the pressure change during the fuel feed period, and determines that the present condition of the fuel injection system corresponds to one of the above (1) through (4).

Fig. 9 is a flowchart explaining the determining operation of the type of the failure in this embodiment. This operation is performed by a routine executed by the ECU 20 at predetermined intervals. In the operation in Fig. 9, the failure type parameter FX is set to one of values 1, 2, 3 and 4 in accordance with the combination of the values of the failure flags XD and XU. The values 1 through 4 of the parameter FX correspond to the types of the failure (1) through (4) explained above (FX = 4 represents the fuel injection system is normal). The value of the failure type parameter FX may be stored in the backup RAM of the ECU 20 to facilitate future inspection and maintenance.

By performing the operation in Fig. 9, the type of the failure in the fuel injection system is determined in accordance with the results of the failure determination by the operations in Figs. 4 and 5. Further, since both the determining operations in Figs. 4 and 5 are performed in each of the fuel injection cycle of the respective cylinders, i.e., two failure determining operations are performed in each cycle, the failure of the fuel injection system can be determined accurately.

Next, another embodiment of the present invention is explained. In the embodiment of Fig. 9, the condition of the fuel injection system is classified in four types as explained above. In these conditions of the fuel injection system, it is preferable to stop the engine immediately if the type (1), in which the fuel injection amount becomes excessively large, and the type (3) failure, in which the fuel in the system leaks to the outside occurs. On the other hand, it may not be necessary to stop the engine immediately in the type (2) failure since this type of the failure also includes the case where the shortage of the fuel supplied to the fuel pump 5 has occurred.

For example, if the fuel leaks from the portion upstream of the check valve 15 or from the pump 5 itself to the outside in the type (2) failure, the engine must be stopped immediately. However, if the type (2) failure is caused by the shortage of the fuel supplied to the fuel pump 5, it is not necessary to stop the engine immediately. The shortage of the fuel supplied to the engine is caused by the clogging of the fuel filter 9b or the failure of the low pressure feed pump 9 and, since the fuel does not leak to the outside of the system in these cases, it is rather preferable to continue the engine operation in order to allow the driver to bring the automobile to the service garage.

Therefore, in this embodiment, when the type of the failure is determined as the type (2), the ECU 20 further determines whether the failure is caused by the shortage of the fuel supply to the pump 5, or the leakage of the fuel in the fuel system.

In this embodiment, it is determined whether the type (2) failure is caused by the shortage of the fuel supply based on the fuel supply pressure detected by the fuel supply pressure sensor 39 disposed in the fuel supply line 13. If a sufficient fuel is supplied to the high pressure fuel pump 5, the pressure at the inlet of the pump 5 (the fuel supply pressure) is a positive pressure. However, if the shortage of the fuel supply occurs, for example, due to the clogging of the fuel filter 9b or the decrease in the capacity of the low pressure fuel feed pump 9, the fuel supply pressure takes a negative value. Therefore, in this embodiment, if it is determined that the type (2) failure has occurred, the ECU 20 further deter-

mines whether the fuel supply pressure PIN to the pump 5 is lower than a predetermined value PIN_0 ($PIN_0 < 0$). If $PIN \geq PIN_0$, it is determined that the failure is caused by the fuel leak such as from the high pressure fuel pump 5, and if $PIN < PIN_0$, it is determined that the failure is caused by the shortage of the fuel supply to the pump 5.

Fig. 10 is a flowchart explaining the determining operation of the type of the failure in this embodiment. This operation is performed by a routine executed by the ECU 20 at predetermined intervals.

The flowchart in Fig. 10 is substantially the same as the flowchart in Fig. 9 except that step 907 in Fig. 9 is replaced by steps 1001 through 1007 in Fig. 10. Therefore, only steps 1001 through 1007 are explained hereinafter.

In Fig. 10, if the value of the flag XD is 0 at step 903, i.e., if the type (2) failure has occurred, the ECU 20 reads the fuel supply pressure PIN from the fuel supply pressure sensor 39 at step 1001 and determines whether PIN is lower than a predetermined negative pressure PIN_0 at step 1003. If $PIN \geq PIN_0$, the ECU 20 sets the value of the failure type parameter FX to 21 at step 1005. If $PIN < PIN_0$ at step 1003, the ECU 20 sets the value of the parameter FX to 22 at step 1007. In this embodiment, $FX = 21$ means that the fuel leaks from the high pressure fuel pump 5 or the fuel supply line, and $FX = 22$ means that the failure is caused by the shortage of the fuel supply to the high pressure fuel pump 5 due to, for example, the clogging of the fuel filter 9b or the decrease in the capacity of the low pressure fuel feed pump 9.

If the value of the failure type parameter FX is 1, 3, or 21, the ECU 20 immediately stops the engine and, if the value of FX is 22, the ECU 20 only activates the alarm and continues the operation of the engine. Further, the value of the failure type parameter FX may be stored in the backup RAM to facilitate future inspection and maintenance.

