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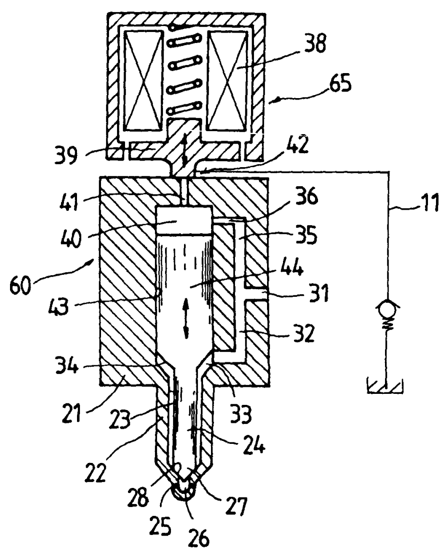
(54) **Common-rail fuel-injection system**

(57) A common-rail fuel-injection system is disclosed, in which varying the effective stroke of an actuator-operated valve (42) results in adjusting an amount of fuel leaking out of a pressure-control chamber (40), thereby controlling the fuel injection in compliance with the engine operating conditions. When the lift of the valve (42) is small and therefore the opening area of the valve (42) is less than the cross-sectioned area of a fuel leakage path (41), the leakage of high-pressure fuel out of the pressure is defined by the lift of the valve (42). According to the pressure fall in the pressure-control chamber (40), the lift of a needle valve (24) is regulated to thereby control the fuel-injection rating, namely, the quantity of fuel injected and the rate of change of the fuel-injection rating. An exciting signal applied to the actuator (65) to operate the its associated valve is determined in accordance with a desired fuel-injection rating or the like, which is found in compliance with the engine operating conditions.

FIG. 3



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Description

[0001] The present invention relates to a common-rail fuel-injection system in which fuel supplied under high pressure from a common rail is injected with the action of a fuel pressure into the combustion chambers of engines.

[0002] Among various types of fuel-injection systems for engines is conventionally well-known a common-rail fuel-injection system in which the fuel stored under high-pressure in the common rail is applied to the injectors, which are in turn actuated by making use of a part of the high-pressure fuel as a working fluid to thereby spray the fuel applied from the common rail into the combustion chambers out of discharge orifices formed at the distal ends of the injectors.

[0003] Referring to FIG. 15 where an example of a conventional common-rail fuel-injection system is illustrated schematically, a fuel feed pump 6 draws fuel from a fuel tank 4 through a fuel filter 5 and forces it under a preselected intake pressure to a high-pressure, fuel-supply pump 8 through a fuel line 7. The high-pressure, fuel-supply pump 8 is of, for example, a fuel-supply plunger pump driven by the engine, which intensifies the fuel to a high pressure determined depending on the engine operating conditions, and supplies the pressurized fuel into the common rail 2 through another fuel line 9. The fuel, thus supplied, is stored in the common rail 2 at the preselected high pressure and forced to the injectors 1 through injection lines 3 from the common rail 2. The engine illustrated is a six-cylinder engine. The injectors 1 are arranged in combustion chambers, each to each chamber, of a multi-cylinder engine, for example, a six-cylinder engine in FIG. 15.

[0004] The fuel relieved from the high-pressure, fuel-supply pump 8 is allowed to flow back the fuel tank 4 through a fuel-return line 10. The unconsumed fuel remaining in each injector 1 out of the fuel fed from the common rail 2 into the injectors 1 may return to the fuel tank 4 through a fuel-recovery line 11. The controller unit 12 is applied with various signals of sensors monitoring the engine operating conditions, such as a crankshaft position sensor for detecting the engine rpm Ne, an accelerator pedal sensor for detecting the depression Ac of an accelerator pedal, a high-pressure fuel temperature sensor and the like. In addition, the sensors for monitoring the engine operating conditions include an engine coolant temperature sensor, an intake manifold pressure sensor and the like. The controller unit 12 is also applied with a detected single as to a fuel pressure in the common rail 2, or a common-rail pressure, which is transmitted from a pressure sensor 13 installed in the common rail 2.

[0005] The controller unit 12 defines the fuel-injection conditions, including the injection timing and the quantity of fuel injected, depending on the applied signals, so as to allow the engine to operate as fuel-efficient as possible and controls the fuel injection in accordance with the consequent fuel-injection conditions. The quantity of fuel injected per cycle is determined by the combination of injection duration with an injection pressure of the fuel sprayed out of the injectors. The injection pressure is substantially equal with the common rail pressure controlled by operating a flow-rate control valve 14, which is to regulate the quantity of delivery of the high-pressure fuel to the common rail 2. In case the injection of fuel out of the injectors 1 consumes the fuel in the common rail 2 or it is required to alter the quantity of fuel injected, the controller unit 12 actuates the fuel flow-rate control valve 14, which in turn regulates the quantity of delivery of the fuel from the high-pressure, fuel-supply pump 8 to the common rail 2 whereby the common rail pressure recovers the preselected fuel pressure.

[0006] Referring to FIG. 16, the injector 1 at which the fuel injection is controlled comprises an injector body 21, and an injection nozzle 22 mounted to the injector body 21 and formed therein with an axial bore 23 in which a needle valve 24 is fitted for a sliding movement. The high-pressure fuel applied to the individual injector 1 from the common rail 2 through the associated injection line 3 fills fuel passages 31, 32 and a fuel pocket 33 formed in the injector body 21. The high-pressure fuel further reaches around the needle valve 24 in the axial bore 23. Therefore, the instant the needle valve 24 is lifted to open discharge orifices 25 at the distal end of the injection nozzle 22, the fuel is injected out of the discharge orifices 25 into the combustion chamber. Provided at the distal end of the injection nozzle 22 is a fuel sac 26 to which are opened the discharge orifices 25. The needle valve 24 has a tapered end 27 that moves upwards off or downwards against a tapered surface 28 inside the injection nozzle 22 whereby the fuel injection starts or ceases.

[0007] The injector 1 is provided with a needle-valve lift mechanism of pressure-control chamber type in order to adjust the lift of the needle valve 24. That is to say, the high-pressure fuel fed from the common rail 2 is partly admitted into a pressure-control chamber 40, which is formed inside the injector 1, past a slot 35 communicating with the fuel passage 31. The injector 1 has at the head section thereof a solenoid-operated valve 15, which constitutes an electronically-operated actuator to control the outflow of working flow to the pressure-control chamber 40. The controller unit 12 actuates the solenoid-operated valve 15 in compliance with the engine operating conditions, thereby adjusting the hydraulic pressure of the working fluid in the pressure-control chamber 40 to either the high pressure of the admitted high-pressure fuel or a low pressure released partially in the pressure-control chamber 40. A control signal issued from the controller unit 12 is an exciting signal applied to a solenoid 38 of a solenoid-operated valve 15. The solenoid-operated valve 15 includes an armature 39 having at its end a valve 42 for opening and closing an egress of a fuel leakage path 41. On energizing a solenoid 38, the armature 39 rises to open the valve 42, as shown by broken lines, whereby the fuel in the pressure-control chamber 40 is allowed to discharge, resulting in relieving the high pressure of the fuel in the pressure-control chamber 40. Although the valve 42 is explained about the type of opening and closing the egress of the fuel leakage path 41, it may be alternatively made of a poppet valve composed of a valve stem extending through the fuel leakage path 41, and a tapered valve body provided at the end of the valve stem and having a valve face to make an engagement with a valve seat at an ingress of the fuel leakage path 41.

[0008] A control piston 44 is arranged for axial linear movement in an axial recess 43 formed in the injector body 21 of the injector 1. Although the control piston 44 shown in the figure is formed integrally with the needle valve 24, the control piston may be formed separately from the needle valve and combined together with each other such that they may be energized so as to follow one another. When the solenoid-operated valve 15 is energized to cause the fuel pressure inside the pressure-control chamber 40 to reduce, the consequent force, acting on the control piston 44 to pushing it downward, is made less than the fuel pressure acting on both a tapered surface 34 exposed to the pocket 33 and the distal end of the needle valve 24, whereby the control valve 44 moves upwards. As a result, the needle valve 24 lifts to allow the fuel to spray out of the discharge orifices 25. The quantity of fuel injected per cycle is defined dependent on the fuel pressure and both the amount and duration of lift of the needle valve 24.

[0009] The common-rail fuel-injection system, or the pressure-balance, fuel-injection system, as described above is disclosed in, for example, Japanese Patent Laid-Open Nos. 165858/1984 and 282164/1987, in which the fuel supplied under pressure from the common rail 2 to the injectors 1 is partly applied to the pressure-control chamber 40, or the pressure balance chamber, in the injectors 1, acting as the working fluid to lift the needle valve 24 to inject the fuel out of the discharge orifices 25. Disclosed in Japanese Patent Laid-Open No. 271881/1986 is a fuel-injection system in which the fuel-injection rating is variably controlled in accordance with the amount of electric charge emission of the piezoelectric actuator.

[0010] It is well known to those skilled in the art that the engine operating conditions in the diesel engines are largely affected by the initial fuel-injection characteristics of the injectors 1. For example, much initial quantity of fuel injected causes much quantity of fuel firing at the initiation of combustion with the heat release rate being increased whereby the diesel engines are apt to decline in noise control and exhaust gas performance.

[0011] The injector 1 shown in FIG. 16 is provided with a second solenoid-operated valve 46, in addition to a first solenoid-operated valve 45 having an armature 39. Energizing and deenergizing the second solenoid-operated valve 46 causes shifting a moving part 47 of the second solenoid-operated valve 46 to thereby stepwise alter the position of the moving part 47 against which the armature 39 abuts to cease its motion, namely, to vary the effective stroke of the armature 39. Where the armature 39 ceases its motion determines that the most narrowed location in the path allowing the fuel to flow out of the pressure-control chamber 40 is either of the fuel leakage path 41 and the opening area defined between the armature 39 and the egress of the fuel leakage path 41 thereby to control the relief of the fuel pressure out of the pressure-control chamber 40. This results in varying the lift of the needle valve 24 by which the fuel pressure in the pressure-control chamber 40 is balanced in equilibrium thereby varying the throttling effect occurring between the tapered end 27 of the needle valve 24 and the tapered valve seat 28 inside the injection nozzle 22 to control a quantity of fuel injected out of the discharge orifices 25. The valve 42 is urged to its closure position by the action of a return spring 48.

