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(54) **LIQUID INJECTION DEVICE**

(57) A liquid injection apparatus 10 includes an injection unit 15 having piezoelectric/electrostrictive elements; a solenoid-operated discharge valve 14 for discharging fuel under pressure into the injection unit; and an electrical control unit 30. The electrical control unit sends a solenoid valve open-close signal to the solenoid-operated discharge valve on the basis of operating conditions of an engine, whereby liquid fuel is fed under pressure to the injection unit from the solenoid-operated discharge valve. At least during periods in which the pressure of liquid in the injection unit is in the process of increasing or lowering because of generation or stoppage of the solenoid valve open-close signal, the electrical control unit activates the piezoelectric/electrostrictive elements, thereby atomizing injected fuel. When the liquid pressure in the injection unit is a constant low pressure because of disappearance of the solenoid valve open-close signal, the electrical control unit inactivates the piezoelectric/electrostrictive elements, thereby reducing electrical power consumption.

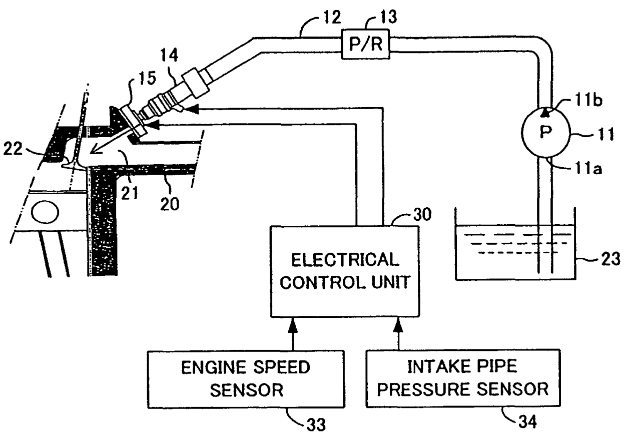

FIG.1

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Description

TECHNICAL FIELD

[0001] The present invention relates to a liquid injection apparatus for injecting liquid in atomized form into a liquid injection space.

BACKGROUND ART

[0002] Conventionally known liquid fuel injection apparatus include a fuel injection apparatus for use in an internal combustion engine. The fuel injection apparatus for use in an internal combustion engine is a so-called electrically controlled fuel injection apparatus, which is in wide use and includes a pressure pump for pressurizing liquid, and a solenoid-operated injection valve. In the electrically controlled fuel injection apparatus, fuel which is pressurized by the pressure pump is injected from an injection port of the solenoid-operated injection valve. Thus, particularly at the time of valve-opening or valve-closing operation for opening or closing the solenoid-operated injection valve, the velocity of injected liquid (injection velocity) is low. As a result, liquid droplets of injected fuel assume a large size and are not of uniform size. Such a size of liquid droplets of fuel and nonuniformity of liquid droplets of fuel increase the amount of unburnt fuel during combustion, leading to increased emission of harmful exhaust gas.

[0003] Meanwhile, conventionally, there has been proposed a liquid droplet ejection apparatus configured such that liquid contained in a liquid feed path is pressurized through operation of a piezoelectric electrostriction element so as to eject the liquid from an outlet in the form of fine liquid droplets (see, for example, Patent Document 1). Such an apparatus utilizes the principle of a conventional ink jet ejection apparatus (see, for example, Patent Document 2) and can eject finer liquid droplets (liquid droplets of injected fuel) of uniform size as compared with the above-mentioned electrically controlled fuel injection apparatus, thereby exhibiting excellent fuel atomization performance.

(Patent Document 1)
Japanese Patent Application Laid-Open (*kokai*) No. S54-90416 (p. 2, FIG. 5)
(Patent Document 2)
Japanese Patent Application Laid-Open (*kokai*) No. H06-40030 (pp. 2-3, FIG. 1)

[0004] Meanwhile, an ink jet ejection apparatus can inject fine liquid droplets as expected when used in a relatively steady atmosphere with little variation in temperature, pressure, and the like (e.g., in an office, a classroom, or a like indoor space). However, a liquid ejection apparatus which utilizes the principle of an ink jet ejection apparatus usually fails to exhibit sufficient fuel atomization performance when used under wildly fluctuating atmospheric conditions as found in an internal combustion engine, which involves fluctuating operating conditions. Under the present circumstances, there has not been provided a liquid (fuel) injection apparatus which utilizes the principle of an ink jet ejection apparatus and can inject sufficiently atomized liquid even when used in a mechanical apparatus involving wildly fluctuating atmospheric conditions as in the case of an internal combustion engine.

DISCLOSURE OF THE INVENTION

[0005] An object of the present invention is to provide a liquid injection apparatus capable of stably injecting liquid in the form of droplets of small size even when used under wildly fluctuating conditions within a liquid injection space.

[0006] The present invention provides a liquid injection apparatus comprising an injection device including a liquid discharge nozzle, a first end of the liquid discharge nozzle being exposed to a liquid injection space, a piezoelectric/electrostrictive element which is activated by a piezoelectric-element drive signal, a chamber whose volume is changed through activation of the piezoelectric/electrostrictive element and which is connected to a second end of the liquid discharge nozzle, a liquid feed path connected to the chamber, and a liquid inlet establishing communication between the liquid feed path and the exterior of the injection device; pressurizing means for pressurizing liquid; a solenoid-operated discharge valve including a solenoid-operated open-close valve which is driven by a solenoid valve open-close signal, and a discharge hole which is opened and closed by the solenoid-operated open-close valve, the solenoid-operated discharge valve receiving the liquid pressurized by the pressurizing means, and discharging the pressurized liquid into the liquid inlet of the injection device via the discharge hole when the solenoid-operated open-close valve is driven to open the discharge hole; and an electrical control unit including piezoelectric-element-drive-signal generation means for generating the piezoelectric-element drive signal and solenoid-valve-open-close-signal generation means for generating the solenoid valve open-close signal. The liquid discharged from the solenoid-operated discharge valve is atomized by means of volume change of the chamber, and injected into the liquid injection space in the form of droplets from the liquid discharge nozzle. The electrical control unit is configured in such a manner as to generate the piezoelectric-element drive signal to thereby activate the piezoelectric/electrostrictive element at least when the pressure of liquid in the liquid feed path is in the process of increasing or lowering upon generation of the solenoid valve open-close signal or stoppage of the generation of the solenoid valve open-close signal, and not to generate the piezoelectric-element drive signal when the pressure of liquid in the liquid feed path is a constant low pressure because of disappearance of the solenoid valve open-close signal.

[0007] According to the above-described configuration, liquid pressurized by the pressurizing means is discharged into the injection device from the solenoid-operated discharge valve. The liquid is atomized through volume change of the chamber of the injection device and is then injected from the liquid discharge nozzle. Since pressure required for injection of liquid into the liquid injection space is generated by the pressurizing means, even when atmospheric conditions (e.g., pressure and temperature) within the liquid injection space fluctuate wildly due to fluctuations in, for example, operating conditions of a machine to which the apparatus is applied, the liquid can be injected and fed stably in the form of expected fine droplets.

[0008] In a conventional carburetor, the flow rate of fuel (liquid) is determined according to air velocity within an intake pipe, which is a liquid droplet discharge space, and the degree of atomization varies depending on the air velocity. By contrast, the above-described liquid injection apparatus of the present invention can eject fuel (liquid) by a required amount in a well-atomized condition irrespective of air velocity. Additionally, in contrast to a conventional apparatus in which assist air is fed to a nozzle portion of a fuel injector so as to accelerate fuel atomization, the liquid injection apparatus of the present invention does not require a compressor for feeding assist air, thereby lowering costs.

[0009] Furthermore, the electrical control unit generates the piezoelectric-element drive signal to thereby activate the piezoelectric/electrostrictive element at least when the pressure of liquid in the liquid feed path is in the process of increasing because of generation of the solenoid valve open-close signal or in the process of lowering because of stoppage of generation of the solenoid valve open-close signal. Therefore, even in the case where the injection velocity of liquid is not sufficiently high to atomize the liquid sufficiently, because of the injection pressure of the liquid being relatively low at the time the pressure of the liquid is in the process of increasing or lowering, the liquid can be appropriately atomized by means of volume change of the chamber caused through activation of the piezoelectric/electrostrictive element.

[0010] The injection device is not required to perform its operation for atomizing liquid during periods in which, due to disappearance of the solenoid valve open-close signal, the pressure of liquid contained in the liquid feed path becomes the constant low pressure (a pressure that the liquid contained in the liquid feed path reaches as a result of continuation of a state in which liquid pressurized by the pressurizing means is not fed to the liquid feed path and that may vary); i.e., during periods in which liquid is not injected into the liquid injection space from the liquid discharge nozzle of the injection device. In view of the above, the electrical control unit is configured not to generate the piezoelectric-element drive signal in such a case. Thus, wasteful power consumption by the liquid injection apparatus can be avoided.

[0011] In this case, preferably, the electrical control unit is configured to start generation of the piezoelectric-element drive signal immediately before a point of time when, because of generation of the solenoid valve open-close signal, the pressure of liquid contained in the liquid feed path starts to increase from the constant low pressure.

[0012] According to the above-described configuration, at a point of time when, because of generation of the solenoid valve open-close signal, the pressure of liquid contained in the liquid feed path starts to rise; i.e., at a point of time when injection of liquid droplets from the liquid discharge nozzle of the injection device may start, the piezoelectric/electrostrictive element has already been driven by the piezoelectric-element drive signal, and thus vibration energy has already been applied to the liquid. Therefore, from the beginning of injection of the liquid, liquid droplets can be injected in a reliably atomized condition.

[0013] Also, preferably, the above-described electrical control unit is configured in such a manner as to continuously generate the piezoelectric-element drive signal up to a point of time immediately after the pressure of liquid contained in the liquid feed path lowers to the aforementioned constant low pressure as a result of stoppage of generation of the solenoid valve open-close signal.

[0014] Since, for a while after a point of time when generation of the solenoid valve open-close signal is stopped, the pressure of liquid contained in the liquid feed path is higher than the aforementioned constant low pressure, the injection of the liquid from the liquid discharge nozzle of the injection device continues. Therefore, through employment of the above-described configuration, in which generation of the piezoelectric-element drive signal is continued up to a point of time immediately after the pressure of liquid contained in the liquid feed path lowers to the aforementioned constant low pressure as a result of stoppage of generation of the solenoid valve open-close signal, the piezoelectric/electrostrictive element can be driven by the piezoelectric-element drive signal so as to apply vibration energy to the liquid during a period in which the injection of liquid droplets from the liquid discharge nozzle of the injection device continues after stoppage of generation of the solenoid valve open-close signal. As a result, even after disappearance of the solenoid valve open-close signal (until termination of injection of liquid), the liquid can be injected in a reliably atomized condition.

[0015] Meanwhile, in any of the above-described liquid injection apparatuses, the electrical control unit is preferably configured not to generate the piezoelectric-element drive signal during periods in which the pressure of liquid in the liquid feed path is a constant high pressure (which may vary slightly) because of generation of the solenoid valve open-close signal.

[0016] When the pressure of liquid in the liquid feed path increases to a sufficiently high pressure because of generation of the solenoid valve open-close signal, the velocity of liquid injected into the liquid injection space from the liquid discharge nozzle of the injection device (the injection velocity, or the travel velocity of a liquid column) becomes sufficiently high, whereby the liquid assumes the form of droplets of a relatively small size by virtue of surface tension. Therefore, in such a case, the electrical power consumption of the liquid injection apparatus can be reduced by stopping the generation of the piezoelectric-element drive signal as in the case of the above-described configuration.

[0017] Also, the electrical control unit may be configured in such a manner as to generate the piezoelectric-element drive signal, when the pressure of liquid in the liquid feed path is higher than the aforementioned constant low pressure because of generation of the solenoid valve open-close signal, and as to generate the solenoid valve open-close signal such that the pressure of liquid contained in the liquid feed path increases immediately after start of generation of the solenoid valve open-close signal and subsequently lowers gradually at a pressure change rate whose absolute value is smaller than that of a pressure change rate at the time of the increase of the liquid pressure.

[0018] According to the above-described configuration, since the pressure of liquid contained in the liquid feed path increases steeply immediately after start of generation of the solenoid valve open-close signal, injection of liquid droplets is started immediately upon generation of the solenoid valve open-close signal. Subsequently, the pressure of liquid contained in the liquid feed path continues to lower in a relatively gradual manner. Therefore, the velocity of a preceding injected liquid droplet is higher than that of a subsequent injected liquid droplet, thereby reducing the possibility that liquid droplets collide to form a liquid droplet of a greater size.

[0019] Moreover, preferably, the electrical control unit is configured to change the frequency of the piezoelectric-element drive signal in accordance with the pressure of liquid contained in the liquid feed path.

[0020] Since the pressure of liquid contained in the liquid feed path determines the velocity of liquid injected from the liquid discharge nozzle (injection velocity), the degree of atomization of liquid varies with the pressure of the liquid. Therefore, through employment of the above-described configuration, in which the frequency of the piezoelectric-element drive signal is changed according to the liquid pressure in the liquid feed path, liquid droplets of a desired size can be obtained.

[0021] In this case, preferably, the electrical control unit changes the piezoelectric-element drive signal such that the frequency of the piezoelectric-element drive signal increases with an increase in the pressure of liquid in the liquid feed path.

[0022] As the pressure of liquid in the liquid feed path increases, the velocity of liquid injected from the liquid discharge nozzle increases, and the flow rate of liquid injected from the liquid discharge nozzle increases. Therefore, through application of the piezoelectric-element drive signal whose frequency increases with the pressure of liquid in the liquid feed path, the size of liquid droplets obtained through atomization can be rendered uniform, irrespective of the liquid pressure.

[0023] Further preferably, the electrical control unit is configured in such a manner as to decrease the quantity of volume change of the chamber, caused by the piezoelectric-element drive signal, with an increase in the pressure of liquid in the liquid feed path.

[0024] As the pressure of liquid in the liquid feed path increases, the velocity of liquid injected from the liquid discharge nozzle increases. Thus, without an increase of the volume change quantity (the maximum value of volume change quantity; i.e., the maximum volume change quantity) of the chamber, injected liquid droplets assume a relatively small size by virtue of surface tension. Therefore, when the pressure of liquid in the liquid feed path is high, a reduction in volume change quantity of the chamber does not lead to an excessive increase in liquid droplet size. Thus, through employment of the above-described configuration, in which the piezoelectric-element drive signal is changed such that the volume change quantity of the chamber decreases with an increase in the pressure of liquid in the liquid feed path, the chamber volume can be prevented from changing to an unnecessarily great extent (i.e., the piezoelectric/electrostrictive element can be prevented from deforming by an unnecessarily large amount), to thereby reduce the electrical power consumption of the liquid injection apparatus.