The predetermined pressure PIN_0 in this embodiment is set at a negative pressure, i.e., a pressure lower than the atmospheric pressure in order to set the value of the parameter FX to 21 if the fuel leak from the fuel supply line 13 has occurred. Namely, the shortage of the fuel supply to the high pressure fuel pump 5 also occurs when the fuel leaks from the fuel supply line 13 even if the fuel filter 9b and the fuel pump 9 are normal. If the fuel leaks from the fuel supply line 13 to the outside, it is preferable to stop the engine immediately. However, when the fuel leak from the fuel supply line 13 occurs, the pressure in the line 13 does not become lower than the atmospheric pressure. In other words, the fuel supply pressure PIN becomes lower than the atmospheric pressure only when the cause of the shortage of the fuel supply is other than the fuel leak from the supply line 13. Therefore, by setting the value of the parameter FX to 22 when the PIN is lower than the predetermined negative pressure PIN_0 , the parameter FX is set to 22 only when the fuel supply shortage, which does not involve the fuel leak to the outside, has occurred.

As explained above, according to this embodiment, the failure type parameter FX is set to 22 only when the fuel leak to the outside has not occurred, and FX is set to either of 1, 3, 21 when the fuel leak to the outside has occurred. Therefore, it is easily determined from the value of the parameter FX whether it is necessary to immediately stop the engine.

In the fuel injection system, fuel is supplied to a common rail from a high pressure fuel pump, and injected into the cylinders of an engine, from the common rail, via fuel injection valves. An electronic control unit (ECU) of the engine controls the pressure in the common rail at a value determined by the operating conditions of the engine. The ECU further detects the pressure and the temperature of the fuel in the common rail, and determines the bulk modulus of elasticity of the fuel based on the pressure and the temperature of the fuel. The ECU calculates an estimated value of the pressure change in the common rail during the fuel injection period using the determined bulk modulus. If the difference between the estimated value of the pressure change and the pressure change actually measured during the fuel injection period is large, the ECU determines that the fuel injection system has failed. Since the estimated value of the pressure change is calculated based on the bulk modulus of elasticity which is determined in accordance with the actual pressure and temperature of the fuel, the accurate estimated value is obtained even if the pressure and the temperature of the fuel in the common rail change over a very wide range.

Claims

1. A fuel injection system for an internal combustion engine comprising:

- a reservoir for storing pressurized fuel;
- a fuel injection valve connected to the reservoir and injecting fuel in the reservoir into an internal combustion engine at a predetermined timing;
- a fuel pump for feeding pressurized fuel to the reservoir at a predetermined timing in order to maintain the pressure of the fuel in the reservoir at a predetermined value;
- pressure detecting means for detecting the pressure of the fuel in the reservoir;
- bulk modulus detecting means for detecting a bulk modulus of elasticity of the fuel in the reservoir; and
- failure determining means for determining whether the fuel injection system of the engine has failed based on the bulk modulus detected by the bulk modulus detecting means and the change in the pressure of the fuel in the reservoir during the operation of the engine.

2. A fuel injection system for an internal combustion engine as set forth in claim 1, wherein said bulk modulus detecting means calculates the bulk modulus of elasticity of the fuel in the reservoir based on at least one of the pressure and the temperature of the fuel in the reservoir.
- 5 3. A fuel injection system for an internal combustion engine as set forth in claim 2, wherein said failure determining means comprises pressure drop calculating means for calculating the pressure drop of the fuel in the reservoir during a fuel injection period of the fuel injection valve based on the operating condition of the engine and the bulk modulus detected by the bulk modulus detecting means, actual pressure drop detecting means for calculating the actual pressure drop of the fuel in the reservoir during the fuel injection period of the fuel injection valve based on
10 the pressures of the fuel in the reservoir detected by the pressure detecting means before and after the fuel injection, and fuel injection failure determining means for determining whether the fuel injection system has failed based on the difference between the pressure drop calculated by the pressure drop calculating means and the actual pressure drop.
- 15 4. A fuel injection system for an internal combustion engine as set forth in claim 2, wherein said failure determining means comprises pressure rise calculating means for calculating the pressure rise in the fuel in the reservoir during a fuel feed period of the fuel pump based on the operating condition of the engine and the bulk modulus detected by the bulk modulus detecting means, actual pressure rise detecting means for calculating the actual pressure rise of the fuel in the reservoir during the fuel feed period of the fuel pump based on the pressures of the fuel in the res-
20ervoir detected by the pressure detecting means before and after the fuel feed, and fuel feed failure determining means for determining whether the fuel injection system has failed based on the difference between the pressure rise calculated by the pressure rise calculating means and the actual pressure rise.
- 25 5. A fuel injection system for an internal combustion engine as set forth in claim 3, wherein said pressure drop calculating means further comprises fuel return amount calculating means for calculating a fuel return amount which is the amount of the fuel returned from the reservoir to a fuel tank during the fuel injection period based on at least one of the fuel pressure, the fuel temperature, the speed of the engine and the opening period of the fuel injection valve, and wherein said pressure drop calculating means calculates the pressure drop based on the bulk modulus, the fuel return amount and a fuel injection amount determined by the operating condition of the engine.
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6. A fuel injection system for an internal combustion engine as set forth in claim 4, wherein said pressure rise calculating means further comprises fuel return amount calculating means for calculating a fuel return amount which is the amount of the fuel returned from the reservoir to a fuel tank during the fuel feed period of the fuel pump based on at least one of the fuel pressure, the fuel temperature and the speed of the engine, and wherein said pressure
35rise calculating means calculates the pressure rise based on the bulk modulus, the fuel return amount and a fuel feed amount determined by the operating condition of the engine.
7. A fuel injection system for an internal combustion engine as set forth in claim 5, wherein said fuel return amount is a sum of a dynamic fuel return amount which is the amount of the fuel returned from the reservoir to the fuel tank
40by the fuel injecting operation of the fuel injection valve and a static fuel return amount which is the amount of the fuel returned from the reservoir to the fuel tank independently of the fuel injecting operation of the fuel injection valve.
8. A fuel injection system for an internal combustion engine as set forth in claim 6, wherein said fuel return amount is
45a static fuel return amount which is the amount of the fuel returned from the reservoir to the fuel tank independently of the fuel injecting operation of the fuel injection valve.
9. A fuel injection system for an internal combustion engine as set forth in claim 7, wherein said fuel return amount
50calculating means further comprises learning means for measuring and storing the amount of the fuel returned from the reservoir to the fuel tank during the period in which both the fuel injection and the fuel feed are stopped, and wherein said fuel return amount calculating means calculates the static fuel return amount based on the value of the amount of the fuel stored in the learning means.
- 55 10. A fuel injection system for an internal combustion engine as set forth in claim 8, wherein said fuel return amount calculating means further comprises learning means for measuring and storing the amount of the fuel returned from the reservoir to the fuel tank during the period in which both the fuel injection and the fuel feed are stopped, and wherein said fuel return amount calculating means calculates the static fuel return amount based on the value of the amount of the fuel stored in the learning means.