[0012] Referring FIG. 17 showing a fragmentary enlarged illustration of a prior injector 50 in which both the discharge orifices and the needle vale 24 are modified in structure to make it possible to vary stepwise the quantity of fuel injected. The fuel is applied to the fuel sac 26 at the distal end of the injector 50 past a fuel passage 58 formed in a radially reduced section 57 of the end of the needle valve 24 and further past a fuel passable hole 56. When the lift of the needle valve 24 is less as shown with a symbol L_1, the fuel in the fuel sac 26 is allowed to spray out of only discharge orifices 51 arranged closer to the bottom of the fuel sac 26. In contrast, when the lift of the needle valve reaches a distance of L_2, the fuel in the fuel sac 26 is also injected out of not only the lower discharge orifices 51 but also upper discharge orifices 52. It will be thus understood that the quantity of fuel injected is made less at a little lift of the needle valve 24 or at an initial portion of the lift of the needle valve 24.

[0013] Nevertheless, the prior injectors as described above involves major problems of the need of using additional solenoid-operated valve, the complication in shape and structure of not only the injection nozzle but also the discharge orifices, with bringing about the increase of the cost of production and the productivity decease. On the structure that the discharge orifices are arranged in rows spaced apart from each other in an axial direction of the injection nozzle, only two patterns of injection rating are permitted and, therefore, it is very hard to control the quantity of fuel injected in accordance with the rotational speed and the engine load, which are variable over the wide ranges, respectively. Regarding the graphic representation of the fuel-injection rating in terms of time, the integral thereof represents the quantity of fuel injected, while the differential thereof is the rate of change of the injection rating. Consequently, the graphic curve of the injection rating at the early portion of the fuel injection affects the heat release rate at the initial combustion and has a great influence on the engine noise and the exhaust gases performance. The fuel-injection rating is controlled by the lift of the needle valve 24, which is defined by the pressure inside the pressure-control chamber, which is in turn determined by the operation of the actuator in the injector. To cope with the problem above, therefore, it is expected to develop the fuel-injection system in which controlling the operation of the actuator results in controlling the injection rating.

[0014] The present invention has for its primary aim to provide a common-rail fuel-injection system in which the fuel injection may be selected arbitrarily and continuously over the wide ranges of the rotational speed and the engine load by only controlling the actuator of conventional type with no need of adding other new means and/or the special modification in structure, which might otherwise causes the increase of the cost of production.

[0015] The present invention is concerned with a common-rail fuel-injection system, comprising injectors for spraying fuel into combustion chambers of an engine, a common rail storing therein the fuel to be applied to the injectors, a high-pressure fuel pump for delivery of the fuel to the common rail detecting means for monitoring engine operating conditions, and a controller unit for regulating fuel injection out of the injectors in compliance with signals transmitted from the detecting means, wherein the injectors each includes a pressure-control chamber applied with a part of the fuel fed from the common rail a needle valve movable upward and downward, depending on a hydraulic action of the fuel in the pressure-control chamber, to thereby open and close discharge orifices at a distal end of the injector, a valve for allowing the fuel to discharge out of the pressure-control chamber thereby resulting in relieving the fuel pressure in the pressure-control chamber, and an actuator for driving the valve, and wherein the controller unit produces an exciting signal, in compliance with the signals transmitted from the detecting means, to energize the actuator that in turn regulates an opening area of the actuator-operated valve thereby resulting in controlling the fuel injection out of the injectors.

[0016] The controller unit produces an exciting signal in accordance with signals transmitted from the detecting means for monitoring the engine operating conditions, and the consequent exciting signal energizes the actuator, which in turn operates its associated valve in such a manner that the valve is controlled within a stroke including a range over which the opening area may vary, thereby regulating the lift of the needle valve with resulting in controlling the fuel injection out of the discharge orifices at the distal end of the injector. By previous provision of data about a correlation between the exciting signal applied to the actuator and the fuel-injection rating or the like, the fuel may be injected with the optimum fuel-injection condition including, for example, the initial fuel injection, in compliance with the engine operating conditions.

[0017] In one aspect of the present invention, a common-rail fuel-injection system is disclosed wherein the actuator is composed of piezoelectric elements. In this case, the exciting signal is of an exciting voltage applied to the piezoelectric elements. As an alternative, the actuator may be composed of an electromagnetic solenoid and the exciting signal is of an exciting voltage applied to the solenoid or an exciting current supplied to the solenoid.

[0018] In another aspect of the present invention, a common-rail fuel-injection system is disclosed, wherein the actuator-operated valve is of a lift valve for opening and closing an egress of a fuel leakage path through which the fuel flows out of the pressure-control chamber. As an alternative, the actuator-operated valve may be of a poppet valve, which comprises a valve stem extending through the fuel leakage path allowing the fuel to leak out of the pressure-control chamber, and a valve head mounted to the valve stem at the side of the pressure-control chamber and having a valve face to make a contact with a valve seat formed at an ingress of the fuel leakage path.

[0019] In another aspect of the present invention, a common-rail fuel-injection system disclosed, wherein the controller unit stores therein a first mapped data of a correlation defined previously between an initial controlled variable of the fuel injection at an early portion of the fuel injection and a desired quantity of fuel injected, and stores therein a second mapped data of a correlation defined previously among a desired common-rail pressure, the initial controlled variable of the fuel injection and the exciting signal, thereby finding, based on the signals transmitted from the detecting means, the desired quantity of fuel injected and the desired common-rail pressure corresponding to the desired quantity of fuel injected, finding on the first mapped data the initial controlled variable of the fuel injection in accordance with the desired quantity of fuel injected, and calculating on the second mapped data the exciting signal corresponding to the initial controlled variable of the fuel injection. That is, following finding the desired quantity of fuel injected and the desired common-rail pressure in accordance with the engine operating conditions, the initial controlled variable of fuel injection is then found on the first mapped data in compliance with the desired quantity of fuel injected, and the exciting signal to drive the injector is calculated on the second mapped data in accordance with the initial controlled variable of the fuel injection whereby the fuel injection may be achieved with the initial controlled variable of the fuel injection.

[0020] In another aspect of the present invention, a common-rail fuel-injection system is disclosed, wherein the initial controlled variable of the fuel injection is any one of an initial quantity of fuel injected, an initial fuel-injection rating and a rate of change of the initial fuel-injection rating. Namely, according to what pattern of the exciting signal is applied, any desired one of the initial quantity of fuel injected, the initial fuel-injection rating and the rate of change of the initial fuel-injection rating may be made to conform with its associated desired value to thereby control the fuel injection. According to the common-rail fuel-injection system of the present invention, it has been known that the injection rating during the early portion of the injection duration, for example, for 0.5msc from the start of the fuel injection, increases linearly as the time of injection proceeds and there is a mutually proportional correlation among the initial quantity of fuel injected at the early portion of the fuel-injection duration, the injection rating and the rate of change of the fuel-injection rating, so that the rate of change of the injection rating may be, for example, used as a parameter for control.

[0021] In the common-rail fuel-injection system of the present invention, the control of the exciting signal to be applied to the actuator results in adjusting the pressure drop in the pressure-control chamber to thereby control the lift of the needle valve. This makes it possible to control the fuel injection in compliance with not only the quantity of fuel injected but also the fuel-injection rating and the rate of change of the injection rating. Accordingly the present invention may provide the common-rail fuel-injection system in which the fuel injection may be selected arbitrarily and continuously over the wide ranges of the rotational speed and the engine load by only modifying the control of the conventional actuator with no need of adding other new means and/or the special modification in structure, which might otherwise causes the increase of the cost of production.

[0022] Other aims and features of the present invention will be more apparent to those skilled in the art on consideration of the accompanying drawings and following specification wherein are disclosed preferred embodiments of the invention with the understanding that such variations, modifications and elimination of parts may be made therein as fall within the scope of the appended claims without departing from the scope of the invention.

[0023] Embodiments of the present invention will now be described by way of example only, with reference to the accompanying drawings, in which:-

FIG. 1 is a flowchart showing a fuel-injection control in which the initial controlled variable of fuel injection is an initial fuel-injection rating in a common-rail fuel-injection system according to the present invention:
FIG. 2 is a block schematic diagram illustrating the control of the rate of change of the initial fuel-injection rating in FIG. 1:
FIG. 3 is a schematic illustration showing an injector adapted to be used in the common-rail fuel-injection system of the present invention:
FIG. 4 is an enlarged fragmentary section of illustrating the fuel leakage out of the pressure-control chamber of the injector shown in FIG. 3:
FIG. 5 is a graphic representation showing a correlation of the opening area of an actuator-operated valve versus the lift of a moving part:
FIG. 6 is a graphic representation showing an attraction characteristic of a solenoid-operated valve controlled under an exciting current:
FIG. 7 is a graphic representation showing an attraction characteristic of a solenoid-operated valve controlled under an exciting voltage:
FIG. 8 is a graphic representation showing a response characteristic of a piezoelectric element:
FIG. 9 is a composite graph showing fuel-injection characteristics caused by the solenoid-operated valve controlled under the exciting voltage:
FIG. 10 is a composite graph showing fuel-injection characteristics caused by the solenoid-operated valve controlled under the exciting current:
Fig. 11 is a composite graph showing fuel-injection characteristics caused by the piezoelectric element:
FIG. 12 is a graphic representation showing a correlation of exciting voltage versus initial fuel-injection rating in case of the solenoid-operated valve controlled under the exciting voltage:
FIG. 13 is a graphic representation showing a correlation of exciting current versus initial fuel-injection rating in case of the solenoid-operated valve controlled under the exciting current:
FIG. 14 is a composite graph showing variations of a common rail pressure and a fuel-injection rating in response to an exciting pulse:
FIG. 15 is a schematic illustration of an arrangement of a conventional common-rail fuel-injection system:
FIG. 16 is a schematic sectional illustration of an injector used in the conventional common-rail fuel-injection system: and
FIG. 17 is an enlarged fragmentary section of another prior injector used in the conventional common-rail fuel-injection system.

[0024] A preferred embodiment of a common-rail fuel-injection system for engines according to the present invention will be explained in detail hereinafter with reference to FIGS. 1 to 14. The common-rail fuel-injection system as described above in connection with FIGS. 15 is substantially applicable to the system according to the present invention. The relationship of the fuel-injection rating with the operating of the actuator will be described in the following in connection with a commonly used injector 60 shown in FIG. 3.

[0025] Compared with the injector shown in FIG. 16, the injector 60 is substantially equal with the injector described above, except for the actuator being composed of a single solenoid-operated valve 65 and the pressure-control chamber 40 being applied with the fuel past fuel passages 35, 36. Most of components of the system, thus, are the same as previously described. To that extent, the components have been given the same reference characters, so that the previous description will be applicable to the injector 60. Moreover, the fuel leaking past the valve 42 is recovered via low-pressure side return line 11.