BRIEF DESCRIPTION OF THE DRAWINGS

[0025]

FIG. 1 is a schematic diagram showing a liquid injection apparatus according to a first embodiment of the present invention and applied to an internal combustion engine.

FIG. 2 is a view showing a solenoid-operated discharge valve and an injection unit shown in FIG. 1.

FIG. 3 is an enlarged sectional view showing portions of the solenoid-operated discharge valve and the injection unit shown in FIG. 2, the portions being located near the distal end portion of the solenoid-operated discharge valve.

FIG. 4 is a plan view of the injection device shown in FIG. 2.

FIG. 5 is a sectional view of the injection device cut by a plane extending along line 1-1 of FIG. 4.

FIG. 6 is a detailed block diagram of an electrical control unit shown in FIG. 1.

FIG. 7 is a timing chart showing signals generated in the electrical control unit shown in FIG. 6.

FIG. 8 is a detailed circuit diagram of the electrical control unit shown in FIG. 6.

FIG. 9 shows a timing chart (A) showing a solenoid valve open-close signal supplied to the solenoid-operated discharge valve, a timing chart (B) showing liquid pressure in a liquid feed path, a timing chart (C) showing a piezoelectric-element drive signal to be applied to piezoelectric/electrostrictive elements, and a timing chart (D) showing timings at which the intake valve is opened.

FIG. 10 is a view showing the condition of liquid injected from the liquid injection apparatus shown in FIG. 1.

FIG. 11 is a timing chart showing the action of a liquid injection apparatus according to a second embodiment of the present invention.

FIG. 12 is a timing chart showing the action of a liquid injection apparatus according to a third embodiment of the present invention.

FIG. 13 is a timing chart showing the action of a liquid injection apparatus according to a fourth embodiment of the present invention.

FIG. 14 is a timing chart showing the action of a liquid injection apparatus according to a fifth embodiment of the present invention.

FIG. 15 a timing chart showing a piezoelectric-element drive signal, among others, in a period of time when liquid pressure in the liquid feed path is in the process of increasing in the liquid injection apparatus according to the fifth embodiment.

FIG. 16 is a timing chart showing the action of a liquid injection apparatus according to a modification of the fifth embodiment of the present invention.

BEST MODE FOR CARRYING OUT THE INVENTION

[0026] Embodiments of a liquid injection apparatus (liquid atomization apparatus, liquid feed apparatus, or liquid droplet discharge apparatus) according to the present invention will be described with reference to the drawings. FIG. 1 schematically shows the configuration of a first embodiment of a liquid injection apparatus 10 according to the present invention. The liquid injection apparatus 10 is applied to an internal combustion engine, which is a mechanical apparatus requiring atomized liquid.

[0027] The liquid injection apparatus 10 is adapted to inject atomized liquid (liquid fuel; e.g., gasoline; hereinafter may be called merely "fuel") into a liquid injection space 21 defined by an intake pipe (intake port) 20 of an internal combustion engine such that the injected atomized liquid is directed to the back surface of an intake valve 22. The liquid injection apparatus 10 includes a pressure pump (fuel pump) 11, which serves as a pressurizing means; a liquid feed pipe (fuel pipe) 12, in which the pressure pump 11 is installed; a pressure regulator 13, which is installed in the liquid feed pipe 12 on the discharge side of the pressure pump 11; a solenoid-operated discharge valve 14; an injection unit (atomization unit) 15, which includes at least a plurality of chambers having respective piezoelectric/electrostrictive elements formed on their walls and a plurality of liquid discharge nozzles in order to atomize fuel to be injected into the fuel injection space 21; and an electrical control unit 30 for sending a solenoid valve open-close signal serving as a drive signal, and a piezoelectric-element drive signal for changing the chamber volume (for activating the piezoelectric/electrostrictive elements), to the solenoid-operated discharge valve 14 and the injection unit 15, respectively.

[0028] The pressure pump 11 communicates with a bottom portion of a liquid storage tank (fuel tank) 23 and includes an introduction portion 11a, to which fuel is fed from the liquid storage tank 23, and a discharge portion 11b connected to the liquid feed pipe 12. The pressure pump 11 takes in fuel from the liquid storage tank 23 through the introduction portion 11a; pressurizes the fuel to a pressure (called "pressure pump discharge pressure") which enables injection of the fuel into the fuel injection space 21 via the pressure regulator 13, the solenoid-operated discharge valve 14, and the injection unit 15 (even when the piezoelectric/electrostrictive elements of the injection unit 15 are inactive); and discharges the pressurized fuel into the liquid feed pipe 12 from the discharge portion 11b.

[0029] Pressure in the intake pipe 20 is applied to the pressure regulator 13 through unillustrated piping. On the basis of the pressure, the pressure regulator 13 lowers (or regulates) the pressure of fuel pressurized by the pressure pump 11 such that the pressure of fuel in the liquid feed pipe 12 extending between the pressure regulator 13 and the solenoid-operated discharge valve 14 becomes a pressure (called "regulation pressure") that is higher by a predetermined pressure (a constant pressure) than the pressure in the intake pipe 20. As a result, when the solenoid-operated discharge valve 14 is opened for a predetermined time, fuel is injected into the intake pipe 20 in an amount substantially proportional to the predetermined time, irrespective of pressure in the intake pipe 20.

[0030] The solenoid-operated discharge valve 14 is a known fuel injector (solenoid-operated. open-close injection valve) which has been widely employed in an electrically controlled fuel injection apparatus of an internal combustion engine. FIG. 2 is a front view of the solenoid-operated discharge valve 14, showing a section of a distal end portion of the valve 14 cut by a plane including the centerline of the valve 14 and a section of the injection unit 15—which is fixedly attached to the valve 14—cut by the same plane. FIG. 3 is an enlarged sectional view showing portions of the solenoid-operated discharge valve 14 and the injection unit 15 shown in FIG. 2, the portions being located near the distal end portion of the solenoid-operated discharge valve 14.

[0031] As shown in FIG. 2, the solenoid-operated discharge valve 14 includes a liquid introduction port 14a, to which the liquid feed pipe 12 is connected; an external tube portion 14c, which defines a fuel path 14b communicating with the liquid introduction port 14a; a needle valve 14d, which serves as a solenoid-operated open-close valve; and an unillustrated solenoid mechanism for driving the needle valve 14d. As shown in FIG. 3, a conical valve seat portion 14c-1—which assumes a shape similar to that of a distal end portion of the needle valve 14d—is provided at a center portion of the distal end of the external tube portion 14c; and a plurality of discharge holes (through-holes) 14c-2—which establish communication between the interior (i.e., the fuel path 14b) of the external tube portion 14c and the exterior of the external tube portion 14c—are provided in the vicinity of an apex (a distal end portion) of the valve seat portion 14c-1. The discharge holes 14c-2 are inclined by an angle θ with respect to an axis CL of the needle valve 14d (solenoid-operated discharge valve 14). Notably, the view is not shown, but when the external tube portion 14c is viewed along the axis CL, the plurality of discharge holes 14c-2 are arranged at uniform circumferential intervals.

[0032] Through employment of the above configuration, the solenoid-operated discharge valve 14 functions in the following manner: the needle valve 14d is driven by the solenoid mechanism so as to open the discharge holes 14c-2, whereby the fuel contained in the fuel path 14b is discharged (injected) via the discharge holes 14c-2. This state is represented as "the solenoid-operated discharge valve 14 is opened." The state in which the needle valve 14d closes the discharge holes 14c-2 is represented as "the solenoid-operated discharge valve 14 is closed." Since the discharge holes 14-2c are inclined with respect to the axis CL of the needle valve 14d, fuel discharged as mentioned above is injected in such a manner as to spread out (in a cone shape) along the side surface of a cone whose centerline coincides with the axis CL.

[0033] As shown in FIG. 2, the injection unit 15 includes an injection device 15A, an injection device fixation plate 15B, a retaining unit 15C for retaining the injection device fixation plate 15B, and a sleeve 15D for fixing the distal end of the solenoid-operated discharge valve 14.

[0034] As shown in FIG. 4, a plan view showing the injection device 15A, and FIG. 5, a sectional view of the injection device 15A cut by a plane extending along line 1-1 of FIG. 4, the injection device 15A assumes the shape of a substantially rectangular parallelepiped whose sides extend in parallel with mutually orthogonal X-, Y-, and Z-axes, and includes a plurality of ceramic thin-plate members (hereinafter called "ceramic sheets") 15a to 15f, which are sequentially arranged in layers and joined under pressure; and a plurality of piezoelectric/electrostrictive elements 15g fixedly attached to the outer surface (a plane extending along the X-Y plane and located toward the positive side along the Z-axis) of the ceramic sheet 15f. The interior of the injection device 15A includes a liquid feed path 15-1; a plurality of (herein seven per row, 14 in total) mutually independent chambers 15-2; a plurality of liquid introduction holes 15-3 for establishing communication between the chambers 15-2 and the liquid feed path 15-1; a plurality of liquid discharge nozzles 15-4, one end of each of the liquid discharge nozzles 15-4 being substantially exposed to the liquid injection space 21 so as to establish communication between the chambers 15-2 and the exterior of the injection device 15A; and a liquid inlet 15-5.

[0035] The liquid feed path 15-1 is a space defined by the side wall surface of an oblong cutout which is formed in the ceramic sheet 15c and whose major and minor axes extend along the X- and Y-axis, respectively; the upper surface of the ceramic sheet 15b; and the lower surface of the ceramic sheet 15d.

[0036] Each of the chambers 15-2 is an elongated space (a longitudinally extending liquid flow path portion) defined by the side wall surface of an oblong cutout formed in the ceramic sheet 15e and having major and minor axes extending along the direction of the Y-axis and the direction of the X-axis, respectively, the upper surface of the ceramic sheet 15d, and the lower surface of the ceramic sheet 15f. One end portion with respect to the direction of the Y axis of each of the chambers 15-2 extends to a position located above the liquid feed path 15-1, whereby each of the chambers 15-2 communicates, at the position corresponding to the one end portion, with the liquid feed path 15-1 via the cylindrical liquid introduction hole 15-3 having diameter d and formed in the ceramic sheet 15d. Hereinafter, the diameter d may be called merely "introduction hole diameter d." The other end portion with respect to the direction of the Y axis of each of the chambers 15-2 is connected to the other end of the corresponding liquid discharge nozzle 15-4. The above configuration allows liquid to flow in the chambers 15-2 (flow path portions) from the liquid introduction holes 15-3 to the side toward the liquid discharge nozzles 15-4.

[0037] Each of the liquid discharge nozzles 15-4 includes a cylindrical through-hole which is formed in the ceramic sheet 15a and has diameter D and whose one end (a liquid injection port or an opening exposed to the liquid injection space) 15-4a is substantially exposed to the liquid injection space 21; and cylindrical communication holes 15-4b to 15-4d, which are formed in the ceramic sheets 15b to 15d, respectively, such that their size (diameter) increases stepwise toward the corresponding chamber 15-2 from the liquid injection port 15-4a. The axes of the liquid discharge nozzles 15-4 are in parallel with the Z-axis. Hereinafter, the diameter D may be called merely "nozzle diameter D."

[0038] The liquid inlet 15-5 is a space defined by the side wall of a cylindrical through-hole which is formed in the ceramic sheets 15d to 15f at an end portion of the injection device 15A as viewed in the positive direction of the X-axis and at a substantially central portion of the injection device 15A as viewed along the Y-axis. The liquid inlet 15-5 is adapted to establish communication between the liquid feed path 15-1 and the exterior of the injection device 15A. The liquid inlet 15-5 is connected to an upper portion of the liquid feed path 15-1 on an imaginary plane located within the boundary plane between the ceramic sheets 15d and 15c. A portion which partially constitutes the liquid feed path 15-1 and faces the imaginary plane; i.e., a portion of the upper surface of the ceramic sheet 15b, is a plane portion in parallel with the imaginary plane.

[0039] The shape and size of the chambers 15-2 will be additionally described. Each of the chambers 15-2 assumes a substantially rectangular cross section as cut at its longitudinally (along the direction of the Y-axis) central portion (flow path portion) by a plane (X-Z plane) perpendicular to the direction of liquid flow. Major axis L (length along the Y-axis) and minor axis W (length along the X-axis, or length of a first side of the rectangle) of the elongated flow path portion are 3.5 mm and 0.35 mm, respectively. Height T (length along the Z-axis, or length of a second side perpendicular to the first side of the rectangle) of the flow path portion is 0.15 mm. In other words, in the rectangular cross-sectional shape of the flow path portion, the ratio (T/W) of the length (height T) of the second side, which is perpendicular to the first side (minor axis W) on which the piezoelectric/electrostrictive element is provided, to the length of the first side (minor axis W) is 0.15/0.35=0.43. Preferably, the ratio (T/W) is greater than zero (0) and smaller than one (1). Through selection of such a ratio (T/W), vibration energy of the piezoelectric/electrostrictive elements 15g can be efficiently transmitted to fuel contained in the corresponding chambers 15-2.

[0040] The diameter D of the liquid discharge nozzle end portion 15-4a and the diameter d of the liquid introduction hole 15-3 are 0.031 mm and 0.025 mm, respectively. In this case, preferably, cross-sectional area S1 (=W×T) of the flow path of the chamber 15-2 is greater than cross-sectional area S2 ($=\pi\cdot(D/2)^2$) of the liquid discharge nozzle end portion 15-4a and greater than cross-sectional area S3 ($=\pi\cdot(d/2)^2$) of the liquid introduction hole 15-3. Also, preferably, for atomization of liquid, the cross-sectional area S2 is greater than the cross-sectional area S3.