11. A fuel injection system for an internal combustion engine as set forth in claim 2, wherein said failure determining means comprises:

5 pressure drop calculating means for calculating the pressure drop of the fuel in the reservoir during a fuel injection period of the fuel injection valve based on the operating condition of the engine and the bulk modulus detected by the bulk modulus detecting means, actual pressure drop detecting means for calculating the actual pressure drop of the fuel in the reservoir during the fuel injection period of the fuel injection valve based on the pressures of the fuel in the reservoir detected by the pressure detecting means before and after the fuel injection, and fuel injection failure determining means for determining whether the fuel injection system has failed
10 based on the difference between the calculated pressure drop and the actual pressure drop; and pressure rise calculating means for calculating the pressure rise in the fuel in the reservoir during a fuel feed period of the fuel pump based on the operating condition of the engine and the bulk modulus detected by the bulk modulus detecting means, actual pressure rise detecting means for calculating the actual pressure rise of the fuel in the reservoir during the fuel feed period of the fuel pump based on the pressures of the fuel in the
15 reservoir detected by the pressure detecting means before and after the fuel feed, and fuel feed failure determining means for determining whether the fuel injection system has failed based on the difference between the calculated pressure rise and the actual pressure rise.

12. A fuel injection system for an internal combustion engine as set forth in claim 11, wherein said failure determining means further comprises failure type determining means for determining the type of the failure of the fuel injection system based on the both determination results of the fuel injection failure determining means and the fuel feed failure determining means.

13. A fuel injection system for an internal combustion engine as set forth in claim 12 further comprising a fuel filter disposed in a supply line for supplying fuel to the fuel pump and fuel supply pressure detecting means for detecting the pressure in the supply line between the fuel filter and the pump, wherein said failure type determining means at least determines whether a fuel supply system including the fuel pump and the supply line upstream thereof has failed based on the determination results of the fuel injection failure determining means and the fuel feed failure determining means and wherein said failure type determining means, when it is determined that the fuel supply system has failed, further determines that the failure of the fuel supply system is caused by the shortage of fuel supplied to the fuel pump if the pressure detected by the fuel supply pressure detecting means is lower than a pre-determined value.