[0026] The following equations apply for the injector 60:

(1) The equation of continuity Eq. [1] as to the pressure-control chamber 40 may be written as

$$\mu_{in}\cdot A_{in}\cdot\sqrt{\frac{2\cdot(P_{cr}-P_{cc})}{\rho}}-\mu_{ex}\cdot A_{ex}\cdot\sqrt{\frac{2\cdot(P_{cc}-P_{b})}{\rho}}+A_{nb}\cdot\frac{dx_n}{dt}-\frac{V_{cc}}{K}\cdot\frac{dP_{cc}}{dt}=0 \qquad \text{Eq. [1]}$$

μ in represents the flow coefficient at the ingress of the pressure-control chamber
Ain is the opening area at the ingress of the pressure-control chamber
Pcr is the common rail pressure
Pcc is the fuel pressure in the pressure-control chamber
ρ is the density of fuel
μ ex is the flow cofficient at the egress of the pressure-control chamber
Aex=f(Xc) is the opening area at the egress of the pressure-control chamber
Xc is the lift of the actuator-operated valve
Pb is the back pressure
Xn is the lift of the needle valve

$$A_{nb}=\frac{\pi}{4}\cdot D_{nb}^2$$

Dnb is the outermost diameter of the needle valve
Vee is the volume of the pressure-control chamber
K is the volume modulus

(2) The equation of continuity Eq. [2] as to the fuel sac 26 may be written as

$$\mu'_{in}\cdot A'_{in}\cdot\sqrt{\frac{2\cdot(P_{cr}-P_{s})}{\rho}}-\mu'_{ex}\cdot A'_{ex}\cdot\sqrt{\frac{2\cdot(P_{s}-P_{b})}{\rho}}+A_{nb}\cdot\frac{dx_n}{dt}-\frac{V_{s}}{K}\cdot\frac{dP_{s}}{dt}=0 \qquad \text{Eq. [2]}$$

μ' in represents the flow coefficient at the ingress of the fuel sac
μ 'ex is the flow coefficient at the egress of the fuel sac
A'in=f(Xn) is the opening area at the ingress of the fuel sac

$$A'_{ex}=\frac{\pi}{4}\cdot D_{nh}^2\cdot n$$

is the opening area at the egress of the fuel sac

$$A_{ns}=\frac{\pi}{4}\cdot D_{ns}^2$$

Dns is the inner diameter of the fuel sac
Dnh is the diameter of one discharge orifice
n is the number of the discharge orifice
Vs is the volume of the fuel sac
K is the volume modulus

[0027] For the above fundamental equations, writing the Eq. [1] in terms of the moving speed of the needle valve 24 yields

$$\frac{dx_n}{dt}=\frac{1}{A_{nb}}\left(\mu_{ex}\cdot A_{ex}\cdot\sqrt{\frac{2\cdot(P_{cc}-P_b)}{\rho}}-\mu_{in}\cdot A_{in}\cdot\sqrt{\frac{2\cdot(P_{cr}-P_{cc})}{\rho}}+\frac{V_{cc}}{K}\cdot\frac{dP_{cc}}{dt}\right) \quad \text{Eq. [3]}$$

[0028] Combining Eq. [2] and Eq. [3] and solving for the term of the fuel-injection rating gives

$$\begin{aligned}\frac{dG}{dt} &= \mu'_{ex}\cdot A'_{ex}\cdot\sqrt{\frac{2\cdot(P_s-P_b)}{\rho}} \\ &= \mu'_{in}\cdot A'_{in}\cdot\sqrt{\frac{2\cdot(P_{cr}-P_s)}{\rho}} \\ &+\frac{A_{ns}}{A_{nb}}\cdot\left(\mu_{ex}\cdot A_{ex}\cdot\sqrt{\frac{2\cdot(P_{cc}-P_b)}{\rho}}-\mu_{in}\cdot A_{in}\cdot\sqrt{\frac{2\cdot(P_{cr}-P_{cc})}{\rho}}+\frac{V_{cc}}{K}\cdot\frac{dP_{cc}}{dt}\right)-\frac{V_s}{K}\cdot\frac{dP_s}{dt}\end{aligned} \quad \text{Eq. [4]}$$

[0029] For the above Eq. [4] , the following equations Eq. [5] may be assumed at the timing the needle valve starts to open and, then, the Eq. [4] may be written as

$$\frac{dP_{cc}}{dt}=0,\ \frac{dP_s}{dt}=0,\ P_{cc}=P_{cr},\ P_s=P_b,\ A'_{in}=0 \quad \text{Eq. [5]}$$

$$\frac{dG}{dt}=\mu_{ex}\cdot A_{ex}\cdot\frac{A_{ns}}{A_{nb}}\cdot\sqrt{\frac{2\cdot P_{cr}}{\rho}} \quad \text{Eq. [6]}$$

[0030] As apparent from the Eq. [6] , the fuel-injection rating should be dependent on only the opening area at the egress of the pressure-control chamber 40 if the designs of the common-rail pressure and the needle valve 24 or the injection nozzle 22 are determined. In the meantime it is to be noted that there is a fixed correlation, as shown in FIG. 5, between the opening area at the egress of the pressure-control chamber 40 and the valve 42. The fuel-injection rating thus may be controlled by shifting the valve 42 to the lift at which the most narrowed location is provided at the egress of the fuel leakage path 41. As an alternative, modifying the Eq. [6] results in

$$\frac{dG}{dt}=\mu_{ex}\cdot A_{ex}\cdot\frac{A_{ns}}{A_{nb}}\cdot\sqrt{\frac{2\cdot P_{cr}}{\rho}}=\mu_{ex}\cdot f(X_c)\cdot\frac{A_{ns}}{A_{nb}}\cdot\sqrt{\frac{2\cdot P_{cr}}{\rho}} \quad \text{Eq. [7]}$$

[0031] The quantity of fuel injected is the integral of the fuel-injection rating in terms of the time and, therefore, may be written as

$$\int dG=\mu_{ex}\cdot\frac{A_{ns}}{A_{nb}}\cdot\sqrt{\frac{2\cdot P_{cr}}{\rho}}\cdot\int f(x_c)\cdot dt \quad \text{Eq. [8]}$$

[0032] In order to reduce the initial quantity of fuel injected, as will be seen from Eq. [8] , the valve 42 does not necessarily need of keeping the given lift, but decelerating its lift motion may be sufficient. Now, the equation of motion of the valve 42 is in general expressed by

$$m\cdot\frac{d^2x_c}{dt^2}+c\cdot\frac{dx_c}{dt}+k\cdot X_c=F_{sv}(t)-F_{set}-F_p \quad \text{Eq. [9]}$$

m represents the weight of the moving part
Xc is the lift of the acruator-operated

valve

c is the damping coefficient
k is the spring constant
Fsv(t) is the force of the actuator
Fset is the set force

$$F_p = \frac{\pi}{4} \cdot D_{ps}^2 \cdot P_{cc}$$

Dps is the diameter of the valve
Pcc is the fuel pressure of the pressure-control chamber

[0033] This Eq. [9] teaches the lift speed of the valve 42 may slow down with suppressing the input from the actuator. It will be said from the foregoing that the fuel-injection rating may be regulated by either position control or speed control of the valve 42.

[0034] The following describes how to control the fuel-injection rating in compliance with the lift of the actuator-operated valve 42. Referring to FIG. 4, which is a fragmentary enlarged section illustrating the fuel leakage of the fuel out of the pressure-control chamber 40 in the injector 60 in FIG. 3, when the lift L of the valve 42 is less, the amount of fuel leaking out of the pressure-control chamber 40 past the fuel leakage path 41 is not depend on the fuel leakage path 41, but defined by an open space 61 provided between the armature 39 and the egress of the fuel leakage path 41. That is to say, the open area Sa spanning across the open space 61 is less than the cross-sectioned area Sb of the fuel leakage path 41 so that the most narrowed location is provided at the open apace 61. As the lift of the valve 42 increases, the open area Sa at the open space 61 becomes wider than the cross-sectioned area Sb of the fuel leakage path 41 so that the amount of fuel leaking out of the pressure-control chamber 40 is dominated by the fuel leakage path 41, which is now the most narrowed location.

[0035] Accordingly, as apparent from FIG. 5, the opening area S of the valve 42 increases as the lift L of the valve 42 increases, so long as the lift L is less than a fixed distance L_0. In contrast, the opening area S is kept at the cross-sectioned area Sb of the fuel leakage path 41 after the lift L reaches the fixed distance L_0. The amount of fuel leaking out of the pressure-control chamber 40 may be controlled in accordance with the lift of the valve 42, provided the lift does not exceed the L_0. This is major ground for conception that controlling the lift of the valve results in adjusting the lift of the needle valve 24 to thereby regulate the fuel-injection rating.

[0036] The actuator used in the present invention may be composed of any one of (a) solenoid-operated valve and (b) piezoelectric element, each of which has the characteristics described below.

(a)Solenoid-operated valve

[0037] On signaling an exciting current to the solenoid-operated valve, an electromagnetic attraction characteristic as shown in FIG. 6 appears between the exciting current and the consequent attractive force in the solenoid-operated valve controlled by the exciting current. On the other hand, when the solenoid-operated valve is applied with a signal of exciting voltage, an attraction-response characteristic as shown in FIG. 7 exists between the exciting voltage and the consequent attraction-response lag in the solenoid-operated valve controlled by the exciting voltage. As a result, the attractive force of the solenoid-operated valve is depressed, as the exciting current applied to the solenoid-operated valve is restricted. Lowering the exciting voltage applied to the solenoid-operated valve causes the time lag required for the acquisition of the preselected attractive force in the valve. This means that the low exciting voltage results in the measure to depress substantially the electromagnetic attractive force.

(b) Piezoelectric element

[0038] Referring to FIG. 8 showing a correlation of an exciting voltage to the piezoelectric element with a displacement, or a lift, of a push rod, the piezoelectric element has a linear response characteristic with respect to the exciting voltage so that the position of the valve 42 may be adjusted in a direct proportion to varying the exciting voltage.