[0041] The piezoelectric/electrostrictive elements 15g are slightly smaller than the corresponding chambers 15-2 as viewed in plane (as viewed from the positive direction of the Z-axis); are fixed to the upper surface (a wall surface including a side of the rectangular cross-sectional shape of the flow path portion of each chamber 15-2) of the ceramic sheet 15f in such a manner as to be disposed within the corresponding chambers 15-2 as viewed in plane; and are activated (driven) in response to a piezoelectric-element drive signal DV (also called a "piezoelectric/electrostrictive-element drive signal DV") which piezoelectric-element-drive-signal generation means (circuit) of the electrical control unit 30 applies between unillustrated electrodes provided on the upper and lower surfaces of each of the piezoelectric/electrostrictive elements 15g, thereby causing deformation of the ceramic sheet 15f (upper walls of the chambers 15-2), and an associated volume change ΔV of the corresponding chambers 15-2.

[0042] The following method is employed for fabricating the ceramic sheets 15a to 15f and a laminate of the ceramic sheets 15a to 15f.

1: Ceramic green sheets are formed from zirconia powder having a particle size of 0.1 to several micrometers.

2: The ceramic green sheets are punched by use of punches and dies so as to form cutouts corresponding to those in the ceramic sheets 15a to 15e shown in FIG. 5 (cutouts corresponding to the chambers 15-2, the liquid introduction holes 15-3, the liquid feed path 15-1, the liquid discharge nozzles 15-4, and the liquid inlet 15-5 (see FIG. 4)).

3: The ceramic green sheets are arranged in layers. The resultant laminate is heated under pressure, then subjected to firing for 2 hours at 1,550°C for integration.

[0043] The piezoelectric/electrostrictive elements 15g each being sandwiched between electrodes are formed on the completed laminate of ceramic sheets at positions corresponding to the chambers 15-2. Thus is fabricated the injection device 15A. Through such fabrication of the injection device 15A in a monolithic form from zirconia ceramics, characteristics of zirconia ceramics allow the injection device 15A to maintain high durability against frequent deformation of the wall surface 15f effected by the piezoelectric/electrostrictive elements 15g; and a liquid injection device having a plurality of liquid discharge nozzles 15-4 can be implemented in such a small size of up to several centimeters in overall length and can be readily fabricated at low cost.

[0044] As shown in FIGS. 2 and 3, the thus-configured injection device 15A is fixedly attached to the injection device fixation plate 15B. The injection device fixation plate 15B assumes a rectangular shape slightly larger than the injection device 15A as viewed in plane. The injection device fixation plate 15B has unillustrated through-holes formed therein such that, when the injection device 15A is fixedly attached thereto, the through-holes face the corresponding liquid injection ports 15-4a of the injection device 15A, thereby exposing the liquid injection ports 15-4a to the exterior of the injection device 15A via the through-holes. The injection device fixation plate 15B is fixedly retained at its peripheral portion by means of the retaining unit 15C.

[0045] The retaining unit 15C assumes an external shape identical with that of the injection device fixation plate 15B as viewed in plane. As shown in FIG. 1, the retaining unit 15C is fixedly attached to the intake pipe 20 of the internal combustion engine at its peripheral portion by use of unillustrated bolts. As shown in FIG.

2, a through-hole whose diameter is slightly greater than that of the external tube portion 14c of the solenoid-operated discharge valve 14 is formed in the retaining unit 15C at a central portion thereof. The external tube portion 14c is inserted into the through-hole.

[0046] As shown in FIGS. 2 and 3, the sleeve (a closed space formation member) 15D assumes such a cylindrical shape that its inside diameter is equal to the outside diameter of the external tube portion 14c of the solenoid-operated discharge valve 14 and that its outside diameter is equal to the inside diameter of the aforementioned through-hole of the retaining unit 15C. One end of the sleeve 15D is closed, and the other end is opened. As shown in FIG. 3, an opening 15D-1 having a diameter substantially equal to that of the liquid inlet 15-5 of the injection device 15A is formed in the closed end portion of the sleeve 15D at the center thereof. An O-ring groove 15D-1 a is formed on the outer surface of the closed end portion of the sleeve 15D so as to surround an inner circumferential wall surface used to form the opening 15D-1.

[0047] The external tube portion 14c of the solenoid-operated discharge valve 14 is press-fitted into the sleeve 15D from the open end of the sleeve 15D until the external tube portion 14c abuts the inside wall surface of the closed end of the sleeve 15D. The sleeve 15D is press-fitted into the aforementioned through-hole of the retaining unit 15C. At this time, an O-ring 16 fitted into the O-ring groove 15D-1a abuts the ceramic sheet 15f of the injection device 15A.

[0048] In this manner, the solenoid-operated discharge valve 14 and the injection unit 15 are assembled together, whereby a closed cylindrical space is formed between the discharge holes 14c-2 of the solenoid-operated discharge valve 14 (a portion that can also be said to be the closed end face (the outside face of the closed end)—where the discharge holes 14c-2 are formed—of the external tube portion 14c of the solenoid-operated discharge valve 14, or a portion that can also be said to be the outside surface of a wall portion of the cylindrical external tube portion 14c where the discharge holes 14c-2 is formed) and the liquid inlet 15-5 of the injection device 15A. In this state, the axis of the opening (closed cylindrical space) 15D-1 of the sleeve 15D coincides with the axis of the liquid inlet 15-5 of the injection device 15A and with the axis CL of the needle valve 14d. As described above, the sleeve 15D is disposed between the discharge holes 14c-2 of the solenoid-operated discharge valve 14 and the liquid inlet (liquid inlet portion) 15-5 of the injection device 15A, and forms a closed cylindrical space—whose diameter is substantially equal to that of the liquid inlet 15-5 and whose axis coincides with the axis of the liquid inlet 15-5 and with the axis CL of the needle valve 14d—between the discharge holes 14c-2 and the liquid inlet 15-5.

[0049] As mentioned previously, the discharge holes 14c-2 are inclined by angle θ with respect to the axis CL of the needle valve 14d (the axis of the closed cylindrical space). Accordingly, fuel discharged from the solenoid-operated discharge valve 14 spreads out toward the injection device 15A at the angle θ with respect to the axis CL, in the opening 15D-1 (i.e., the aforementioned closed cylindrical space) of the sleeve 15D. In other words, with increasing distance from the discharge holes 14c-2 toward the liquid inlet 15-5, the distances between the axis CL of the closed cylindrical space and the paths of fuel discharged from the discharge holes 14c-2 increase.

[0050] In the present embodiment, the angle θ is determined such that the thus-discharged fuel reaches the aforementioned plane portion of the liquid feed path 15-1 (the upper surface of the ceramic sheet 15b) without reaching the inner circumferential wall surface (excluding the inner circumferential wall surface of the O-ring groove 15D-1 a) which forms the opening 15D-1 (i.e., the aforementioned closed cylindrical space) of the sleeve 15D, and without reaching a wall surface WP (represented in FIG. 3 by the double-dot-and-dash line) which is formed through imaginary extension of the inner circumferential wall surface to the plane portion of the liquid feed path 15-1.

[0051] In other words, the solenoid-operated discharge valve 14 is arranged and configured such that the discharge flow line (represented in FIG. 3 by the dot-and-dash line DL) of liquid discharged from the discharge holes 14c-2 directly intersects the plane portion of the liquid feed path 15-1 without intersecting the cylindrical side wall of the opening 15D-1 which forms the closed space of the sleeve 15D, and without intersecting the side wall WP which is formed through imaginary extension of the side wall of the opening 15D-1 to the plane portion of the liquid feed path 15-1.

[0052] Through employment of the above configuration, fuel which is discharged from the discharge holes 14c-2 of the solenoid-operated discharge valve 14 and fed into the liquid feed path 15-1 via the liquid inlet 15-5 is introduced into the chambers 15-2 via the corresponding liquid introduction holes 15-3. Vibration energy is applied to the fuel contained in the chambers 15-2, whereby the fuel is injected in the form of fine (atomized) liquid droplets into the intake pipe 20 via the liquid injection ports 15-4a of the liquid discharge nozzles 15-4 and the through-holes formed in the injection device fixation plate 15B.

[0053] As shown in FIG. 6, the electrical control unit 30 includes an electronic engine control unit 31 and an electronic fuel injection control circuit 32, which is connected to the electronic engine control unit 31.

[0054] The electronic engine control unit 31 is connected to sensors, such as an engine speed sensor 33 and an intake pipe pressure sensor 34. Receiving engine speed N and intake pipe pressure P from these sensors, the electronic engine control unit 31 determines the amount of fuel and injection start timing required for an internal combustion engine, and sends a drive voltage signal to the electronic fuel injection control circuit 32, the drive voltage signal relating to the determined amount of fuel and the injection start timing.

[0055] The electronic fuel injection control circuit 32 includes a fuel injection control microcomputer 32a, a solenoid-operated discharge valve drive circuit section 32b, and a piezoelectric/electrostrictive-element drive circuit section 32c. The fuel injection control microcomputer 32a receives the aforementioned drive voltage signal from the electronic engine control unit 31 and sends a control signal based on the received drive voltage signal to the solenoid-operated discharge valve drive circuit section 32b and the piezoelectric/electrostrictive-element drive circuit section 32c.

[0056] As shown in the timing chart of FIG. 7, the solenoid-operated discharge valve drive circuit section 32b outputs a solenoid valve open-close signal INJ of rectangular wave to an unillustrated solenoid mechanism of the solenoid-operated discharge valve 14. Upon generation of the solenoid valve open-close signal INJ (i.e., when the solenoid valve open-close signal becomes a high-level signal (valve opening signal)), the needle valve 14d of the solenoid-operated discharge valve 14 is moved to open the discharge holes 14c-2, and thus fuel is discharged into the liquid feed path 15-1 from the solenoid-operated discharge valve 14 via the liquid inlet 15-5 of the injection device 15A. By contrast, when generation of the solenoid valve open-close signal INJ is stopped (i.e., when the solenoid valve open-close signal becomes a low-level signal (valve closing signal)), the needle valve 14d closes the discharge holes 14c-2, and thus discharge of fuel into the liquid feed path 15-1 is stopped.

[0057] As shown in FIG. 7, the piezoelectric/electrostrictive-element drive circuit section 32c applies the piezoelectric-element drive signal DV of frequency f (period T=1/f) between unillustrated electrodes of each of the piezoelectric/electrostrictive elements 15g on the basis of a control signal from the fuel injection control microcomputer 32a. The piezoelectric-element drive signal DV has such a waveform as to increase steeply from 0 (V) to a predetermined maximum electric potential Vmax (V), subsequently maintain the maximum electric potential Vmax for only a short period of time, and then decrease steeply toward 0 (V).

[0058] The drive frequency f of the piezoelectric-element drive signal DV is set to a frequency; for example, near 50 kHz, equal to the resonance frequency (natural frequency) of the injection device 15A, which depends on the structure of the chambers 15-2, the structure of the liquid discharge nozzles 15-4, the nozzle diameter D, the introduction hole diameter d, the shape of a portion of each of the piezoelectric/electrostrictive elements 15g which causes deformation of the ceramic sheet 15f, liquid to be used, and the like.

[0059] When a state in which the solenoid valve open-close signal INJ is generated (the solenoid valve open-close signal INJ assumes a high level) continues, the pressure of liquid contained in the liquid feed path 15-1 converges to a constant high pressure, whereby injection of liquid from the liquid discharge nozzles 15-4 continues. When a state in which the solenoid-operated open-close signal INJ is not generated (the solenoid valve open-close signal INJ assumes a low level) continues, the pressure of liquid contained in the liquid feed path 15-1 converges to a constant low pressure. At this time, liquid is not injected from the liquid discharge nozzles 15-4.

[0060] The configuration and action of the above-described solenoid-operated discharge valve drive circuit section 32b and those of the above-described piezoelectric/electrostrictive-element drive circuit section 32c will next be described in detail with reference to FIG. 7 and FIG. 8, which shows electric circuit diagrams of these circuit sections.

[0061] As shown in FIG. 8, the solenoid-operated discharge valve drive circuit section 32b includes two Schmitt trigger circuits ST1 and ST2; three field effect transistors (MOS FETs) MS1 to MS3; a plurality of resistors RST1, RST2, and RS1 to RS4; and one capacitor CS. Among these resistors, the resistors RST1 and RST2 are output current limiting resistors for the Schmitt trigger circuits ST1 and ST2, respectively.

[0062] As shown in FIG. 7, when the electronic engine control unit 31 outputs the drive voltage signal INJ, which changes from a low level to a high level, to the fuel injection control microcomputer 32a, the fuel injection control microcomputer 32a outputs to the Schmitt trigger circuit ST1 a signal (not shown) which changes from a high level to a low level. Also, the fuel injection control microcomputer 32a outputs to the Schmitt trigger circuit ST2 a signal (not shown) which changes from a low level to a high level.

[0063] This causes the Schmitt trigger circuit ST1 to output a high-level signal. Accordingly, the field effect transistor MS3 turns ON (becomes electrically conductive). As a result, the field effect transistor MS1 also turns ON. Since the Schmitt trigger circuit ST2 outputs a low-level signal, the field effect transistor MS2 turns OFF (becomes electrically nonconductive).

[0064] This causes the power supply voltage VP1 to be applied to the capacitor CS and the solenoid-operated discharge valve 14 (the solenoid mechanism thereof), and thus the capacitor CS is charged. At this time, current flows to the solenoid-operated discharge valve 14, and after the elapse of time Td—which is a predetermined delay time (a so-called ineffective injection time) stemming from an inductor component—the needle valve 14d starts to move. As a result, discharge of liquid into the liquid feed path 15-1 from the solenoid-operated discharge valve 14 starts, so that the liquid pressure in the liquid feed path 15-1 starts to rise from a constant low pressure.

[0065] Meanwhile, when the electronic engine control unit 31 sends to the fuel injection control microcomputer 32a the drive voltage signal INJ which changes from a high level to a low level, the fuel injection control microcomputer 32a outputs to the Schmitt trigger circuit ST1 a signal (not shown) which changes from a low level to a high level. Also, the fuel injection control microcomputer 32a outputs to the Schmitt trigger circuit ST2 a signal (not shown) which changes from a high level to a low level.

[0066] This causes the Schmitt trigger circuit ST1 to output a low-level signal. Accordingly, the field effect transistor MS3 turns OFF, and thus the field effect transistor MS1 turns OFF. Also, since the Schmitt trigger circuit ST2 outputs a high-level signal, the field effect transistor MS2 turns ON. As a result, the power supply voltage VP1 is not applied to the capacitor CS and the solenoid-operated discharge valve 14 (the solenoid mechanism thereof); and the capacitor CS is grounded via the field effect transistor MS2, whereby charges stored in the capacitor CS are discharged. Thus, application of electricity to the solenoid-operated discharge valve 14 is stopped, and, after the elapse of a predetermined time after the field effect transistor MS2 has been turned ON, the needle valve 14d starts to move toward the initial position. Accordingly, the amount of liquid discharged into the liquid feed path 15-1 from the solenoid-operated discharge valve 14 decreases; as a result, liquid pressure in the liquid feed path 15-1 lowers toward the aforementioned constant low pressure from the aforementioned constant high pressure.