Fig.1

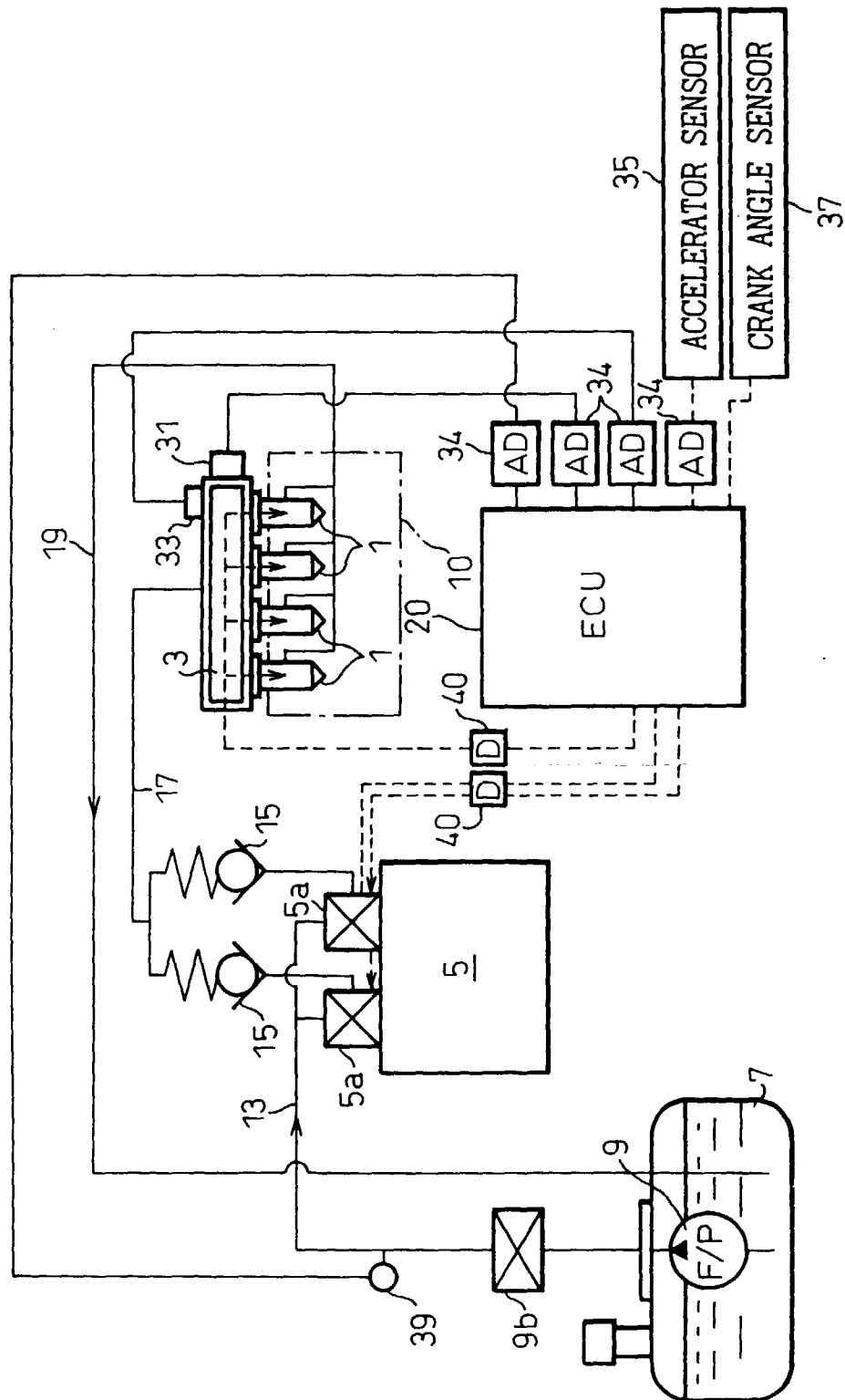


Fig.2

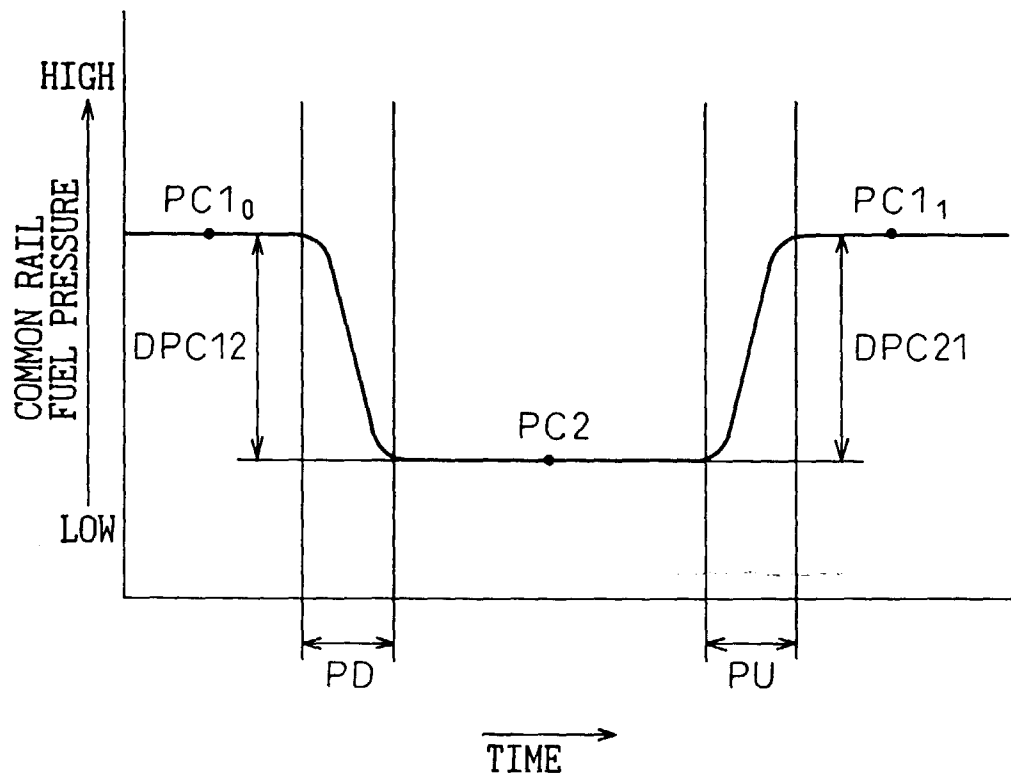