[0039] FIG. 9 shows fuel-injection characteristics in the event in which the solenoid-operated valve is controlled under the exciting voltage. As will be seen in the top graph in which the value of current is plotted with the exciting voltage, signaled to the solenoid-operated valve, as a parameter, even if the exciting voltage is reduced in magnitude, the value of current has no tendency to lower suddenly provided there is no largely sudden voltage fall. As illustrated in middle graph about the lift of the solenoid-operated valve, as the exciting voltage lowers, the valve starts to lift with a time lag while the lift motion of the valve is made less in speed as well as in peak. Moreover, reducing the exciting voltage, as shown in the bottom graph regarding the fuel-injection rating, causes the start of fuel injection to delay and also makes the rate, or the slope, of the fuel-injection rating less steep. In addition, as apparent from FIG. 12 showing the correlation between the initial fuel-injection rating and the exciting voltage to control the solenoid-operated valve, the initial quantity of fuel injected goes down steeply with the reduction of the exciting voltage.

[0040] FIG. 10 shows fuel-injection characteristics in the event in which the solenoid-operated valve is controlled under the exciting current. As will be seen in the top graph in which the attractive force is plotted with the exciting current, signaled to the solenoid-operated valve, as a parameter, the attractive force lowers in accordance with the reduction of the exciting current at the early stage of the instruction to start the fuel injection. The middle graph about the lift of the solenoid-operated valve shows that, as the exciting current lowers, the lift motion of the valve is made less in speed as well as in peak. Nevertheless, the time lag for the start of lift of the valve is less, compared to the case of the exciting voltage. Moreover, reducing the exciting voltage, as shown in the bottom graph regarding the fuel-injection rating, causes the start of fuel injection to delay and also has trend of making the rate, or the slope, of the fuel-injection rating less steep. The time lag of the start of the fuel injection is also less, compared with the case of the exciting voltage. In addition, as apparent from FIG. 13 showing the correlation between the rate of reduction of the initial fuel-injection rating and the exciting current, the initial quantity of fuel injected goes down in approximately direct proportion with the reduction of the exciting current.

[0041] FIG. 11 shows fuel-injection characteristics about the control with the piezoelectric element. As will seen from the top graph, the displacement of the push rod, or the output of the piezoelectric element, may vary with good response to the voltage fall, while the bottom graph teaches the rate of change, or the slope, of the injection rating is affected largely by the voltage fall.

[0042] Next, referring to FIG. 14 showing a composite graph of the common rail pressure, the rate of change of the injection rating in response to the exciting pulse, a time t_0 the command pulse falls is a timing at which an instruction to initiate the fuel injection is applied to the injector 1, which in turn begins an actual fuel injection at a timing t , after a lapse of the start-delay time T caused by the response lag of the working fluid inthe pressure-control chamber 40. Thereafter, the common-rail pressure Pcr starts to drop. In the meantime, disclosed in our co-pending senior Patent application, Japanese Patent Laid-Open No. 101149/1999 is a method of finding the start-delay time T spanning from a command pulse fall to control the exciting signal applied to the actuator in the injector to the timing for the initiation of the actual fuel injection. The method in our co-pending application will be explained with reference to FIG. 14. After finding an approximate straight line Ld of a curve in the range of from the start of common-rail pressure drop owing to the fuel injection to a time t_4 at which the first minimal value appears, the timing for the start of common rail-pressure drop is defined at a time-coordinate t_3 where the approximate straight line Ld intersects with an approximate line Lp prior to the descending trend, which shows a mean pressure before the start of common-rail pressure drop. Based the mean common-rail pressure Lp before the start of the pressure drop and the timing t_3 for the start of the common-rail pressure drop, the start-delay time T spanning from the timing t_0 for the command pulse fall to the timing t , for the start of the fuel injection is found in accordance with the functional relation, which has been experimentally.

[0043] As apparent from a curve of fuel-injection rating q, the initial injection rating, or the early portion of the injection rating q, increases linearly. Consequently, it will be said that the initial quantity of fuel injected, or the quantity of fuel injected during an early preselected duration after the start of the fuel injection, and the initial fuel-injection rating are in proportional relation with the rate of change, or a fixed slope, of the fuel-injection rating. The initial fuel-injection rating, or the early portion of the fuel-injection rating q, as well as the rate k_1 of change thereof becomegreater in value at a timing t_1 for the actual fuel injection, or another start-delay time T_1 no later than the start-delay time T and, therefore, the quantity of fuel injected no later than a preselected length of time increases in proportion to the rate of change. In contrast, the initial injection rating as well as the rate k_2 of change thereof become less in value at a timing t_2 for the actual fuel injection, or another start-delay time T_2 later than the start-delay time T and, therefore, the quantity of fuel injected later than a preselected length of time made less in proportion to the rate k_2 of change.

[0044] FIGS. 1 and 2 are to explain the processing procedure in the fuel-injection system of the present invention. The processing step in FIGS. 1 will be referred to as a letter "S" hereinafter. Sensors for monitoring includes a tachometer monitoring the engine rpm and an accelerator pedal depression sensor monitoring the engine load. The engine rpm Ne and the engine load Ac are detected (S1). A desired quantity Q_0 of fuel injected per cycle is found, in compliance with the engine rpm Ne and the engine load Ac transmitted from the associated sensors, on a lookup map A in which is previously defined a correlation of the desired quantity Q_0 of fuel injected with the engine rpm Ne and the engine load Ac (S2). A desired common-rail pressure Pf is found on a lookup map B, which is also defined previously, in compliance with the engine rpm Ne and the desired quantity Q_0 of fuel injected, which has been found on the map A. The desired common-rail pressure Pf is signaled to the controller unit, which in turn controls both the high-pressure fuel pump 8 and the flow-rate control valve 14 to thereby make the desired common-rail pressure Pf of an actual common-rail pressure.

[0045] A lookup map C is previously defined, in which the correlation among the desired quantity Q_0 of fuel injected, the engine rpm Ne and a desired rate k_0 of change of the initial fuel-injection rating, or the second differential of the initial fuel-injection rating in terms of the time, is plotted at the subject of smoke emission control and specific fuel consumption on such event that it is not permitted to achieve the noise control or the exhaust gas circulation of the engine. The lookup map C corresponds to the first mapped data of the present invention. A desired rate k_0 of change of the initial fuel-injection rating is defined on the lookup map C in compliance with the desired quantity Q_0 calculated above and the engine rpm Ne detected (S3). A pull-in voltage Vp or a pull-in current Ip to be applied to the actuator of the injector 1 is found in compliance with the rate k_0 of change, found at the (S3), on a lookup map D, which is also defined previously (S4). The lookup map D corresponds to the second mapped data according to the present invention, in which the pull-in voltage Vp is found for the actuator of the piezoelectric elements while the pull-in current Ip is for the solenoid-operated actuator.

[0046] When taking into consideration the pull-in voltage Vp or current Ip found in the (S4), there is a possibility that the total quantity of fuel injected differs from the desired quantity Q_0 of fuel injected. To cope with this possibility, a command pulse width Pw making the quantity of fuel injected conform with the desired quantity Q_0 of fuel injected is determined based on a three-dimensional lookup map E in which the desired quantity Q_0 of fuel injected, the command pulse width Pw and the pull-in voltage Vp or current Ip are plotted with the desired common-rail pressure Pf as a parameter (S5). The injector driver is energized with the pull-in voltage Vp or current Ip found at the (S4) and the command pulse of the pulse width Pw determined at the (S5) thereby to carry out the actual fuel injection (S6). The lookup map E may be of a two-dimensional map of the desired quantity Q_0 and the command pulse width Pw plotted in accordance with several pull-in voltages Vp or currents Ip.

[0047] As this invention may be embodied in several forms without departing from the spirit of essential characteristics thereof, the present embodiment is therefore illustrative and not restrictive, since the scope of the invention is defined by the appended claims rather than by the description proceeding them, and all changes that fall within meets and bounds of the claims, or equivalence of such meets and bounds are therefore intended to embraced by the claims.

Claims

1. A common-rail fuel-injection system, comprising injectors(1) for spraying fuel into combustion chambers of an engine, a common rail(2) storing therein the fuel to be applied to the injectors (1), a high-pressure fuel pump(8) for delivery of the fuel to the common rail(2), detecting means for monitoring engine operating conditions, and a controller unit(12) for regulating fuel injection out of the injectors(1) in compliance with signals transmitted from the detecting means,

   wherein the injectors(1) each includes a pressure-control chamber(40) applied with a part of the fuel fed from the common rail(2), a needle valve(24) movable upward and downward, depending on a hydraulic action of the fuel in the pressure-control chamber(40), to thereby open and close discharge orifices(25) at a distal end of the injector(1), a valve(42) for allowing the fuel to discharge out of the pressure-control chamber(40) thereby resulting in relieving the fuel pressure in the pressure-control chamber(40), and an actuator(65) for driving the valve(42), and
   wherein the controller unit(12) produces an exciting signal, in compliance with the signals transmitted from the detecting means, to energize the actuator(65) that in turn regulates an opening area of the valve thereby resulting in controlling the fuel injection out of the injectors(1).

2. A common-rail fuel-injection system constructed as defined in claim 1, wherein the actuator(65) is composed of piezoelectric elements and the exciting signal is an exciting voltage to be applied to the piezoelectric elements.

3. A common-rail fuel-injection system constucted as defined in claim 1, wherein the actuator(65) is composed of an electromagnetic solenoid and the exciting signal is any one of an exciting voltage and an exciting current to be applied to the electromagnetic solenoid.

4. A common-rail fuel-injection system constructed as defined in claim 1, wherein the actuator-operated valve(42) is of a lift valve for opening and closing an egress of a fuel leakage path (41) through which the fuel flows out of the pressure-control chamber(140).

5. A common-rail fuel-injection system constructed as defined in claim 1, wherein the actuator-operated valve(42) is of a poppet valve, which comprises a valve stem extending through the fuel leakage path(41) allowing the fuel to

leak out of the pressure-control chamber(40), and a valve head mounted to the valve stem at the side of the pressure-control chamber(40) and having a valve face to make a contact with a valve seat formed at an ingress of the fuel leakage path(41).

6. A common-rail fuel-injection system constructed as defined in claim 1, wherein the controller unit(12) stores therein a first mapped data of a correlation defined previously between an initial controlled variable of the fuel injection at an early portion of the fuel injection and a desired quantity of fuel injected, and stores therein a second mapped data of a correlation defined previously among a desired common-rail pressure(Pf), the initial controlled variable of the fuel injection and the exciting signal, thereby finding, based on the signals transmitted from the detecting means, the desired quantity of fuel injected and the desired common-rail pressure(Pf) corresponding to the desired quantity of fuel injected, finding on the first mapped data the initial controlled variable of the fuel injection in accordance with the desired quantity of fuel injected, and calculating on the second mapped data the exciting signal corresponding to the initial controlled variable of the fuel injection.

7. A common-rail fuel-injection system constructed as defined in claim 6, wherein the initial controlled variable of the fuel injection is any one of an initial quantity of fuel injected, an initial fuel-injection rating and a rate of change of the initial fuel-injection rating.