[0067] The above is the action of the solenoid-operated discharge valve drive circuit section 32b. Notably, the capacitor CS functions to maintain voltage to be applied to the solenoid mechanism of the solenoid-operated discharge valve 14 when the power supply voltage VP1 is applied to the solenoid mechanism. Next, the piezoelectric/electrostrictive-element drive circuit section 32c will be described.

[0068] As shown in FIG. 8, the piezoelectric/electrostrictive-element drive circuit section 32c includes two Schmitt trigger circuits ST11 and ST12; three field effect transistors (MOS FETs) MS11 to MS13; a plurality of resistors RST11, RST12, and RS11 to RS14; and two coils L1 and L2. Among these resistors, the resistors RST11 and RST12 are output current limiting resistors for the Schmitt trigger circuits ST11 and ST12, respectively.

[0069] As shown in FIG. 7, when the electronic engine control unit 31 outputs to the fuel injection control microcomputer 32a a signal which changes from a low level to a high level, on the basis of this signal, the fuel injection control microcomputer 32a outputs, as a control signal (not shown), a pulse of a constant width (a rectangular wave formed such that voltage drops to 0 (V) from a constant voltage, is then maintained at 0 (V) for a predetermined period of time, and is subsequently restored to the constant voltage) to the Schmitt trigger circuit ST11 every elapse of period T (frequency f=1/T). The fuel injection control microcomputer 32a outputs a similar pulse, as a control signal, to the Schmitt trigger circuit ST12 in such a manner as to slightly lag the control signal sent to the Schmitt trigger circuit ST11.

[0070] When a pulse is input to the Schmitt trigger circuit ST11, the Schmitt trigger circuit ST11 outputs a high-level signal. Accordingly, the field effect transistor MS13 turns ON; as a result, the field effect transistor MS11 also turns ON. At this point of time, the Schmitt trigger circuit ST12 outputs a low-level signal; thus, the field effect transistor MS12 remains OFF. Therefore, since the power supply voltage VP2 is applied to the piezoelectric/electrostrictive elements 15g via the coil L1 and the resistor RS11, the piezoelectric/electrostrictive elements 15g cause deformation of the ceramic sheet 15f, whereby the corresponding chambers 15-2 decrease in volume.

[0071] Subsequently, the pulse input to the Schmitt trigger circuit ST11 disappears. This causes the Schmitt trigger circuit ST11 to output a low-level signal, and thus the field effect transistors MS13 and MS11 turn OFF. Even at this point of time, no pulse is input to the Schmitt trigger circuit ST12. Therefore, the Schmitt trigger circuit ST12 outputs a low-level signal, and thus the field effect transistor MS12 remains OFF. As a result, the piezoelectric/electrostrictive elements 15g retain stored charges, whereby the electric potential between electrodes of each of the piezoelectric/electrostrictive elements 15g is maintained at the maximum value Vmax.

[0072] Subsequently, the fuel injection control microcomputer 32a inputs the aforementioned pulse to the Schmitt trigger circuit ST12 only. This causes the Schmitt trigger circuit ST12 to output a high-level signal, and thus the field effect transistor MS12 turns ON. As a result, the piezoelectric/electrostrictive elements 15g are grounded via the resistor RS12, the coil L2, and the field effect transistor MS12, whereby charges stored in the piezoelectric/electrostrictive elements 15g are discharged. Thus, the piezoelectric/electrostrictive elements 15g begin to be restored to their initial shape, whereby the corresponding chambers 15-2 increase in volume.

[0073] As mentioned previously, such an action is repeated every elapse of the period T (frequency f=1/T), whereby vibration energy is transmitted to liquid contained in the chambers 15-2. The above is the action of the piezoelectric/electrostrictive-element drive circuit section 32c.

[0074] Notably, herein the expression "to generate the solenoid valve open-close signal INJ" means applying the power supply voltage VP1 to the solenoid-operated valve 14 via the field effect transistor MS1 and the like; and the expression "to stop generation of the solenoid valve open-close signal INJ" means stopping application of the power supply voltage VP1 to the solenoid-operated valve 14. The expression "to generate the piezoelectric-element drive signal DV" means performing charge and discharge of the piezoelectric/electrostrictive elements 15g at the above-mentioned frequency f (period T); and the expression "to stop generation of the piezoelectric-element drive signal DV" means stopping the above-described charge and discharge repeatedly performed on the piezoelectric/electrostrictive elements 15g (i.e., it means starting continuous grounding of the piezoelectric/electrostrictive elements 15g via the field effect transistor MS12).

[0075] Next, the action of the liquid injection apparatus 10 having the above-described configuration will be described with reference to the timing chart of FIG. 9. On the basis of engine operation conditions, such as engine speed N and intake pipe pressure P, the electronic engine control unit 31 determines time (fuel discharge time Tfuel) during which the solenoid-operated discharge valve 14 is opened. Further, the electronic engine control unit 31 determines a timing (valve opening timing) at which the solenoid-operated discharge valve 14 is caused to start opening. Here, time t2 of FIG. 9 is assumed to be a valve opening timing in the present cycle.

[0076] At time t0, which occurs a predetermined time before time t1, which in turn occurs a slight time (a so-called ineffective injection time Td, which is a delay time stemming from inductance of the solenoid mechanism of the solenoid-operated discharge valve 14) before time t2, the electronic engine control unit 31 sends to the fuel injection control microcomputer 32a a signal which instructs start of activation of the piezoelectric/electrostrictive elements 15g. Further, when time t1 is reached, the electronic engine control unit 31 sends a drive voltage signal to the fuel injection control microcomputer 32a until elapse, from time t1, of a time corresponding to the sum of the ineffective injection time Td and the fuel discharge time Tfuel determined as described above.

[0077] Upon reception of the signal which instructs start of activation of the piezoelectric/electrostrictive elements 15g, the fuel injection control microcomputer 32a sends a control signal to the piezoelectric/electrostrictive-element drive circuit section 32c and causes the drive circuit section 32c to apply, from time t0, the piezoelectric-element drive signal DV of frequency f between the electrodes of each of the piezoelectric/electrostrictive elements 15g. Further, upon reception of the drive voltage signal, the fuel injection control microcomputer 32a sends a control signal to the solenoid-operated discharge valve drive circuit section 32b. As a result, the solenoid-operated discharge valve drive circuit section 32b generates the solenoid valve open-close signal INJ (a high-level signal) to the solenoid-operated discharge valve 14 from time t1.

[0078] When time t2, which is slightly later than time t1, is reached (that is, upon elapse of the ineffective injection time Td of the solenoid-operated discharge valve 14), the needle valve 14d is moved, whereby the discharge holes 14c-2 are opened (that is, the solenoid-operated discharge valve 14 is opened). This causes start of discharge/feed of fuel contained in the fuel path 14b into the liquid feed path 15-1 of the injection device 15A from the discharge holes 14c-2 via the closed cylindrical space of the sleeve 15D and the liquid inlet 15-5 of the injection device 15A. As a result, as shown in FIG. 9(B), the pressure of liquid contained in the liquid feed path 15-1 starts to rise.

[0079] When, after time t2, the pressure of fuel contained in the chambers 15-2 has increased to a sufficient level (level sufficient for injection of fuel into the liquid injection space 21), as shown in FIG. 10, fuel is extruded (injected) from the end face of each of the liquid injection ports 15-4a toward the liquid injection space 21 in the intake pipè 20. At this time, since vibration energy induced by the activation of the piezoelectric/electrostrictive elements 15g is applied to fuel contained in the corresponding chambers 15-2, constricted portions are formed on the fuel which is extruded toward the liquid injection space 21 from the end face of each of the liquid injection ports 15-4a. Thus, a leading end portion of the fuel leaves the remaining portion of the fuel while being torn off at its constricted portion. As a result, uniformly and finely atomized fuel is injected into the intake pipe 20.

[0080] As described above, the electrical control unit 30 starts generation of the piezoelectric-element drive signal DV at time t0, which is immediately before time t2 at which the pressure of liquid in the liquid feed path 15-1 starts to increase from the aforementioned constant low pressure upon generation of the solenoid valve open-close signal INJ.

[0081] Accordingly, at a point of time at which injection of liquid from the liquid discharge nozzles 15-4 of the injection device 15A is likely to start, vibration energy has already been applied to liquid through drive of the respective piezoelectric/electrostrictive elements 15g by means of the piezoelectric-element drive signal DV. As a result, atomized liquid droplets can be injected, without fail, from the beginning of injection of liquid.

[0082] Upon elapse from time t1 of the time corresponding to the sum of the ineffective injection time Td and the fuel discharge time Tfuel, and when time t3 is reached, at which the drive voltage signal from the electronic engine control unit 31 disappears, the fuel injection control microcomputer 32a again sends a control signal to the solenoid-operated discharge valve drive circuit section 32b so as to cause the same to stop the generation of the solenoid valve open-close signal INJ.

[0083] The fuel injection control microcomputer 32a continues application of the piezoelectric-element drive signal DV to the piezoelectric/electrostrictive elements 15g up to time t4 (time t4 immediately after time t3), which occurs a predetermined time after time t3 and by which the pressure of liquid in the liquid feed path 15-1 decreases to the aforementioned constant low pressure, which is the stationary pressure during periods in which the solenoid-operated discharge valve 14 is closed. The fuel injection control microcomputer 32a stops the generation of the piezoelectric-element drive signal DV at time t4.

[0084] As described above, the electrical control unit 30 continues the generation of the piezoelectric-element drive signal DV up to time t4, immediately after the pressure of liquid in the liquid feed path 15-1 has lowered to the aforementioned constant low pressure because of stoppage of the generation of the solenoid valve open-close signal INJ.

[0085] For a period of time after time t3, at which the generation of the solenoid valve open-close signal INJ was stopped, the pressure of liquid in the liquid feed path 15-1 is higher than the aforementioned constant low pressure, and thus injection of liquid from the liquid discharge nozzles 15-4 of the injection device 15A continues. Therefore, the generation of the piezoelectric-element drive signal DV is continued up to time t4, which is immediately after the pressure of liquid in the liquid feed path 15-1 has lowered to the aforementioned constant low pressure because of stoppage of the generation of the solenoid valve open-close signal INJ.

[0086] By virtue of the above-described operation, in a period after time t3, at which the generation of the solenoid valve open-close signal INJ was stopped, the drive of the piezoelectric/electrostrictive elements 15g by means of the piezoelectric-element drive signal DV is continued until injection of liquid from the liquid discharge nozzles 15-4 of the injection device 15A ends, whereby vibration energy can be applied to the liquid during that period. As a result, liquid can be atomized and injected, without fail, until injection of the liquid into the liquid injection space 21 ends, even after disappearance (after stoppage of generation) of the solenoid valve open-close signal INJ.

[0087] Notably, preferably, in the above-described embodiment, when Q (cc/min) represents the amount of liquid to be discharged per unit time (discharge flow rate) from the solenoid-operated discharge valve 14, and V (cc) represents the volume of a liquid path formed between the solenoid-operated discharge valve 14 and the distal ends of the discharge nozzles 15-4 of the injection device 15A, their ratio (V/Q) is 0.03 or less.

[0088] Herein, the volume V is the sum total of the volume of the closed cylindrical space of the sleeve 15D, the volume of the liquid inlet 15-5, the volume of the liquid feed path 15-1, the volume of the chambers 15-2, the volume of the liquid introduction holes 15-3, and the volume of the liquid discharge nozzles 15-4.

[0089] Also, preferably, a time when the solenoid valve open-close signal INJ assumes a high level is set in such a manner as to only fall within a time when the intake valve 22 of the internal combustion engine is opened, as shown in FIG. 9. Through employment of this feature, when fuel injected from the liquid injection apparatus 10 reaches the intake valve 22, the intake valve 22 is open, whereby the fuel can be taken directly into a cylinder without adhesion to, for example, the back surface of the intake valve 22, and the fuel injected in an atomized condition is taken directly into the cylinder. Since the injected fuel does not adhere to the intake valve 22 and the wall surface of the intake pipe 20, the fuel economy of the internal combustion engine can be enhanced, and the amount of an unburnt gas contained in exhaust can be reduced.

[0090] Notably, preferably, the velocity of fuel injected in an atomized condition from the liquid discharge nozzles 15-4 (the velocity of liquid droplets or atomized droplets) is varied according to the amount of lift of the intake valve 22 and/or the intake air velocity (wind velocity) within the intake pipe. By virtue of this, fuel injected in an atomized condition is taken directly into each cylinder, and adhesion of fuel to the wall surface of the cylinder is prevented more reliably. The velocity of fuel injected in an atomized condition from the liquid discharge nozzles 15-4 can be changed through changing the waveform of the piezoelectric-element drive signal DV applied to the piezoelectric/electrostrictive elements 15g (in particular, the rising speed or the highest voltage of the piezoelectric-element drive signal DV), or changing the pressure of fuel (fuel pressure) to be fed to the solenoid-operated discharge valve 14. The fuel pressure can be changed through changing the regulation pressure of the pressure regulator 13, or when the pressure regulator 13 is not provided, the fuel pressure can be changed through changing the discharge pressure of the pressure pump.

[0091] Next, a liquid injection apparatus 10 according to a second embodiment of the present invention will be described. The liquid injection apparatus 10 according to the second embodiment differs from the liquid injection apparatus 10 according to the first embodiment only in a pattern for generating the solenoid valve open-close signal INJ and the piezoelectric-element drive signal DV. Thus, while the main focus is placed on the above point of difference, the second embodiment will next be described with reference to the timing chart of FIG. 11.

[0092] In the second embodiment, during periods in which the liquid contained in the liquid feed path 15-1 stably has the aforementioned constant high pressure as a result of opening of the solenoid-operated discharge valve 14 (in a period between t13 to t15 in FIG. 11), the activation of the piezoelectric/electrostrictive elements 15g (atomization of fuel through activation of the piezoelectric/electrostrictive elements 15g) is stopped.