Fig.3

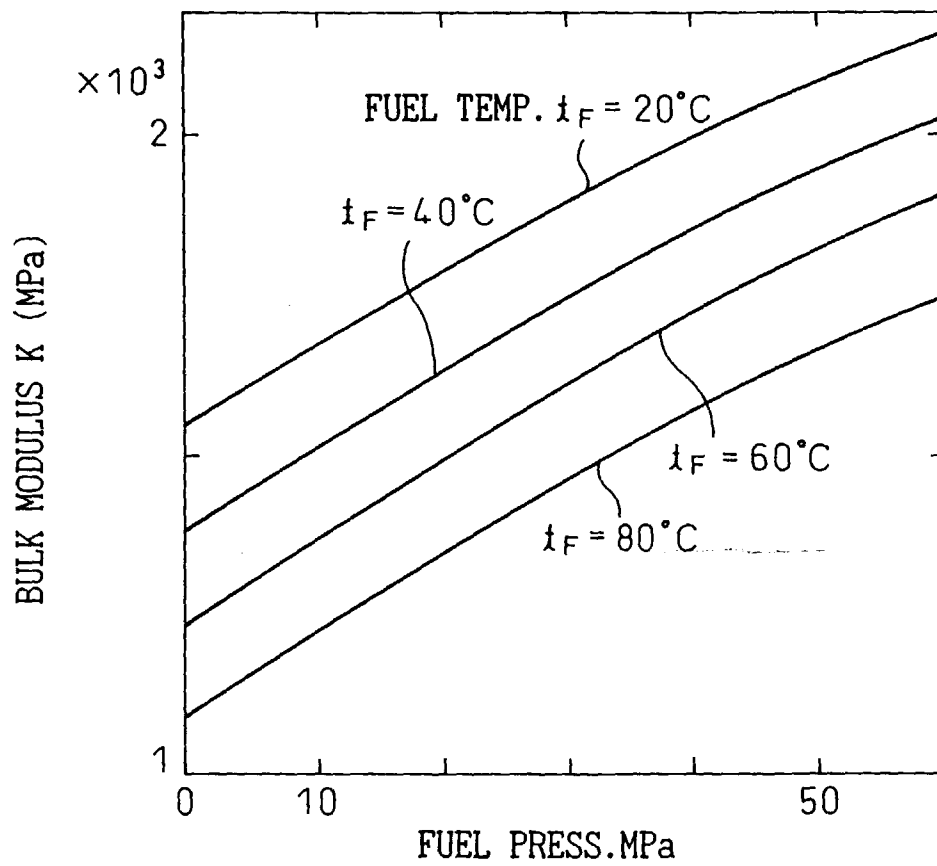


Fig.4

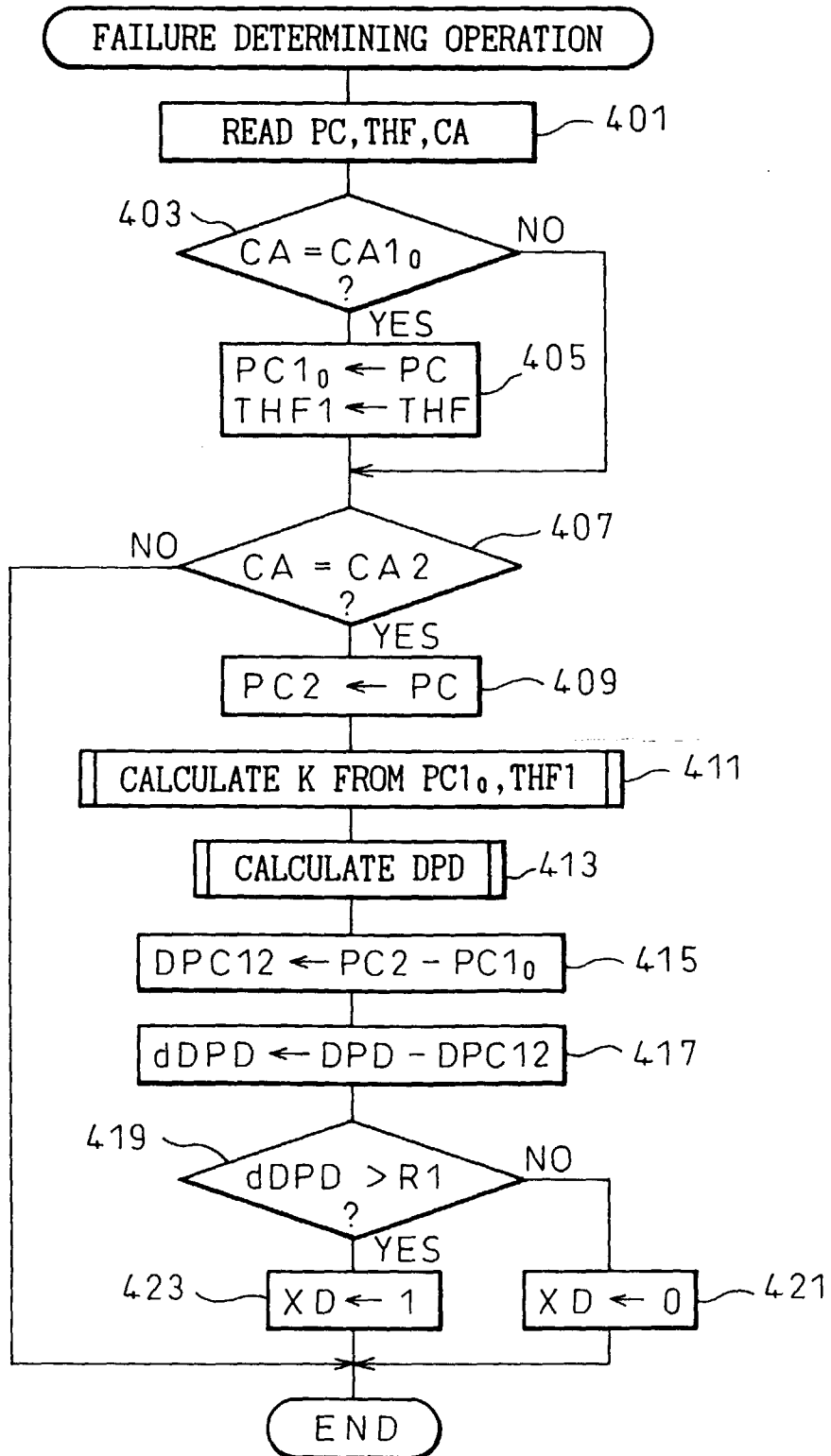