FIG. 1

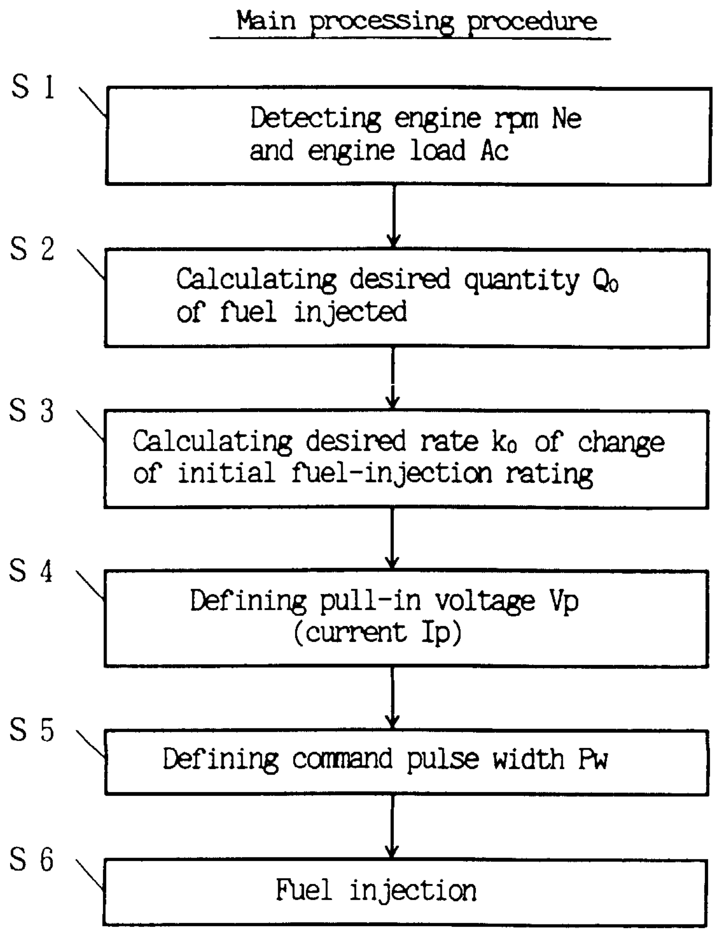
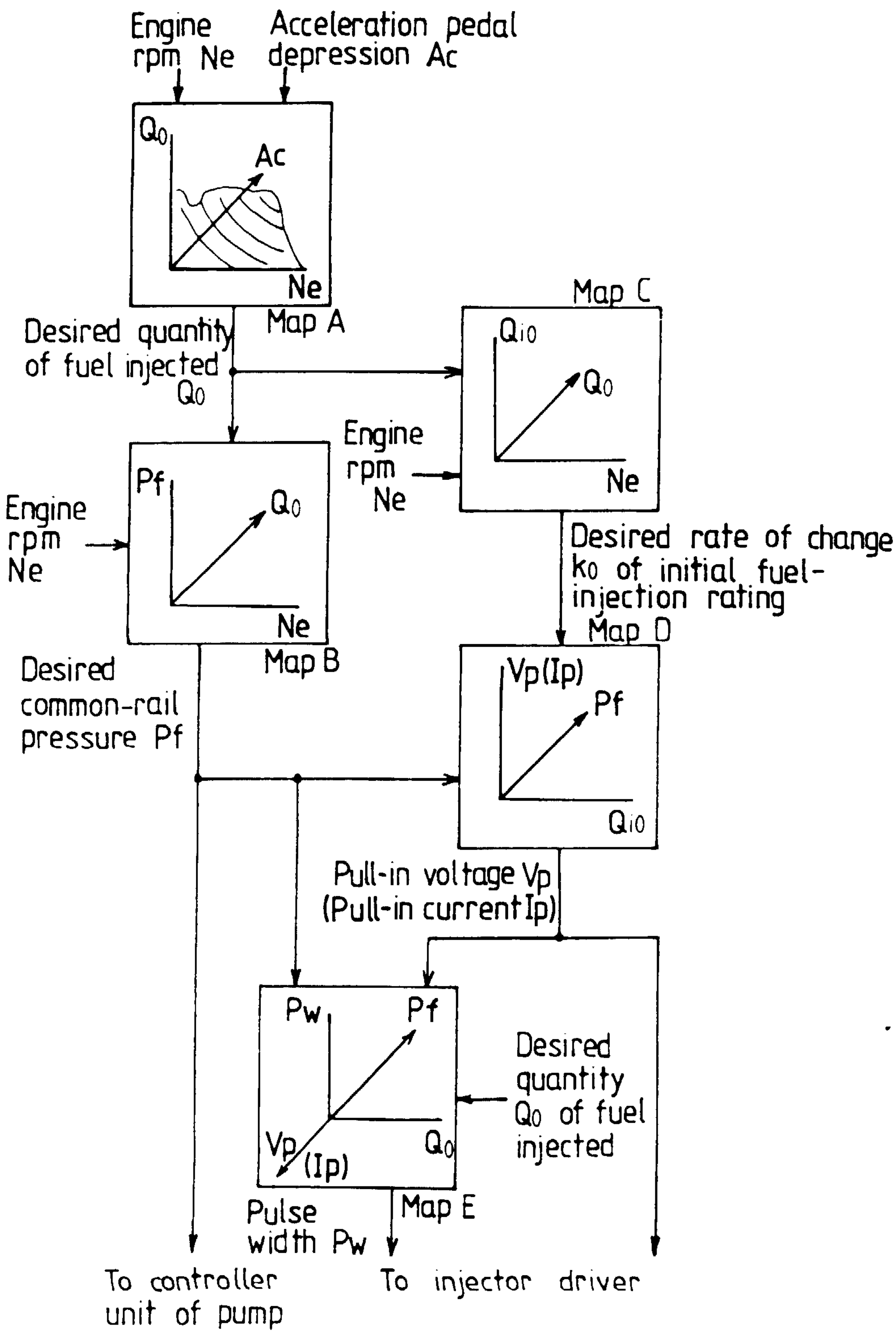

Main processing procedure
S1
Detecting engine rpm Ne and engine load Ac
S2
Calculating desired quantity Q_0 of fuel injected
S3
Calculating desired rate k_0 of change of initial fuel-injection rating
S4
Defining pull-in voltage Vp (current Ip)
S5
Defining command pulse width Pw
S6
Fuel injection

FIG. 2


Engine rpm Ne
Acceleration pedal depression Ac
Q0
Ac
Ne
Map A
Desired quantity of fuel injected Q0
Map C
Qi0
Q0
Ne
Engine rpm Ne
Pf
Q0
Ne
Engine rpm Ne
Map B
Desired rate of change k0 of initial fuel-injection rating
Map D
Vp(Ip)
Pf
Qi0
Desired common-rail pressure Pf
Pull-in voltage Vp
(Pull-in current Ip)
Pw
Pf
Vp
(Ip)
Q0
Desired quantity Q0 of fuel injected
Map E
Pulse width Pw
To controller unit of pump
To injector driver