[0093] More specifically, when the electronic engine control unit generates a drive voltage signal shown in (A) of FIG. 11 at time t11, the fuel injection control microcomputer 32a generates the solenoid valve open-close signal INJ for the solenoid-operated discharge valve drive circuit section 32b. As a result, at time t12 (after passage of the ineffective injection time Td), the solenoid-operated discharge valve 14 opens, whereby the pressure of liquid in the liquid feed path 15-1 starts to increase as shown in (C) of FIG. 11.

[0094] The fuel injection control microcomputer 32a determines, through monitoring, whether time t12 has been reached; i.e., whether the ineffective injection time Td has elapsed from time t11. When the fuel injection control microcomputer 32a determines that time t12 has been reached, the fuel injection control microcomputer

32a causes the piezoelectric/electrostrictive-element drive circuit section 32c to generate the piezoelectric-element drive signal DV. Subsequently, at time t13, by which the pressure of liquid in the liquid feed path 15-1 has increased to the aforementioned constant high pressure, the fuel injection control microcomputer 32a causes the piezoelectric/electrostrictive-element drive circuit section 32c to stop the generation of the piezoelectric-element drive signal DV. The length of the period between t12 and t13 is previously determined, and is stored in the fuel injection control microcomputer 32a.

[0095] Notably, a piezoelectric/electrostrictive element for detecting the liquid pressure in the liquid feed path 15-1 may be provided separately. In this case, a signal output from the piezoelectric/electrostrictive element is input to the fuel injection control microcomputer 32a, and the fuel injection control microcomputer 32a is configured to stop the generation of the piezoelectric-element drive signal DV when the signal from the piezoelectric/electrostrictive element indicates that the pressure of liquid in the liquid feed path 15-1 has reached the above-described predetermined high pressure.

[0096] Subsequently, when the drive voltage signal from the electronic engine control unit disappears at time t14, the fuel injection control microcomputer 32a causes the solenoid-operated discharge valve drive circuit section 32b to stop the generation of the solenoid valve open-close signal INJ. As a result, at time t15 occurring slightly after time t14 (that is, a point in time at which the solenoid-operated discharge valve 14 starts to close as a result of progress of discharge of the capacitor CS), the solenoid-operated discharge valve 14 starts to close. As a result, as shown in (C) of FIG. 11, the pressure of liquid in the liquid feed path 15-1 starts to decrease.

[0097] Meanwhile, the fuel injection control microcomputer 32a determines, through monitoring, whether time t15 has been reached; i.e., whether a predetermined period of time has elapsed after time t14. When the fuel injection control microcomputer 32a determines that time t15 has been reached, the fuel injection control microcomputer 32a again causes the piezoelectric/electrostrictive-element drive circuit section 32c to generate the piezoelectric-element drive signal DV. Subsequently, at time t16, by which the liquid contained in the liquid feed path 15-1 has lowered to the above-described predetermined, constant low pressure, the fuel injection control microcomputer 32a causes the piezoelectric/electrostrictive-element drive circuit section 32c to stop the generation of the piezoelectric-element drive signal DV. The length of the period between t15 and t16 is previously determined, and is stored in the fuel injection control microcomputer 32a.

[0098] Notably, in this case as well, a piezoelectric/electrostrictive element for detecting the liquid pressure in the liquid feed path 15-1 may be provided separately. In this case, a signal output from the piezoelectric/electrostrictive element for detection is input to the fuel injection control microcomputer 32a, and the fuel injection control microcomputer 32a is configured to stop the generation of the piezoelectric-element drive signal DV when the signal from the piezoelectric/electrostrictive element for detection indicates that the pressure of liquid in the liquid feed path 15-1 has reached the aforementioned constant low pressure.

[0099] As described above, the liquid injection apparatus 10 according to the second embodiment is configured in such a manner that the electrical control unit 30 does not generate the piezoelectric-element drive signal DV during periods (time t13 to time t15) in which the liquid in the liquid feed path 15-1 is maintained at a constant high pressure by means of the solenoid valve open-close signal INJ.

[0100] When the pressure of liquid in the liquid feed path 15-1 has increased to a sufficiently high pressure (the aforementioned constant higher pressure) as a result of generation of the solenoid valve open-close signal INJ, the velocity of liquid injected into the liquid injection space 21 from the liquid discharge nozzles 15-4 of the injection device 15A (the injection velocity, or the travel velocity of a liquid column) becomes sufficiently high, whereby the liquid assumes the form of droplets of a relatively small size by virtue of surface tension. Therefore, in such a case (time t13 to time t15), generation of the piezoelectric-element drive signal DV is stopped as in the second embodiment, whereby the power consumption of the liquid injection apparatus 10 can be reduced.

[0101] Next, a liquid injection apparatus 10 according to a third embodiment of the present invention will be described. The liquid injection apparatus 10 according to the third embodiment differs from the liquid injection apparatus 10 according to the first embodiment only in a pattern for generating the solenoid valve open-close signal INJ and the piezoelectric-element drive signal DV. Thus, while the main focus is placed on the above point of difference, the third embodiment will next be described with reference to the timing chart of FIG. 12. Notably, (B) of FIG. 12 shows the duty ratio (or average current) of the solenoid valve open-close signal INJ, which will be described later.

[0102] In the third embodiment, when the pressure of liquid contained in the liquid feed path 15-1 is higher than the aforementioned constant low pressure as a result of opening of the solenoid-operated discharge valve 14; in other words, when liquid can be injected from the liquid discharge nozzles 15-4, generation of the piezoelectric-element drive signal DV is continued. Further, the solenoid valve open-close signal INJ is generated such that the pressure of liquid contained in the liquid feed path 15-1 increases steeply immediately after start of generation of the solenoid valve open-close signal INJ and subsequently lowers gradually (slowly) at a pressure change rate whose absolute value is smaller than that of a pressure change rate at the time of the increase of the liquid pressure.

[0103] More specifically, when the electronic engine control unit 31 generates a drive voltage signal shown in (A) of FIG. 12 at time t21, the fuel injection control microcomputer 32a causes the solenoid-operated discharge valve drive circuit section 32b to generate the solenoid valve open-close signal INJ. At time t21 and immediately after time t21, the fuel injection control microcomputer 32a generates respective control signals to the Schmitt trigger circuits ST1 and ST2 such that the field effect transistor MS1 of the solenoid-operated discharge valve drive circuit section 32b maintains the ON state, whereas the field effect transistor MS2 maintains the OFF state. In other words, a pulsing voltage which changes between 0 (V) and the power supply voltage VP1 (V) in a predetermined period Tp and whose duty ratio (=(time during which VP1 (V) is maintained)/Tp) is 100% is applied to the solenoid-operated discharge valve 14. Hereinafter, the duty ratio will be simply referred to as the "duty ratio of the solenoid valve open-close signal INJ").

[0104] This causes the needle valve 14d of the solenoid-operated discharge valve 14 to start to move toward its maximum movement position at time t22, which is reached after the elapse of the ineffective injection time Td, and thus the discharge holes 14c-2 start to be opened. Accordingly, as shown in (C) FIG. 12, the pressure of liquid contained in the liquid feed path 15-1 starts to rise steeply at a predetermined increase rate $\alpha 1$. At and after time t22, the fuel injection control microcomputer 32a causes the piezoelectric/electrostrictive-element drive circuit section 32c to generate the piezoelectric-element drive signal DV.

[0105] Subsequently, at time t23, by which the pressure of liquid contained in the liquid feed path 15-1 has increased to the aforementioned constant high pressure, the fuel injection control microcomputer 32a gradually reduces the duty ratio of the solenoid valve open-close signal INJ applied to the solenoid-operated discharge valve 14. As a result, since the needle valve 14d of the solenoid-operated discharge valve 14 starts to gradually move toward the initial position, the opening area of the discharge holes 14c-2 gradually reduces. Accordingly, the pressure of liquid contained in the liquid feed path 15-1 starts to lower at a predetermined reduction rate $\alpha 2$. At this time, the absolute value of the reduction rate $\alpha 2$ is smaller than that of the increase rate $\alpha 1$.

[0106] Subsequently, at time t24, because of disappearance of the drive voltage signal from the electronic engine control unit 31, the fuel injection control microcomputer 32a steeply reduces the aforementioned duty ratio of the solenoid valve open-close signal INJ applied to the solenoid-operated discharge valve 14. Then, at time t25 when the duty ratio of the solenoid valve open-close signal INJ applied to the solenoid-operated discharge valve 14 becomes 0%, the fuel injection control microcomputer 32a stops the generation of the solenoid valve open-close signal INJ.

[0107] As a result, from time t24, the needle valve 14d of the solenoid-operated discharge valve 14 moves faster toward the initial position, and thus the opening area of the discharge holes 14c-2 decreases steeply. Accordingly, from time t26 subsequent to time t24, the pressure of liquid contained in the liquid feed path 15-1 starts to lower steeply at a predetermined reduction rate $\alpha 3$ whose absolute value is greater than that of the reduction rate $\alpha 2$. At time t27, the pressure of liquid contained in the liquid feed path 15-1 becomes the aforementioned constant low pressure. Notably, a time ranging from time t24 to time t26 arises because of an operation lag of the needle valve 14d.

[0108] Meanwhile, from time t22, the fuel injection control microcomputer 32a continues generation of the piezoelectric-element drive signal DV. At time t27, or when a predetermined period of time elapses after time t24, the fuel injection control microcomputer 32a stops the generation of the piezoelectric-element drive signal DV.

[0109] Notably, in this case as well, a piezoelectric/electrostrictive element for detecting the liquid pressure in the liquid feed path 15-1 may be provided separately. In this case, a signal output from the piezoelectric/electrostrictive element for detection is input to the fuel injection control microcomputer 32a, and the fuel injection control microcomputer 32a is configured to stop the generation of the piezoelectric-element drive signal DV when the signal from the piezoelectric/electrostrictive element for detection indicates that the pressure of liquid in the liquid feed path 15-1 has reached the aforementioned constant low pressure.

[0110] As described above, the liquid injection apparatus 10 according to the third embodiment is configured as follows. When the pressure of liquid in the liquid feed path 15-1 is made higher than the constant low pressure by means of the solenoid valve open-close signal INJ (time t22 to time t27), the electrical control unit 30 generates the piezoelectric-element drive signal DV. Furthermore, the electrical control unit 30 generates the solenoid valve open-close signal INJ in such a manner that immediately after start of generation of the solenoid valve open-close signal INJ (time t22 to time t23), the pressure of liquid contained in the liquid feed path 15-1 increases and then gradually lowers at the pressure change rate $\alpha 2$ whose absolute value ($|\alpha 2|$) is smaller than that ($|\alpha 1|$) of the pressure change rate $\alpha 1$ at the time of pressure increase.

[0111] By virtue of the above-described configuration, the pressure of liquid contained in the liquid feed path 15-1 steeply increases immediately after start of generation of the solenoid valve open-close signal INJ (time t22 to time t23). Therefore, the generation of the solenoid valve open-close signal INJ leads to immediate start of injection of liquid droplets. Subsequently, the pressure of liquid contained in the liquid feed path 15-1 continues to lower in a relatively gradual manner (at reduction rate $\alpha 2$). Therefore, the velocity of a preceding injected liquid droplet is higher than that of a subsequent injected liquid droplet, thereby reducing the possibility that liquid droplets injected from the respective liquid discharge nozzles 15-4 collide within the liquid injection space 21 to form a liquid droplet of a greater size.

[0112] Next, a liquid injection apparatus 10 according to a fourth embodiment of the present invention will be described. The liquid injection apparatus 10 according to the fourth embodiment differs from the liquid injection apparatus 10 according to the first embodiment only in a pattern for generating the solenoid valve open-close signal INJ and the piezoelectric-element drive signal DV. Thus, while the main focus is placed on the above point of difference, the fourth embodiment will next be described with reference to the timing chart of FIG. 13.

[0113] In the fourth embodiment, when the pressure of liquid contained in the liquid feed path 15-1 is in the process of increasing or lowering as a result of opening and closing, respectively, of the solenoid-operated discharge valve 14, the frequency f of the piezoelectric-element drive signal DV is set lower than that when the liquid pressure is the aforementioned constant high pressure. In other words, when the pressure of liquid contained in the liquid feed path 15-1 is lower than the aforementioned constant high pressure, the period of volume change of each of the chambers 15-2 is set to a longer time.

[0114] More specifically, when the drive voltage signal from the electronic engine control unit 31 arises at time t31, the fuel injection control microcomputer 32a causes the solenoid-operated discharge valve drive circuit section 32b to generate the solenoid valve open-close signal INJ. As a result, at time t32, which is reached after the elapse of the ineffective injection time Td, the pressure of liquid contained in the liquid feed path 15-1 starts to rise, and, at time t33, reaches the aforementioned constant high pressure.

[0115] In this liquid pressure rise period (from time t32 to time t33), the fuel injection control microcomputer 32a causes the piezoelectric/electrostrictive-element drive circuit section 32c to generate the piezoelectric-element drive signal DV of a first frequency f1. In other words, the frequency f of the piezoelectric-element drive signal DV applied to the piezoelectric/electrostrictive elements 15g is set to the first frequency f1.

[0116] Subsequently, at time t33, by which the pressure of liquid contained in the liquid feed path 15-1 has increased to the aforementioned constant high pressure, the fuel injection control microcomputer 32a sets the frequency f of the piezoelectric-element drive signal DV applied to the piezoelectric/electrostrictive elements 15g to a second frequency f2 higher than the first frequency f1. Notably, such a change in frequency f is performed through changing (shortening) the period T (see FIG. 7) of pulses to be sent to the Schmitt trigger circuits ST11 and ST12 from the fuel injection control microcomputer 32a.

[0117] Subsequently, when the drive voltage signal from the electronic engine control unit 31 disappears at time t34, the fuel injection control microcomputer 32a stops the generation of the solenoid valve open-close signal INJ applied to the solenoid-operated discharge valve 14. As a result, at time t35, which is reached after the elapse of a predetermined time from time t34, the pressure of liquid contained in the liquid feed path 15-1 starts to lower. Then, at time t36, the liquid pressure becomes the aforementioned constant low pressure.

[0118] Meanwhile, the fuel injection control microcomputer 32a determines, through monitoring, whether or not time t35 has been reached after elapse of a predetermined period of time after time t34. When the time t35 has been reached, the fuel injection control microcomputer 32a again sets the frequency f of the piezoelectric-element drive signal DV applied to the piezoelectric/electrostrictive element drive circuit section 32c to the first frequency f1. The fuel injection control microcomputer 32a stores the length of the period between time t35 and time t36. At time t36; i.e., after elapse of a period of the stored length from time t35, the fuel injection control microcomputer 32a stops the generation of the piezoelectric-element drive signal DV.