Fig.5

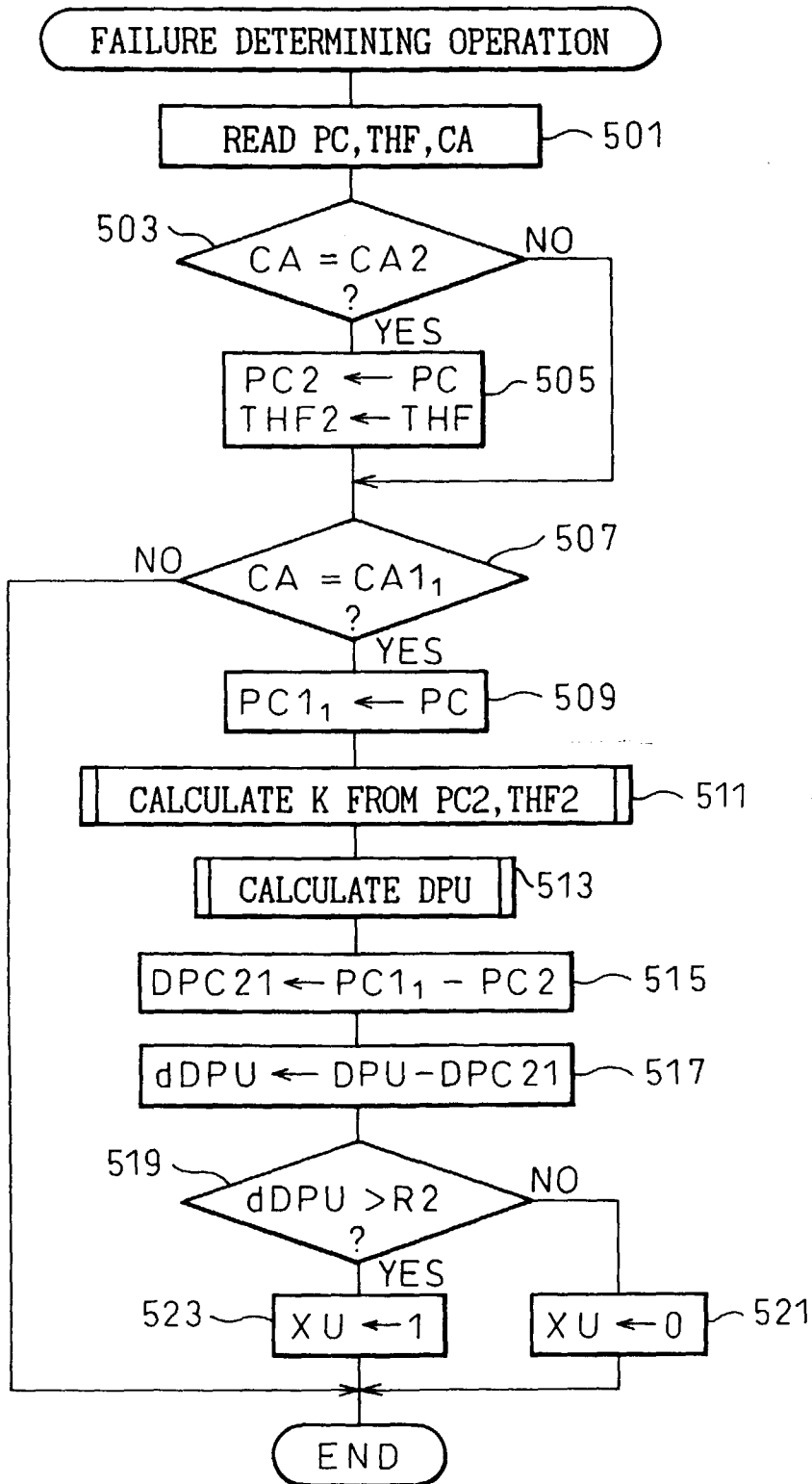


Fig.6