F I G. 3

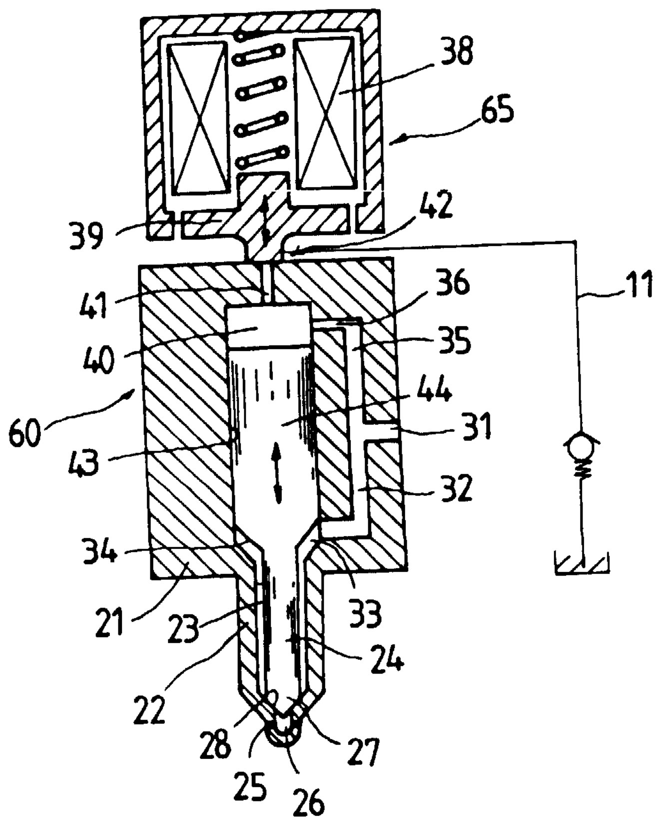


FIG. 4

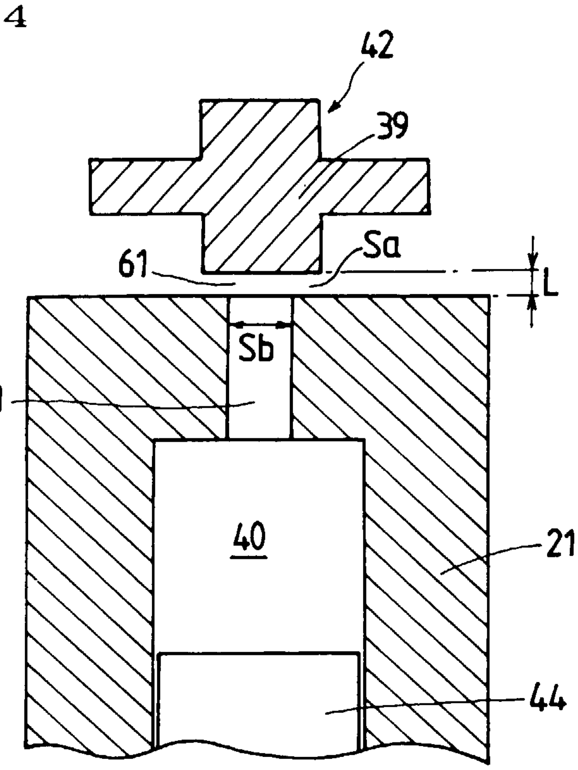
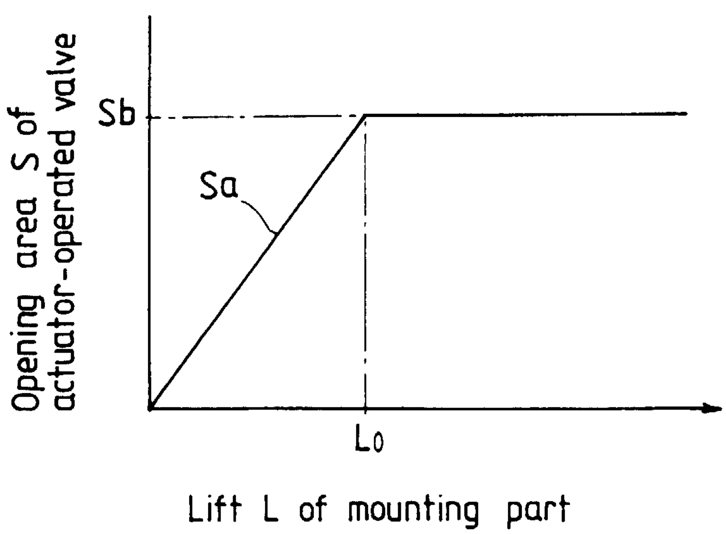
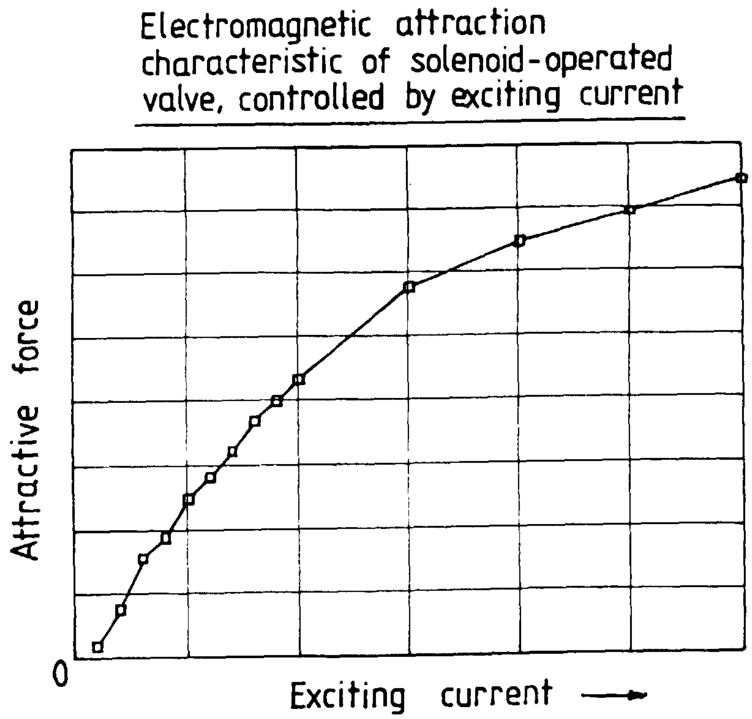

42
39
Sa
61
L
Sb
41
40
21
44

FIG. 5


Opening area S of actuator-operated valve
Sb
Sa
L0
Lift L of mounting part

F I G. 6


Electromagnetic attraction
characteristic of solenoid-operated
valve, controlled by exciting current
Attractive force
0
Exciting current

F I G. 7

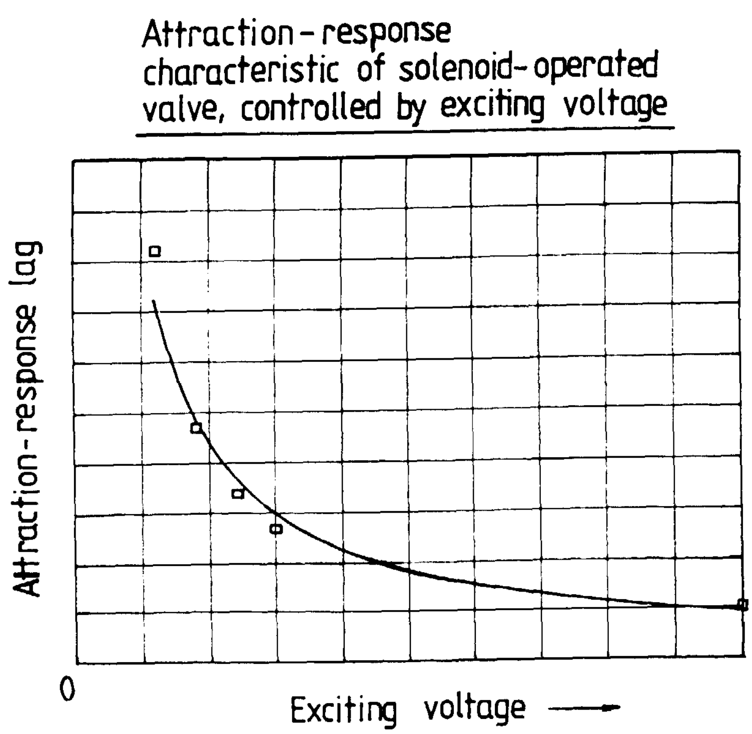
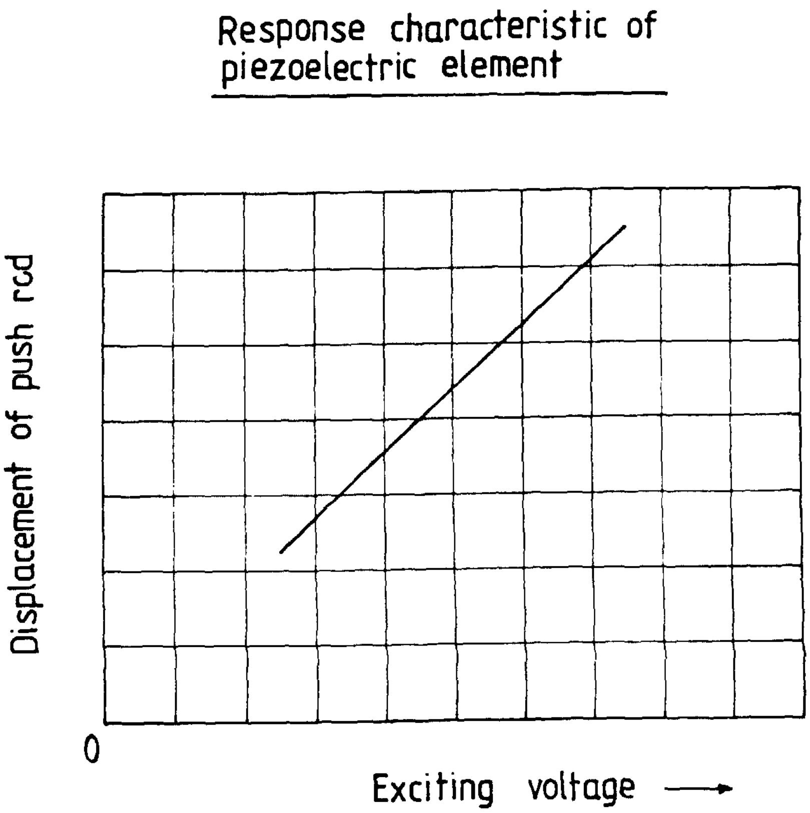
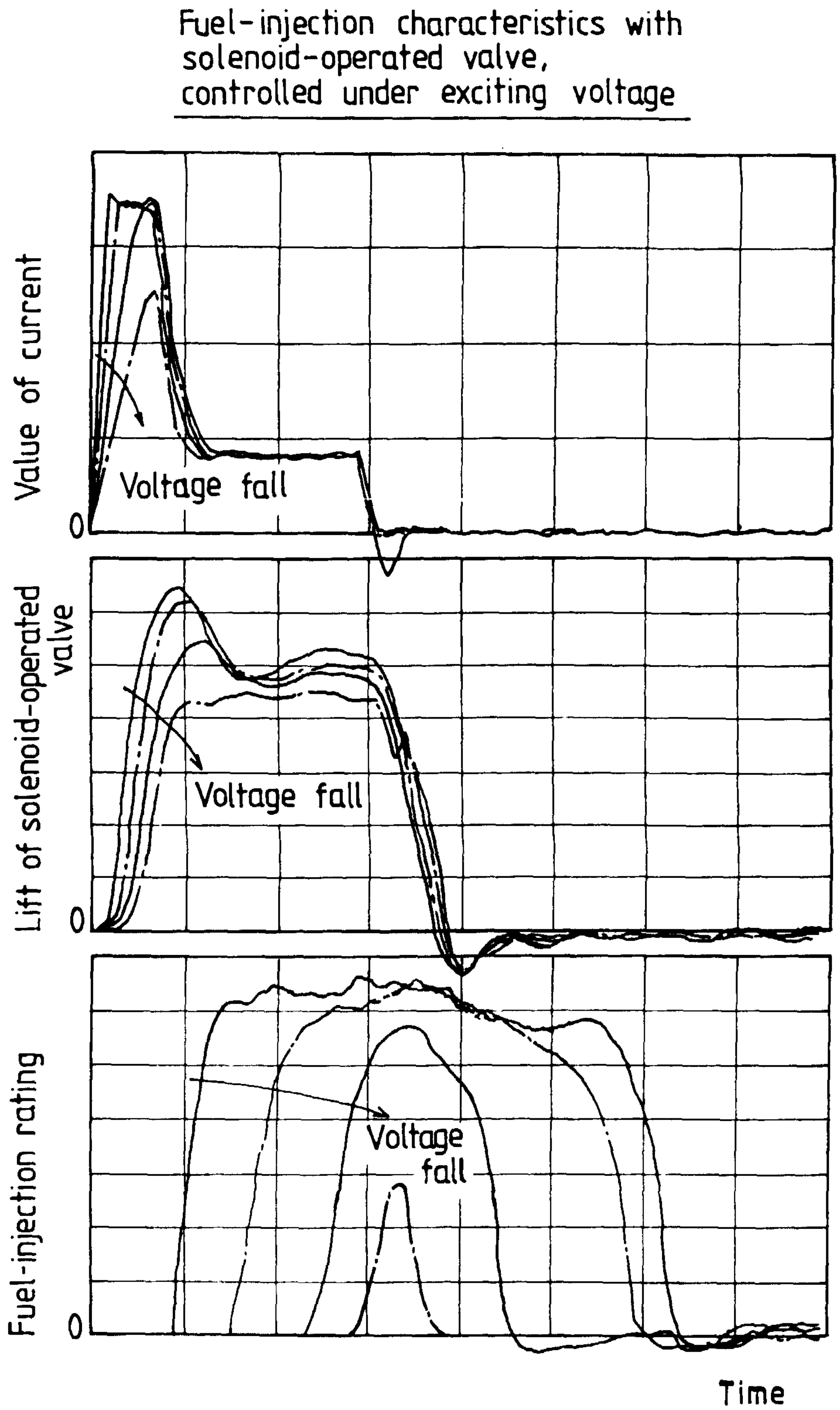