[0119] Notably, in this case as well, a piezoelectric/electrostrictive element for detecting the liquid pressure in the liquid feed path 15-1 may be provided separately. In this case, a signal output from the piezoelectric/electrostrictive element for detection is input to the fuel injection control microcomputer 32a, and the fuel injection control microcomputer 32a is configured to change the frequency of the piezoelectric-element drive signal DV and stop the generation of the piezoelectric-element drive signal DV, when, on the basis of the signal from the piezoelectric/electrostrictive element for detection, the pressure of liquid in the liquid feed path 15-1 is detected to have reached the above-described constant high and low pressures, respectively.

[0120] As described above, the liquid injection apparatus 10 according to the fourth embodiment is configured in such a manner that the electrical control unit 30 changes the frequency of the piezoelectric-element drive signal DV according to the pressure of liquid in the liquid feed path 15-1. In other words, as the pressure of liquid in the liquid feed path 15-1 increases, the electrical control unit 30 applies the piezoelectric-element drive signal DV having a higher frequency to the piezoelectric/electrostrictive elements 15g, thereby increasing the frequency of volume change of the chambers 15-2.

[0121] Since the pressure of liquid contained in the liquid feed path 15-1 determines the velocity (injection velocity) of liquid injected from each of the liquid discharge nozzles 15-4, the degree of atomization of liquid varies with the pressure of the liquid. Therefore, as in the case of the above-described fourth embodiment, through changing the frequency f of the piezoelectric-element drive signal DV according to the pressure of liquid contained in the liquid feed path 15-1, liquid droplets of a desired size can be obtained.

[0122] Also, in the above-described fourth embodiment, the piezoelectric-element drive signal DV is changed such that the frequency f of the piezoelectric-element drive signal DV increases with an increase in the pressure of liquid contained in the liquid feed path 15-1. This configuration is employed for the following reason. As the pressure of liquid contained in the liquid feed path 15-1 increases, the velocity of liquid injected from the respective liquid discharge nozzles 15-4 increases, and the flow rate of liquid injected from the respective liquid discharge nozzles 15-4 (the length of a liquid column extruded into the liquid injection space 21 per unit time from each of the liquid discharge nozzles 15-4) increases. Therefore, through application, to the piezoelectric/electrostrictive elements 15g, of the piezoelectric-element drive signal DV whose frequency f increases with the pressure of liquid contained in the liquid feed path 15-1, the size of liquid droplets obtained through atomization can be rendered uniform, irrespective of the liquid pressure. Notably, in the above-described embodiment, the frequency f of the piezoelectric-element drive signal DV is changed in two stages, consisting of the first frequency f1 and the second frequency f2. However, the frequency f may be changed continuously according to the pressure of liquid in the liquid feed path 15-1.

[0123] Next, a liquid injection apparatus 10 according to a fifth embodiment of the present invention will be described. The liquid injection apparatus 10 according to the fifth embodiment differs from the liquid injection apparatus 10 according to the first embodiment only in a pattern for generating the solenoid valve open-close signal INJ and the piezoelectric-element drive signal DV. Thus, while the main focus is placed on the above point of difference, the fifth embodiment will next be described with reference to the timing chart of FIG. 14.

[0124] In the fifth embodiment, as in the case of the second embodiment, during the period of time (ranging from time t13 to time t15 in FIG. 14) when the liquid pressure in the liquid feed path 15-1 is stabilized at the aforementioned constant high pressure, atomization of fuel effected through activation of the piezoelectric/electrostrictive elements 15g (atomization of fuel through activation of the piezoelectric/electrostrictive elements 15g) is stopped. Also, during the period of time when the pressure of liquid contained in the liquid feed path 15-1 is in the process of increasing or lowering (ranging from time t12 to time t13 and from time t15 to time t16), the quantity of volume change of the chambers 15-2 caused by the piezoelectric-element drive signal DV is reduced with an increase in the liquid pressure.

[0125] More specifically, during the period of time ranging from time t12 to time t13, the pressure of liquid in the liquid feed path 15-1 increases with time. Accordingly, the fuel injection control microcomputer 32a sequentially shortens voltage application time spans with the elapse of time, without changing the period T between start of application of the power supply voltage VP2 to the piezoelectric/electrostrictive elements 15g and start of subsequent application of the power supply voltage VP2 to the piezoelectric/electrostrictive elements 15g.

[0126] More specifically, as shown in FIG. 15, while the period T between times at which application of power supply voltage VP2 is started (the period of time ranging from time t41 to time t45 and the period of time ranging from time t45 to time t49) is held constant, times Tp1, Tp3, and Tp5—which are voltage application time spans during which the output signal of the Schmitt trigger circuit ST11 is at high level—are gradually shortened with the elapse of time. Through employment of this feature, as the pressure of liquid in the liquid feed path 15-1 increases, the maximum voltage Vmax applied to the piezoelectric/electrostrictive elements 15g lowers. Accordingly, the amount of deformation per activation of each of the piezoelectric/electrostrictive elements 15g reduces, whereby the volume change quantity ΔV in a single volume change of each of the chambers 15-2 gradually decreases.

[0127] Similarly, in the period of time ranging from time t15 to time t16 shown in FIG. 14, the pressure of liquid contained in the liquid feed path 15-1 lowers with the elapse of time. Accordingly, the fuel injection control microcomputer 32a gradually prolongs voltage application time spans with the elapse of time without changing the period T of starting application of the power supply voltage VP2 to the piezoelectric/electrostrictive elements 15g. Specifically, a time during which the output signal of the Schmitt trigger circuit ST11 is at high level; i.e., a voltage application time span, is prolonged with the elapse of time. Through employment of this feature, as the pressure of liquid in the liquid feed path 15-1 decreases, the amount of deformation per activation of each of the piezoelectric/electrostrictive elements 15g increases, whereby the volume change quantity ΔV in a single volume change of each of the chambers 15-2 gradually increases.

[0128] As described above, the liquid injection apparatus 10 according to the fifth embodiment is configured in such a manner that the electrical control unit 30 reduces the quantity of volume change of each of the chambers 15-1 effected by the piezoelectric-element drive signal DV with an increase in the pressure of liquid contained in the liquid feed path 15-1.

[0129] As the pressure of liquid contained in the liquid feed path 15-1 increases, the velocity of liquid injected from the liquid discharge nozzles 15-4 increases. Thus, without an increase of the volume change quantity ΔV (the maximum value of volume change quantity; i.e., the maximum volume change quantity) of each of the chambers 15-2, injected liquid droplets assume a ,relatively small size by virtue of surface tension. Therefore, according to the above-described fifth embodiment, in which the quantity ΔV of volume change of each of the chambers 15-2 effected by the piezoelectric-element drive signal DV decreases with an increase in the pressure of liquid contained in the liquid feed path 15-1, the volume of each of the chambers 15-2 can be prevented from changing to an unnecessarily great extent (i.e., the piezoelectric/electrostrictive elements 15g can be prevented from deforming by an unnecessarily large amount), thereby reducing the electrical power consumption of the liquid injection apparatus 10.

[0130] Notably, in the above-described fifth embodiment, while the pressure of liquid contained in the liquid feed path 15-1 is the aforementioned constant high pressure (from time t13 to time t15), generation of the piezoelectric-element drive signal DV is suspended. However, as shown in FIG. 16, the piezoelectric-element drive signal DV may be continuously generated. Also, the fourth embodiment and the fifth embodiment may be combined; specifically, the frequency of the piezoelectric-element drive signal DV increases with an increase in the pressure of liquid contained in the liquid feed path 15-1, and the quantity ΔV of volume change of each of the chambers 15-2 effected by the piezoelectric-element drive signal DV decreases with an increase in the liquid pressure.

[0131] As described above, in the liquid injection apparatus according to the embodiments of the present invention, fuel is pressurized by the pressure pump 11, whereby fuel under pressure is injected into the liquid injection space 21 in the intake pipe 20; therefore, even when pressure in the liquid injection space 21 (intake pressure) fluctuates, a required amount of fuel can be stably injected.

[0132] Vibration energy is applied to fuel through variation of the volume of the chambers 15-2 of the injection device 15A, whereby the fuel is atomized and then injected from the liquid discharge nozzles 15-4a. As a result, the present liquid fuel injection apparatus can inject liquid droplets which are atomized to a highly fine degree. Furthermore, since the injection device 15A includes a plurality of chambers 15-2 and a plurality of discharge nozzles 15-4, even when bubbles are generated within fuel, the bubbles tend to be finely divided, thereby avoiding great fluctuations in the amount of injection which would otherwise result from the presence of bubbles.

[0133] The direction of fuel discharge from the discharge holes 14c-2 of the solenoid-operated discharge valve 14 is determined such that, with increasing distance from the discharge holes 14c-2 toward the liquid feed path 15-1, the distances between the axis CL of the closed cylindrical space and the paths of fuel discharged from the discharge holes 14c-2 increase. Accordingly, discharged fuel produces a flow in a large region of the closed cylindrical space formed in the sleeve 15D. As a result, bubbles become unlikely to be generated, particularly in a corner portion (marked with solid black triangles in FIG. 3) of the closed cylindrical space in the vicinity of the discharge holes 14c-2 of the solenoid-operated discharge valve 14, or the performance of eliminating bubbles generated in the corner portion is enhanced. Therefore, in the above-described liquid injection apparatus, bubbles are unlikely to hinder a rise in fuel pressure. Thus, since fuel pressure can be increased as expected, fuel droplets can be injected in an amount and at timing as required by mechanical apparatus such as an internal combustion engine.

[0134] Also, the above-described liquid injection apparatus are configured such that, before liquid discharged from the solenoid-operated discharge valve 14 is injected into the liquid injection space 21 from the liquid discharge nozzles 15-4, the flow of the liquid makes a substantially right-angled turn at least once (in the present example, four times).

[0135] Specifically, in the present liquid injection apparatus, since the liquid inlet 15-5 and the liquid feed path 15-1 meet at right angles, the flow of liquid discharged from the solenoid-operated discharge valve 14 makes a right-angled turn at a connection portion of the liquid inlet 15-5 and the liquid feed path 15-1. Next, since the major-axis direction of the liquid feed path 15-1 is in parallel with the X-axis, and the axis of each of the liquid introduction holes 15-3 is in parallel with the Z-axis, the flow of liquid makes a right-angled turn at a connection portion of the liquid feed path 15-1 and each of the liquid introduction holes 15-3.

[0136] Furthermore, since the major axis of each of the chambers 15-2 is in parallel with the Y-axis, and the axis of each of the liquid introduction holes 15-3 is in parallel with the Z-axis, the flow of liquid makes a right-angled turn at a connection portion of each of the chambers 15-2 and the corresponding liquid introduction hole 15-3. Also, since the major axis of each of the chambers 15-2 is in parallel with the Y-axis, and the axis of each of the liquid discharge nozzles 15-4 is in parallel with the Z-axis, the flow of liquid also makes a right-angled turn at a connection portion of each of the chambers 15-2 and the corresponding liquid discharge nozzle 15-4.

[0137] According to the above-described configuration, since the flow of liquid discharged from the solenoid-operated discharge valve 14 makes a right-angled turn at least once, pulsation of liquid pressure which accompanies opening of the solenoid-operated discharge valve 14 is reduced, thereby enabling stable injection of liquid droplets. In other words, a dynamic pressure which accompanies opening of the solenoid-operated discharge valve 14 becomes a static pressure, and fuel is injected under the static pressure. As a result, fuel can be stably injected from the liquid discharge nozzles 15-4.

[0138] Particularly, in the above-described liquid injection apparatus, the injection device 15A includes a plurality of chambers 15-2 connected to the common liquid feed path 15-1, and the flow of liquid discharged from the solenoid-operated discharge valve 14 makes a substantially right-angled turn at a connection portion of the liquid inlet 15-5 and the liquid feed path 15-1, whereby the pressure of liquid contained in the liquid feed path 15-1 is stabilized. Accordingly, the pressure of liquid contained in the chambers 15-2 becomes a static pressure to thereby be stabilized, thereby enabling discharge of uniform liquid droplets from the liquid discharge nozzles 15-4 connected to the corresponding chambers 15-2.

[0139] The solenoid-operated discharge valve 14 is arranged and configured such that the discharge flow line (represented in FIG. 3 by the dot-and-dash line DL) of liquid discharged from the discharge holes 14c-2 directly intersects a plane portion of the liquid feed path 15-1 (the upper surface of the ceramic sheet 15b) without intersecting the side wall of the opening 15D-1 which forms the closed cylindrical space of the sleeve 15D, and without intersecting the side wall WP which is formed through imaginary extension of the side wall of the opening 15D-1 to the plane portion of the liquid feed path 15-1.

[0140] As a result, since liquid discharged from the solenoid-operated discharge valve 14 reaches the plane portion of the liquid feed path 15-1 while maintaining high kinetic energy (velocity), the liquid is strongly reflected from the plane portion toward the discharge holes 14c-2 in the closed cylindrical space. Accordingly, since the flow of reflected liquid eliminates bubbles that are stagnant in a corner portion (marked with solid black triangles in FIG. 3) of the closed cylindrical space in the vicinity of the discharge holes 14c-2, the amount of bubbles present in liquid decreases. Accordingly, in the above-described liquid injection apparatus, a rise in liquid pressure is less likely to be hindered by bubbles. Thus, since liquid pressure can be increased as expected, liquid droplets can be injected in an amount and at a timing as required by an internal combustion engine.

[0141] Furthermore, since the axis of each of the liquid discharge nozzles 15-4 of the above-described embodiments is in parallel with the Z-axis, liquid droplets discharged into the liquid injection space 21 from the liquid discharge nozzles 15-4 substantially do not intersect in the process of flying, thereby avoiding formation of liquid droplets of a greater size, which would otherwise result from collision of fuel liquid droplets in the liquid injection space 21. Thus, fuel can be sprayed in a uniformly atomized condition.

[0142] In the liquid injection apparatus according to the above-described embodiments, the electrical control unit 30 is configured in such a manner as to generate the piezoelectric-element drive signal DV so as to activate the piezoelectric/electrostrictive elements 15g at least when the pressure of liquid contained in the liquid feed path 15-1 is in the process of increasing or lowering because of generation of the solenoid valve open-close signal INJ or stoppage of generation of the solenoid valve open-close signal INJ, and in such a manner as not to generate the piezoelectric-element drive signal DV when the pressure of liquid contained in the liquid feed path 15-1 is a constant low pressure because of disappearance of the solenoid valve open-close signal INJ.