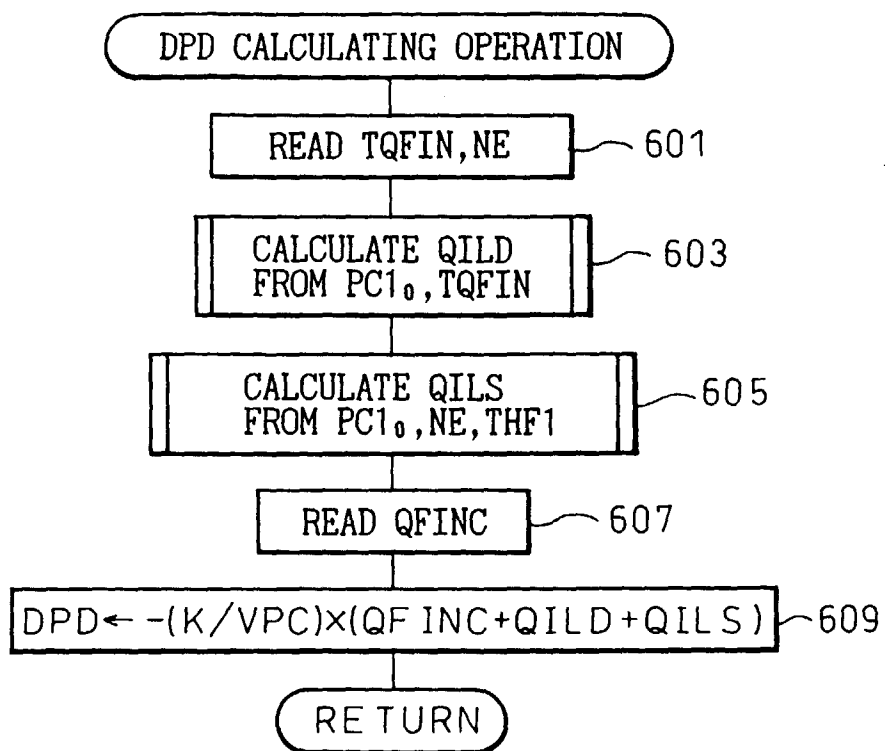


Fig.7

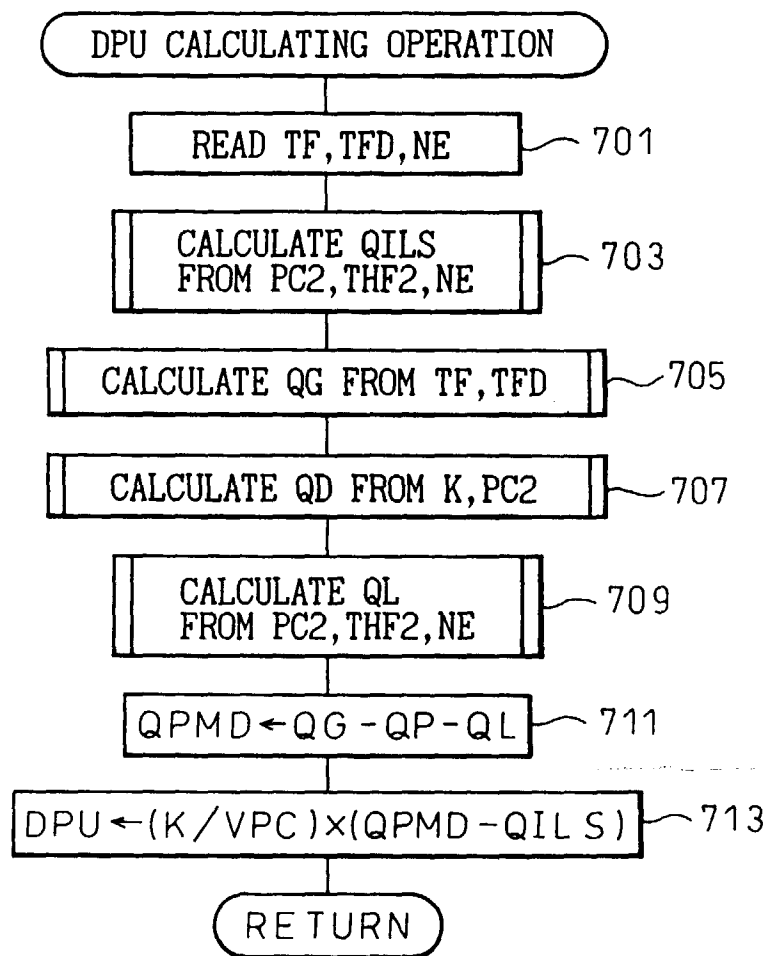


Fig.8