Attraction-response
characteristic of solenoid-operated
valve, controlled by exciting voltage
Attraction-response lag
0
Exciting voltage

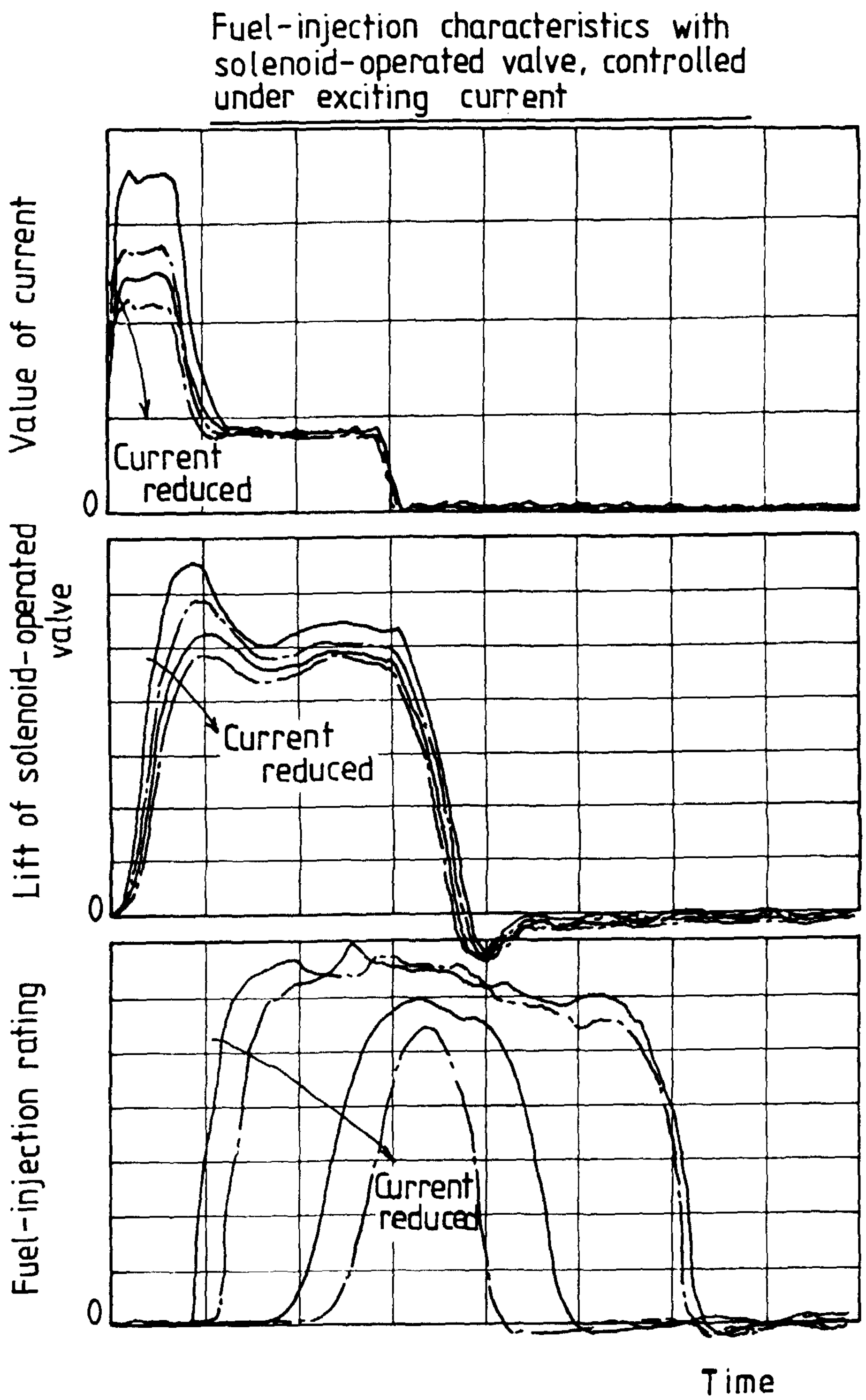
FIG. 8


Response characteristic of piezoelectric element
Displacement of push rod
0
Exciting voltage →

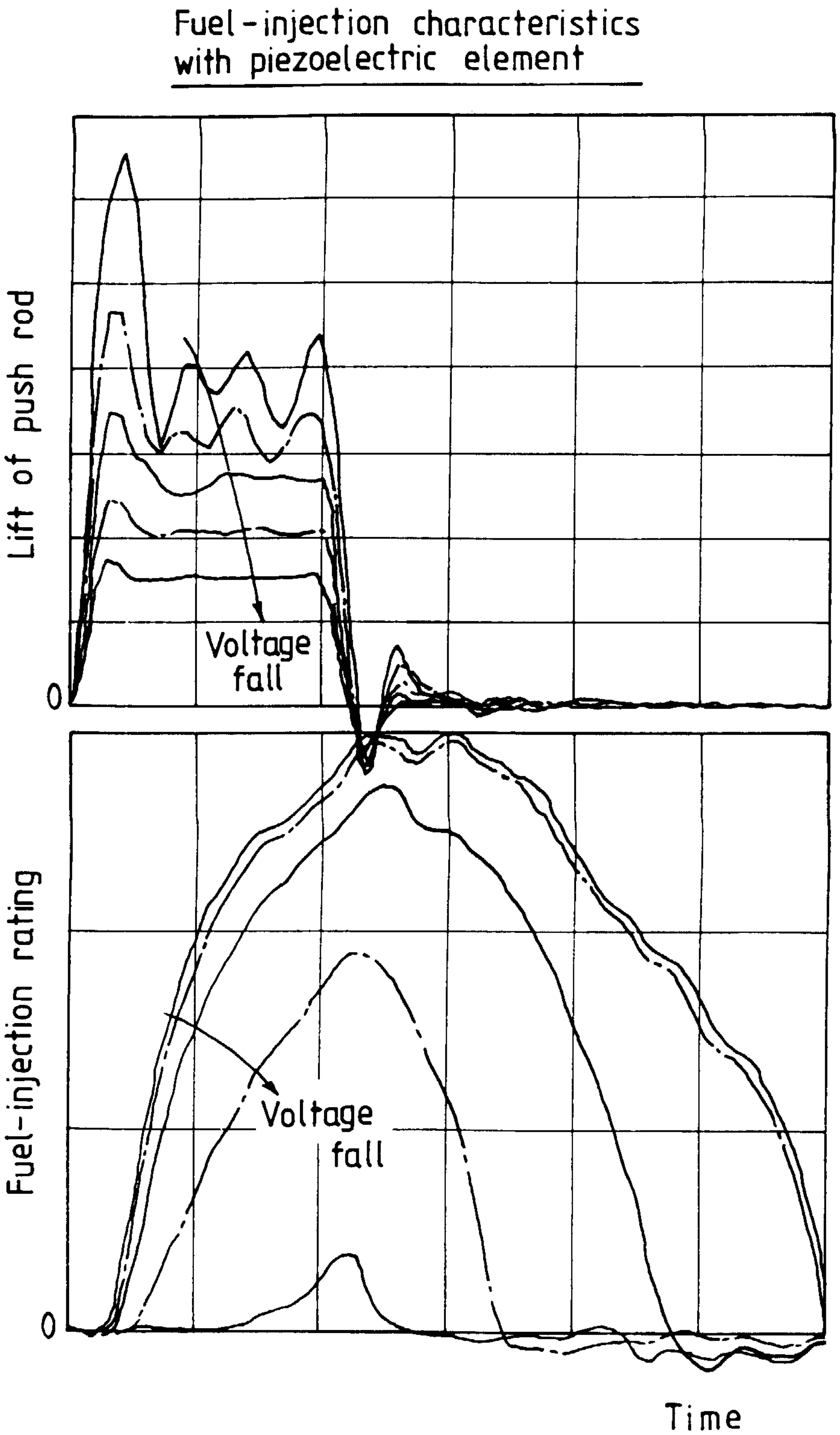
F I G. 9


Fuel-injection characteristics with solenoid-operated valve, controlled under exciting voltage
Value of current
0
Voltage fall
Lift of solenoid-operated valve
0
Voltage fall
Fuel-injection rating
0
Voltage fall
Time

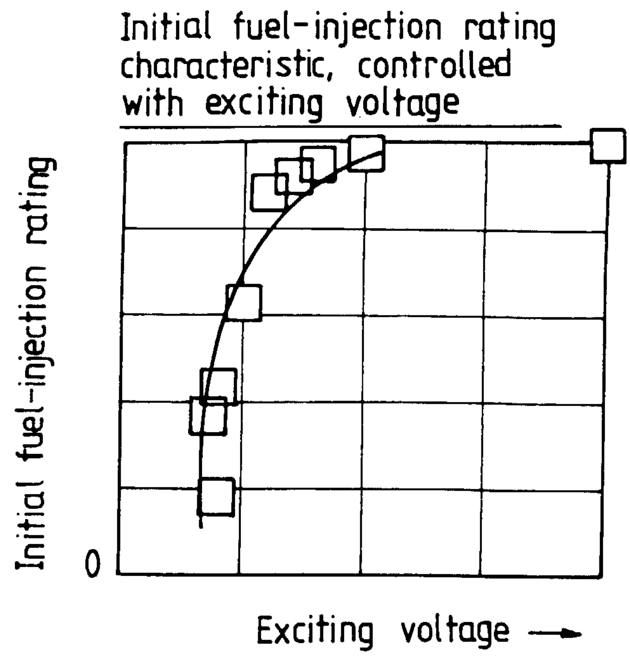
F I G. 1 0


Fuel-injection characteristics with solenoid-operated valve, controlled under exciting current
Value of current
Current reduced
0
Lift of solenoid-operated valve
Current reduced
0
Fuel-injection rating
Current reduced
0
Time