[0143] Accordingly, even in the case where the injection velocity of liquid is not sufficiently high to atomize the liquid sufficiently, because of the pressure of liquid contained in the liquid feed path 15-1 (and the chambers 15-2) being relatively low at the time of the pressure of the liquid being in the process of increasing or lowering, the liquid can be appropriately atomized by changing the volume of the chambers 15-2 through activation of the piezoelectric/electrostrictive elements 15g.

[0144] Also, when the pressure of liquid contained in the liquid feed path 15-1 is a constant low pressure (a pressure that the liquid contained in the liquid feed path 15-1 reaches as a result of continuation of a state in which the liquid feed path 15-1 is not fed with liquid pressurized by the pressurizing means) because of disappearance of the solenoid valve open-close signal INJ; i.e., when liquid is never injected into the liquid injection space 21 from the liquid discharge nozzles 15-4 of the injection device 15A, the injection device 15A does not need to perform the action of atomizing liquid. Thus, in such a case, the electrical control unit 30 does not generate the piezoelectric-element drive signal DV. This allows the liquid injection apparatus to avoid waste of electricity.

[0145] Notably, the present invention is not limited to the above-described embodiments, but may be modified in various forms without departing from the scope of the invention. For example, the liquid injection apparatus of the above-described embodiments are applied to a gasoline-fueled internal combustion engine in which fuel is injected into the intake pipe (intake port). However, the liquid injection apparatus of the present invention can be applied to a so-called "direct-injection-type gasoline-fueled internal combustion engine," in which fuel is injected directly into cylinders. Specifically, when fuel is injected directly into a cylinder by an electrically controlled fuel injection apparatus which uses a conventional fuel injector, fuel may be caught in a gap (crevice) between a cylinder and a piston, potentially resulting in an increase in the amount of unburnt HC (hydrocarbon). By contrast, when fuel is injected directly into a cylinder by use of the liquid injection apparatus according to the present invention, fuel is injected in an atomized condition into the cylinder, whereby the amount of fuel adhesion to the inner wall surface of the cylinder can be reduced, or the amount of fuel entering the gap between a cylinder and a piston can be reduced, thereby reducing exhaust of unburnt HC.

[0146] Furthermore, the liquid injection apparatus according to the present invention is effectively used as a direct injector for use in a diesel engine. Specifically, a conventional injector involves a problem of failure to inject atomized fuel, particularly in low-load operation of the engine, in which fuel pressure is low. In this case, if a common-rail-type injection apparatus is used, fuel pressure can be increased to a certain extent even when the engine is rotating at low speed, and thus atomization of injected fuel can be accelerated. However, since fuel pressure is lower as compared with the case where the engine is rotating at high speed, fuel cannot be sufficiently atomized. By contrast, since the liquid injection apparatus according to the present invention is configured such that fuel is atomized through activation of the piezoelectric/electrostrictive elements 15g, sufficiently atomized fuel can be injected irrespective of engine load (i.e., even when the engine is running at low load).

Claims

1. A liquid injection apparatus comprising:

an injection device including a liquid discharge nozzle, a first end of the liquid discharge nozzle being exposed to a liquid injection space, a piezoelectric/electrostrictive element which is activated by a piezoelectric-element drive signal, a chamber whose volume is changed through activation of the piezoelectric/electrostrictive element and which is connected to a second end of the liquid discharge nozzle, a liquid feed path connected to the chamber, and a liquid inlet establishing communication between the liquid feed path and the exterior of the injection device;
pressurizing means for pressurizing liquid;
a solenoid-operated discharge valve including a solenoid-operated open-close valve which is driven by a solenoid valve open-close signal, and a discharge hole which is opened and closed by the solenoid-operated open-close valve, the solenoid-operated discharge valve receiving the liquid pressurized by the pressurizing means, and discharging the pressurized liquid into the liquid inlet of the injection device via the discharge hole when the solenoid-operated open-close valve is driven to open the discharge hole; and
an electrical control unit including piezoelectric-element-drive-signal generation means for generating the piezoelectric-element drive signal and solenoid-valve-open-close-signal generation means for generating the solenoid valve open-close signal,

wherein the liquid discharged from the solenoid-operated discharge valve is atomized by means of volume change of the chamber, and injected into the liquid injection space in the form of droplets from the liquid discharge nozzle,

the liquid injection apparatus being **characterized in that** the electrical control unit is configured in such a manner as to generate the piezoelectric-element drive signal to thereby activate the piezoelectric/electrostrictive element at least when the pressure of liquid in the liquid feed path is in the process of increasing or lowering upon generation of the solenoid valve open-close signal or stoppage of the generation of the solenoid valve open-close signal, and not to generate the piezoelectric-element drive signal when the pressure of liquid in the liquid feed path is a constant low pressure because of disappearance of the solenoid valve open-close signal.

2. A liquid injection apparatus according to claim 1, wherein the electrical control unit is configured to start generation of the piezoelectric-element drive signal immediately before a point of time when, because of generation of the solenoid valve open-close signal, the pressure of liquid contained in the liquid feed path starts to increase from the constant low pressure.

3. A liquid injection apparatus according to claim 1 or 2, wherein the electrical control unit is configured in such a manner as to continuously generate the piezoelectric-element drive signal up to a point of time immediately after the pressure of liquid contained in the liquid feed path lowers to the constant low pressure as a result of stoppage of generation of the solenoid valve open-close signal.

4. A liquid injection apparatus according to any one of claims 1 to 3, wherein the electrical control unit is configured not to generate the piezoelectric-element drive signal during periods in which the pressure of liquid in the liquid feed path is a constant high pressure because of generation of the solenoid valve open-close signal.

5. A liquid injection apparatus according to any one of claims 1 to 3, wherein the electrical control unit is configured in such a manner as to generate the piezoelectric-element drive signal when the pressure of liquid in the liquid feed path is higher than the constant low pressure because of generation of the solenoid valve open-close signal, and as to generate the solenoid valve open-close signal such that the pressure of liquid contained in the liquid feed path increases immediately after start of generation of the solenoid valve open-close signal and subsequently lowers gradually at a pressure change rate whose absolute value is smaller than that of a pressure change rate at the time of the increase of the liquid pressure.

6. A liquid injection apparatus according to any one of claims 1 to 5, wherein the electrical control unit is configured to change the frequency of the piezoelectric-element drive signal in accordance with the pressure of liquid contained in the liquid feed path.

7. A liquid injection apparatus according to claim 6, wherein the electrical control unit is configured to change the piezoelectric-element drive signal such that the frequency of the piezoelectric-element drive signal increases with an increase in the pressure of liquid in the liquid feed path.

8. A liquid injection apparatus according to any one of claims 1 to 7, wherein the electrical control unit is configured in such a manner as to decrease the quantity of volume change of the chamber, caused by the piezoelectric-element drive signal, with an increase in the pressure of liquid in the liquid feed path.

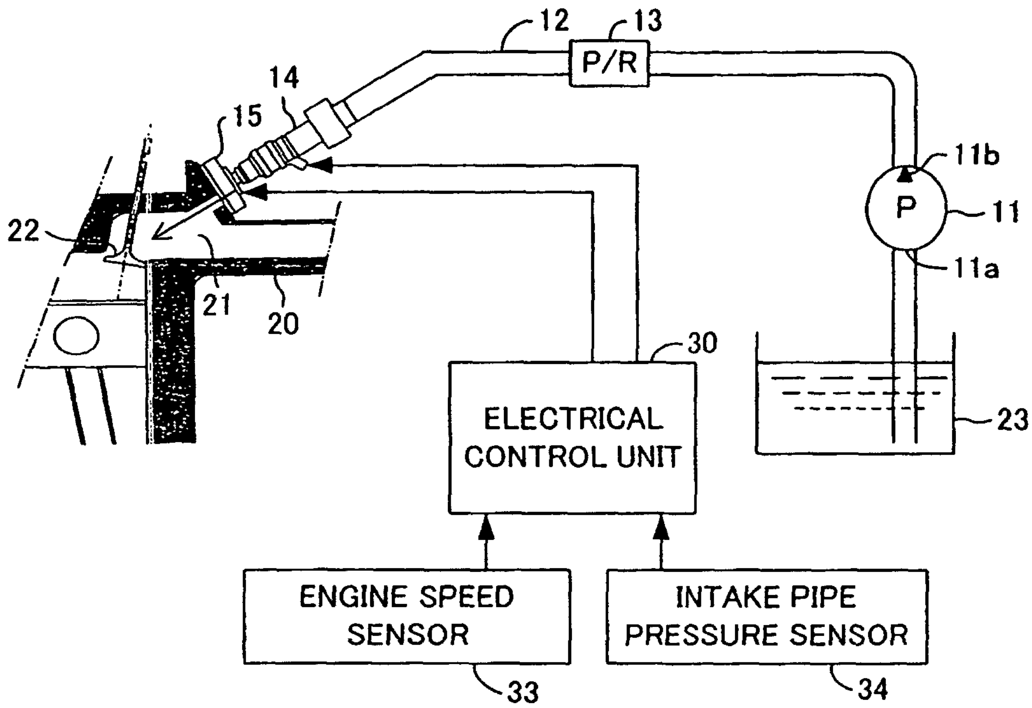
12
13
P/R
14
15
11b
P
11
11a
22
21
20
30
23
ELECTRICAL
CONTROL UNIT
ENGINE SPEED
SENSOR
INTAKE PIPE
PRESSURE SENSOR
33
34

FIG.1

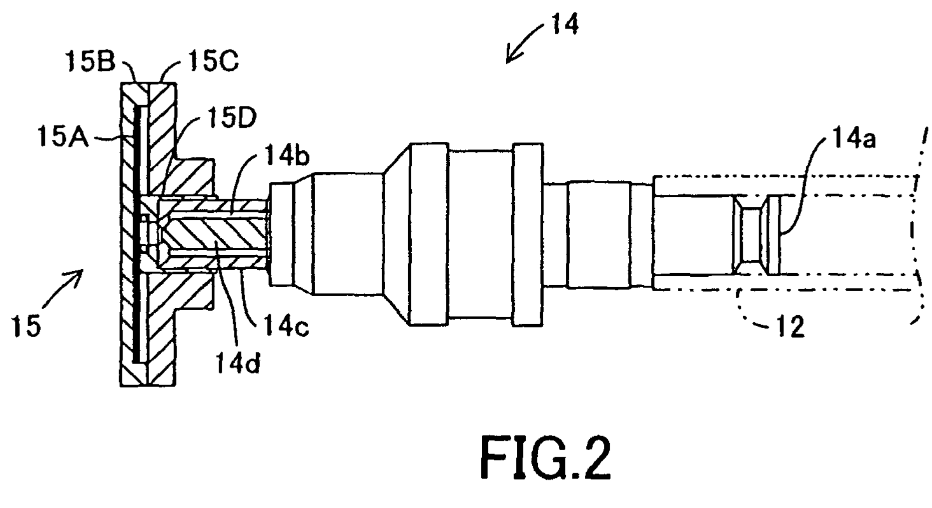
14
15B
15C
15D
15A
14b
14a
15
14c
14d
12

FIG.2

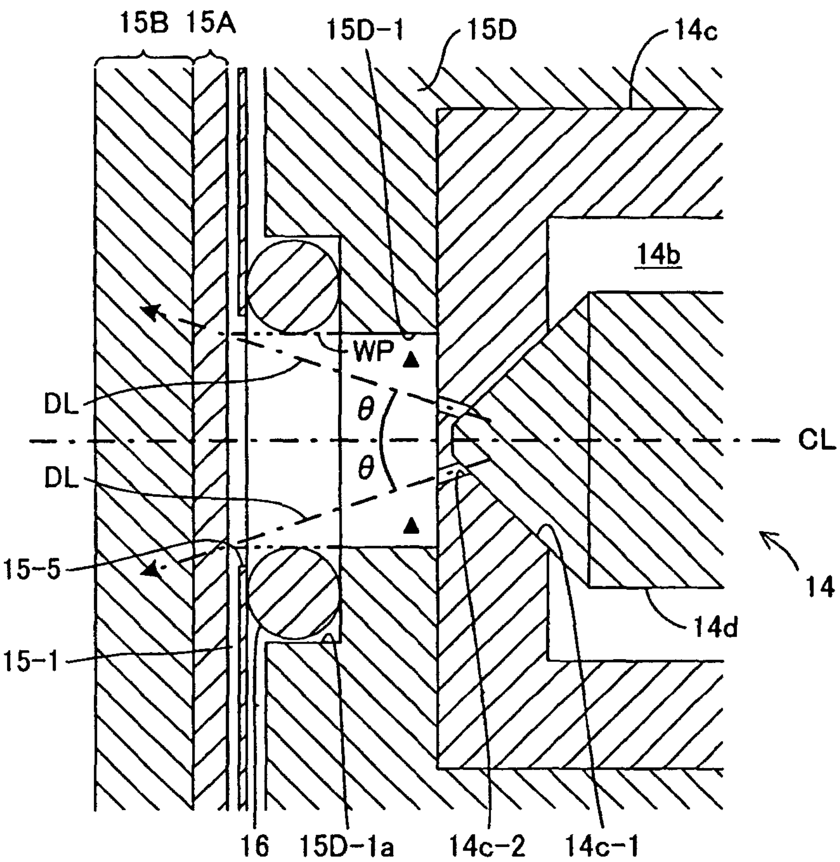
15B
15A
15D-1
15D
14c
14b
WP
DL
θ
θ
CL
DL
15-5
14
14d
15-1
16
15D-1a
14c-2
14c-1