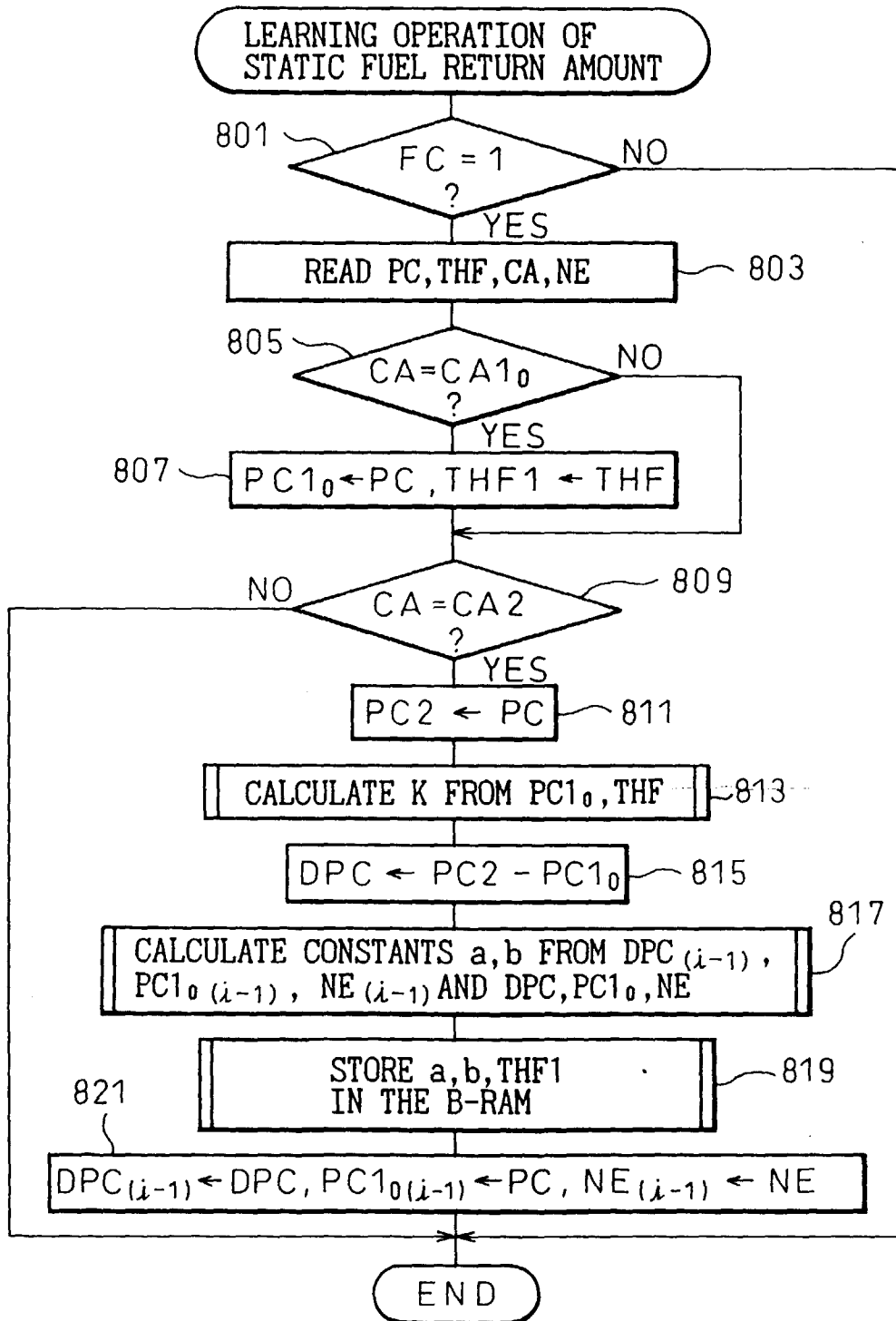


Fig.9

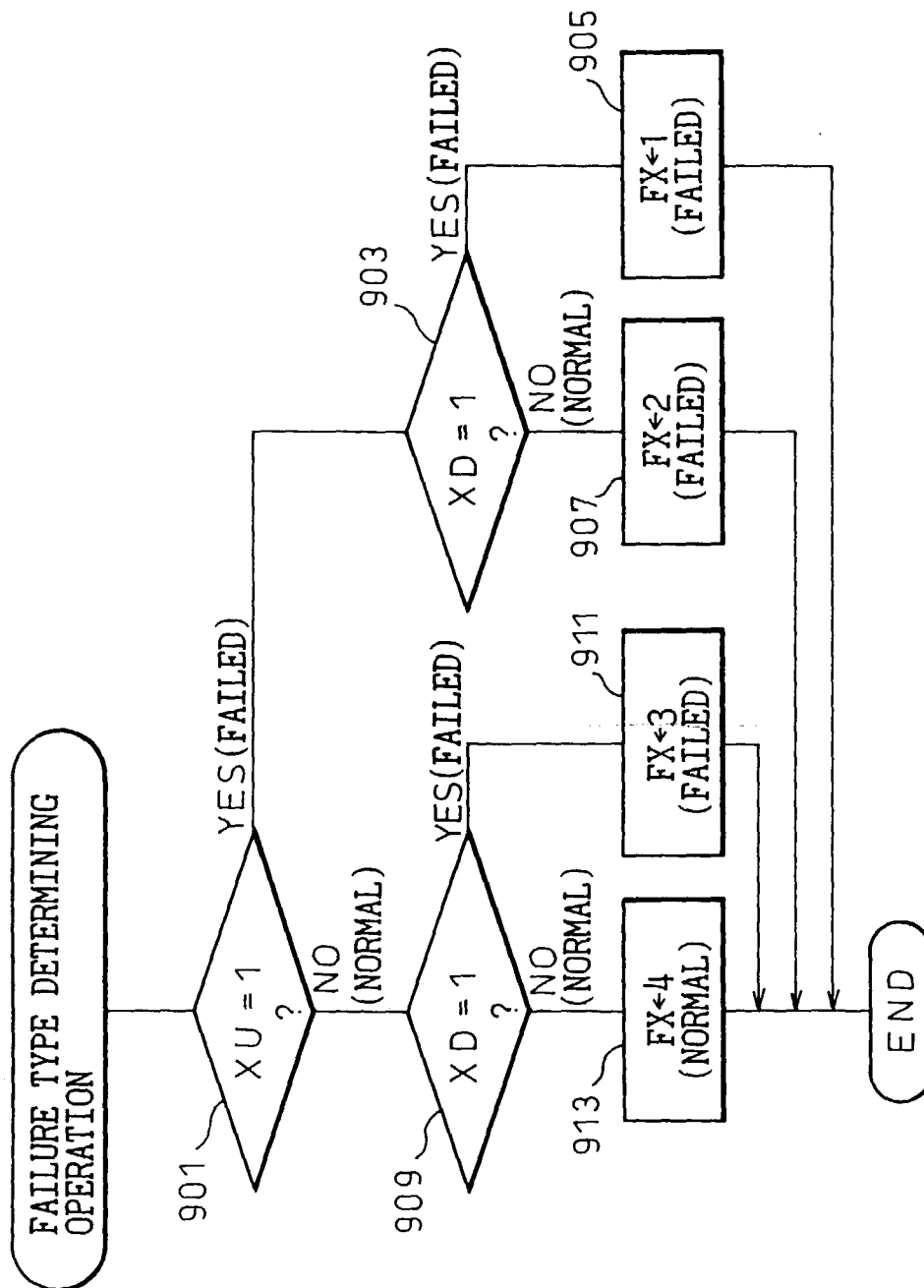


Fig.10