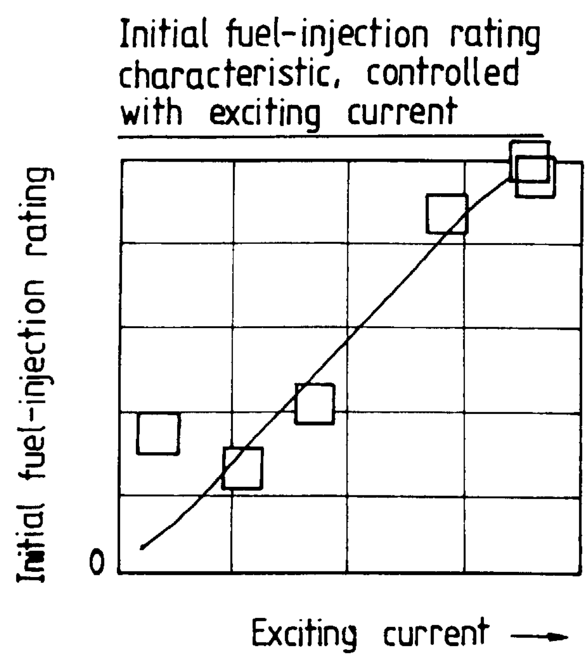
F I G. 1 1


Fuel-injection characteristics
with piezoelectric element
Lift of push rod
0
Voltage
fall
Fuel-injection rating
0
Voltage
fall
Time

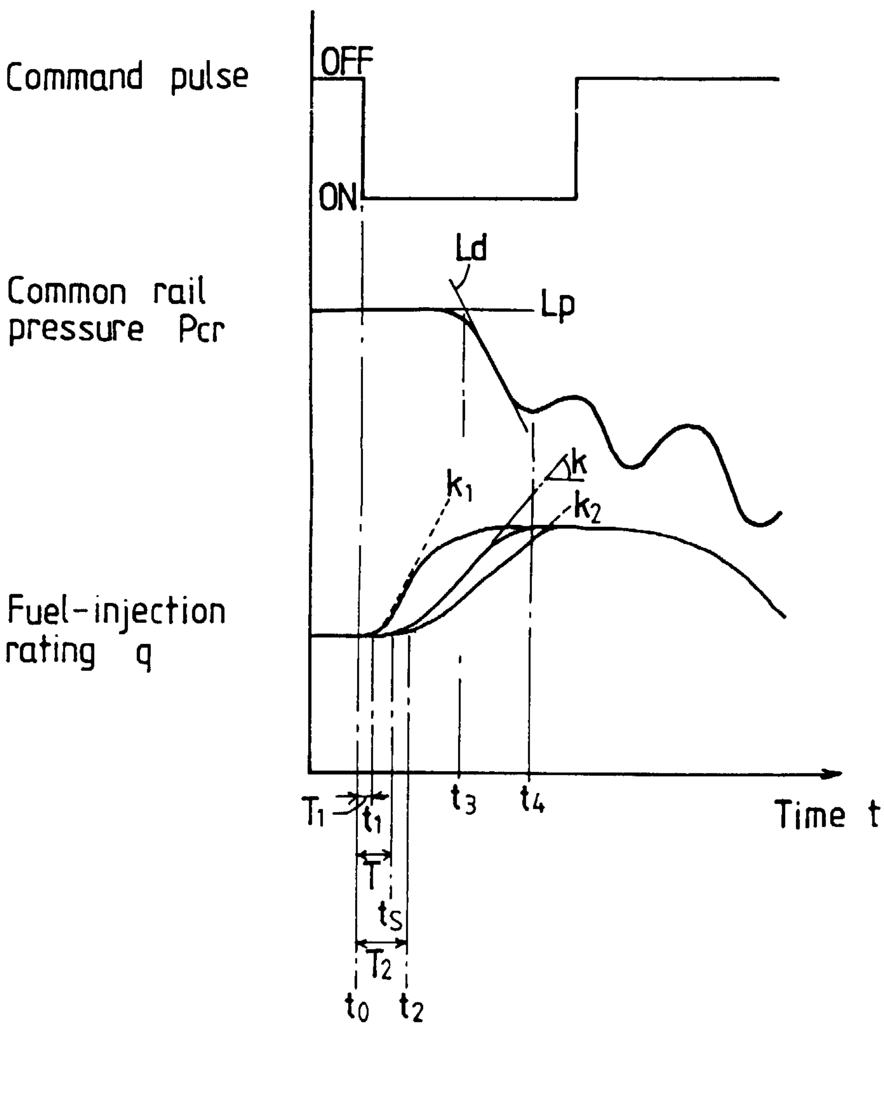
F I G. 1 2


Initial fuel-injection rating characteristic, controlled with exciting voltage
Initial fuel-injection rating
0
Exciting voltage →

F I G. 1 3


Initial fuel-injection rating characteristic, controlled with exciting current
Initial fuel-injection rating
0
Exciting current →

F I G. 1 4


Command pulse
OFF
ON
Common rail pressure Pcr
Ld
Lp
k1
k
k2
Fuel-injection rating q
T1
t1
t3
t4
Time t
T
ts
T2
t0
t2

F I G. 1 5

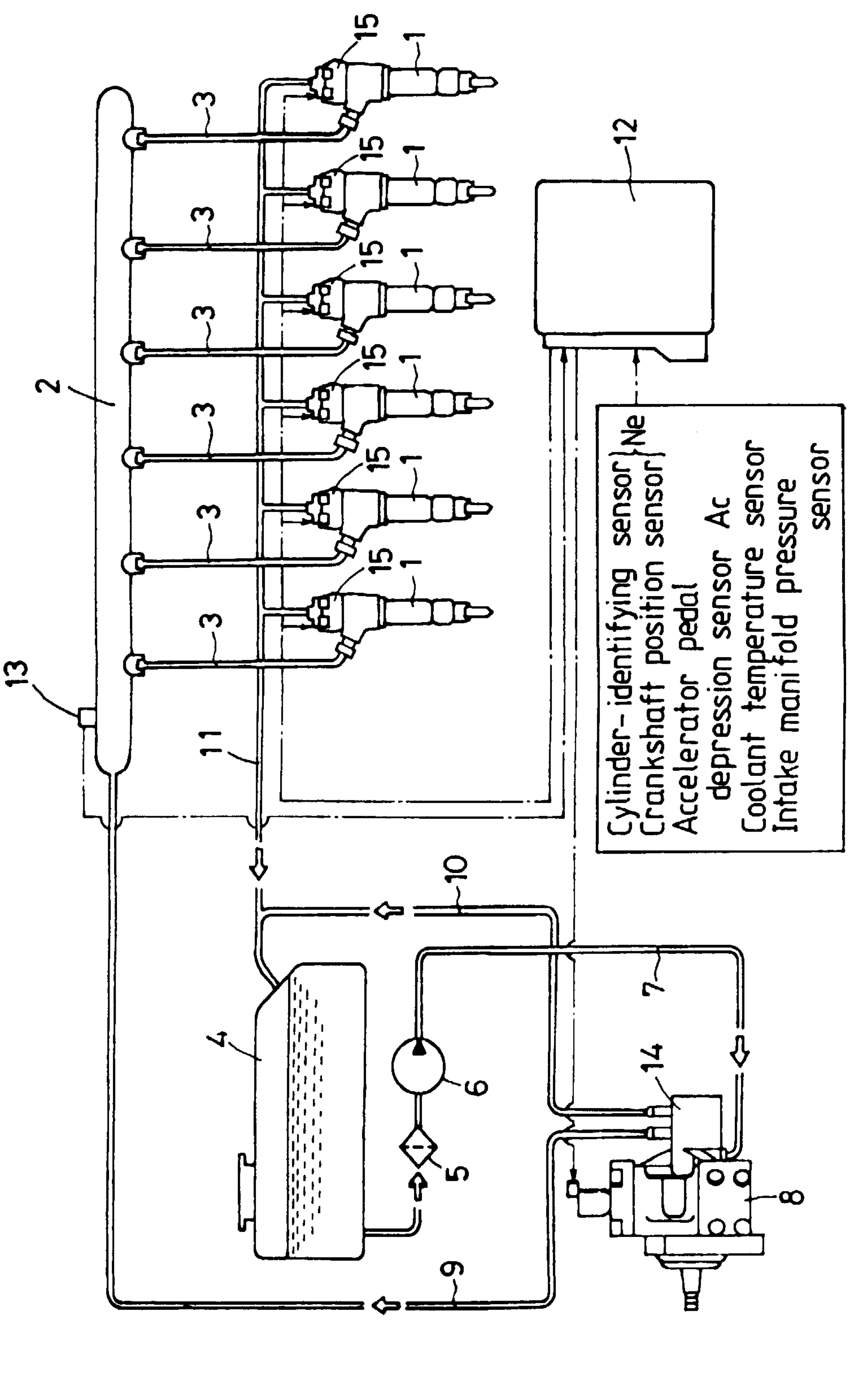
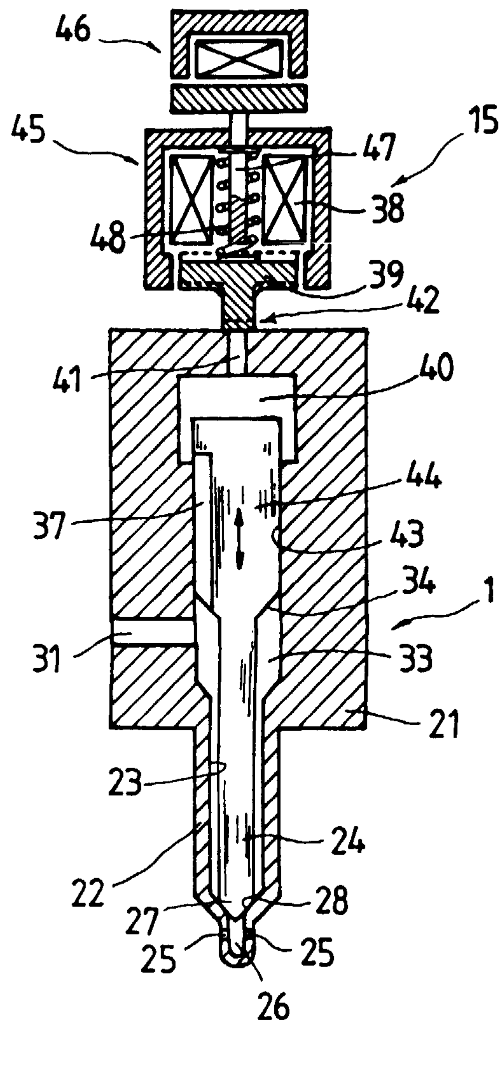

Cylinder-identifying sensor
Crankshaft position sensor
Ne
Accelerator pedal depression sensor Ac
Coolant temperature sensor
Intake manifold pressure sensor
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

FIG. 16


46
45
15
47
38
48
39
42
41
40
44
37
43
34
1
31
33
21
23
24
22
28
27
25
25
26

F I G. 1 7