FIG.3

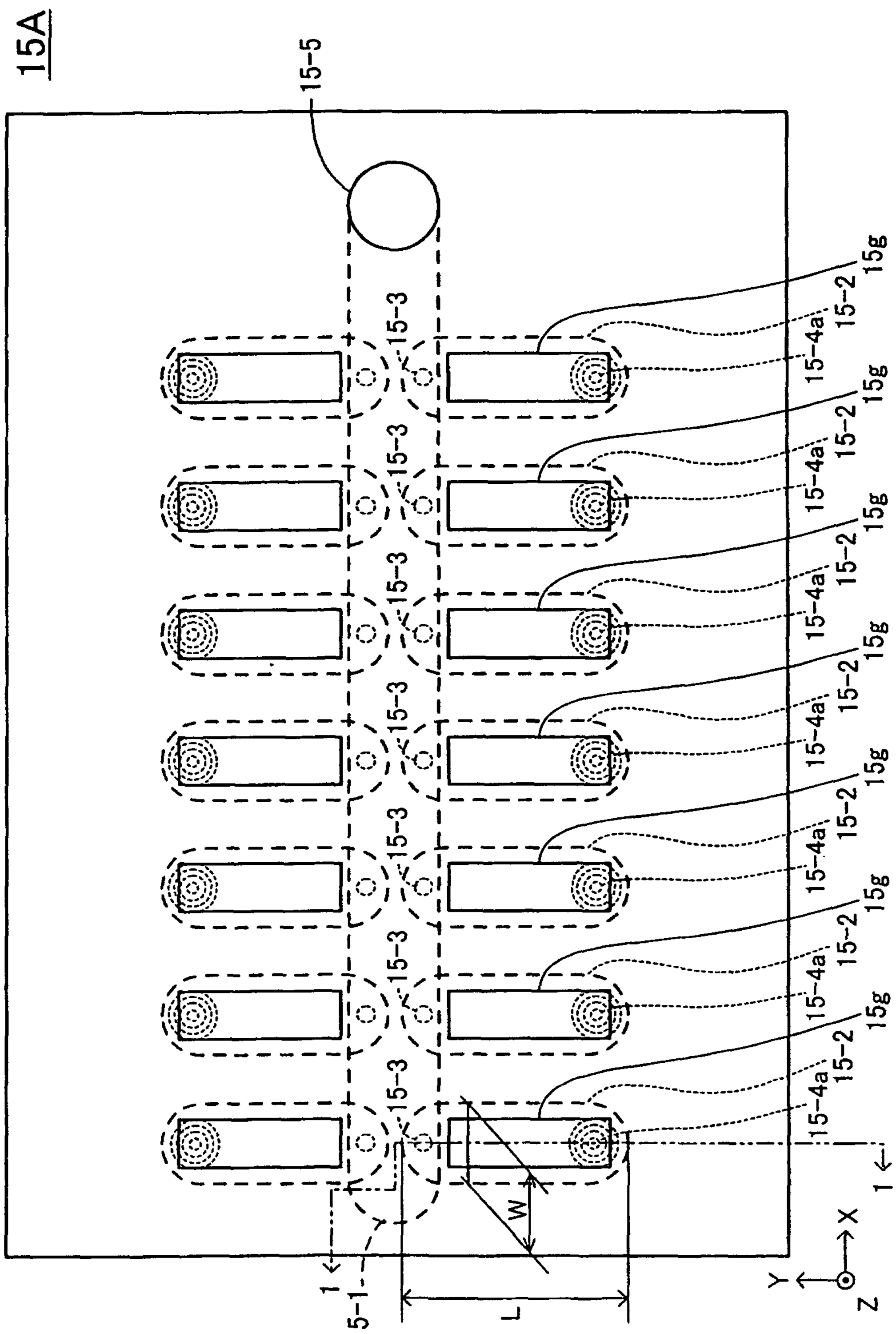

FIG.4

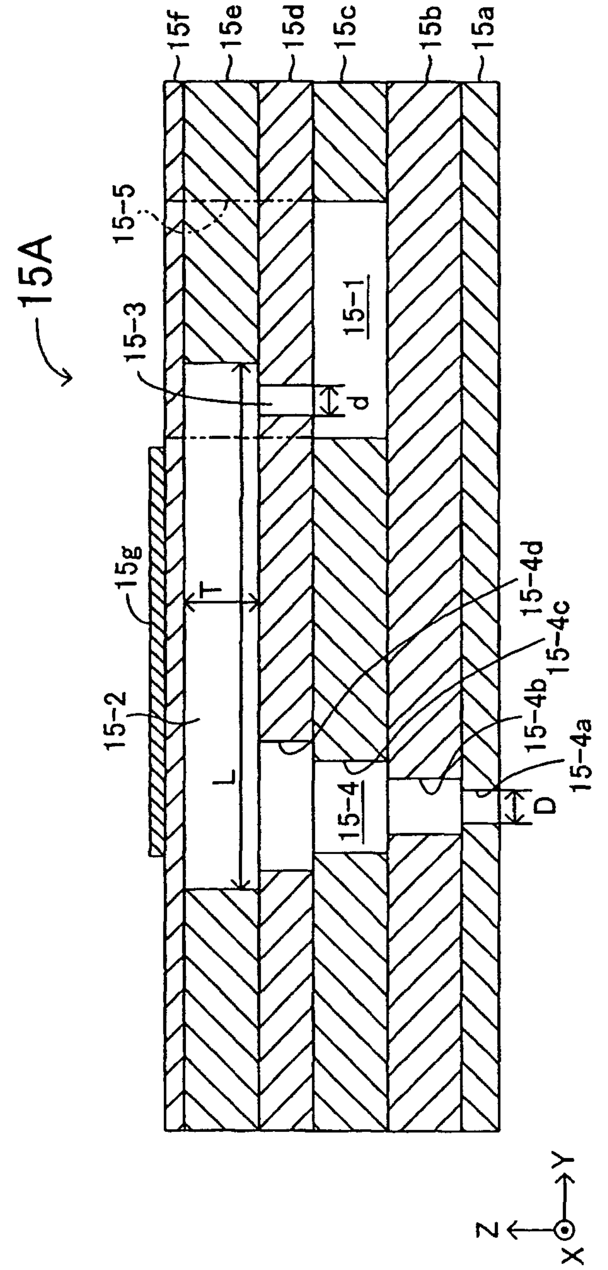
15A
15f
15e
15d
15c
15b
15a
15-5
15-1
15-3
d
15g
T
15-2
L
15-4
15-4d
15-4c
15-4b
15-4a
D
Z
Y
X

FIG.5

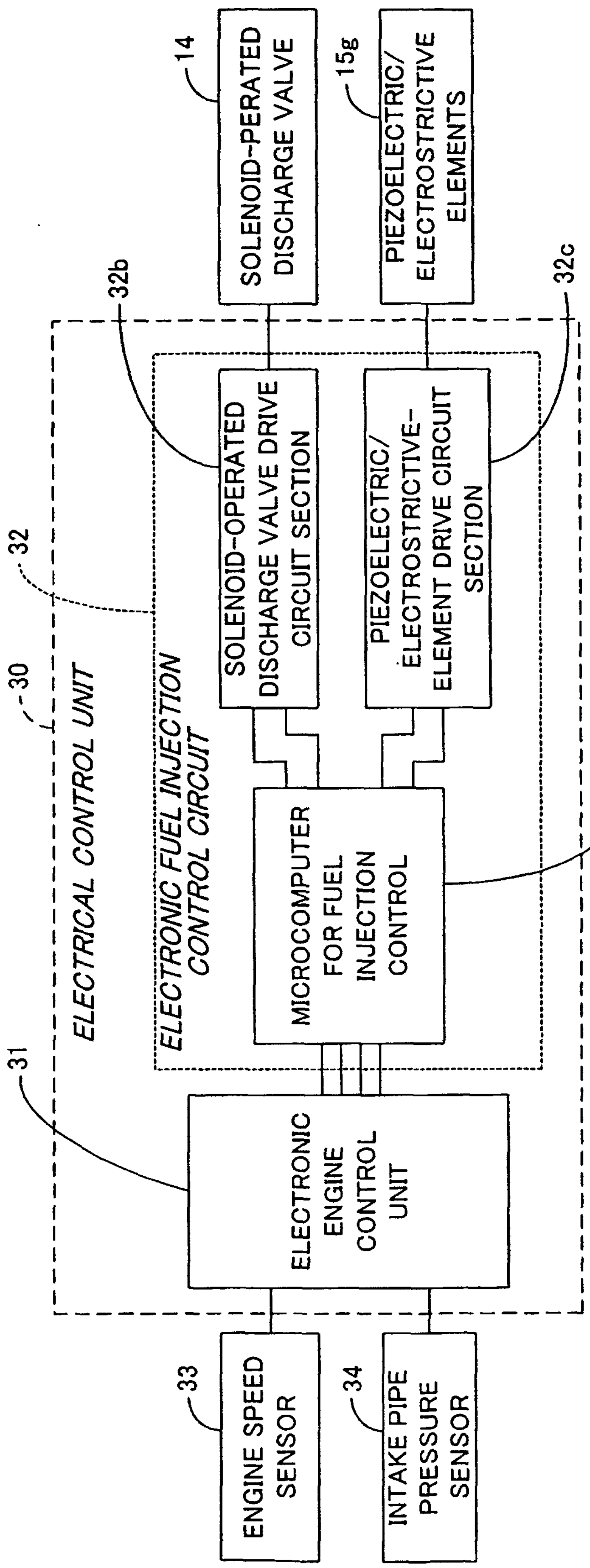
ELECTRICAL CONTROL UNIT
30
ELECTRONIC FUEL INJECTION CONTROL CIRCUIT
32
31
ELECTRONIC ENGINE CONTROL UNIT
MICROCOMPUTER FOR FUEL INJECTION CONTROL
32a
SOLENOID-OPERATED DISCHARGE VALVE DRIVE CIRCUIT SECTION
32b
PIEZOELECTRIC/ ELECTROSTRICTIVE- ELEMENT DRIVE CIRCUIT SECTION
32c
SOLENOID-PERATED DISCHARGE VALVE
14
PIEZOELECTRIC/ ELECTROSTRICTIVE ELEMENTS
15g
ENGINE SPEED SENSOR
33
INTAKE PIPE PRESSURE SENSOR
34

FIG.6

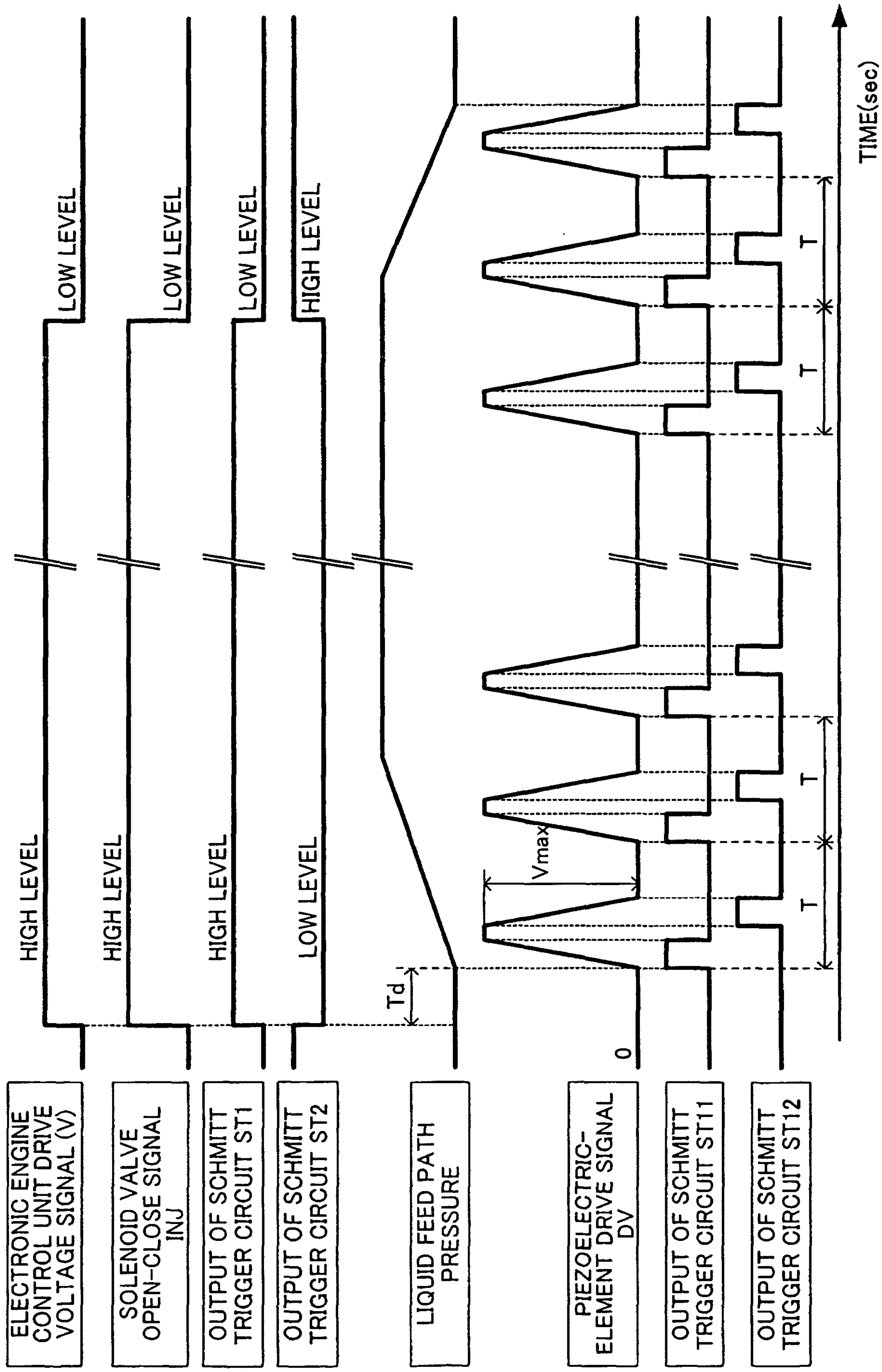
ELECTRONIC ENGINE CONTROL UNIT DRIVE VOLTAGE SIGNAL (V)
SOLENOID VALVE OPEN-CLOSE SIGNAL INJ
OUTPUT OF SCHMITT TRIGGER CIRCUIT ST1
OUTPUT OF SCHMITT TRIGGER CIRCUIT ST2
LIQUID FEED PATH PRESSURE
PIEZOELECTRIC-ELEMENT DRIVE SIGNAL DV
OUTPUT OF SCHMITT TRIGGER CIRCUIT ST11
OUTPUT OF SCHMITT TRIGGER CIRCUIT ST12
HIGH LEVEL
HIGH LEVEL
HIGH LEVEL
LOW LEVEL
LOW LEVEL
LOW LEVEL
LOW LEVEL
HIGH LEVEL
Td
0
Vmax
T
T
T
T
TIME(sec)

FIG.7

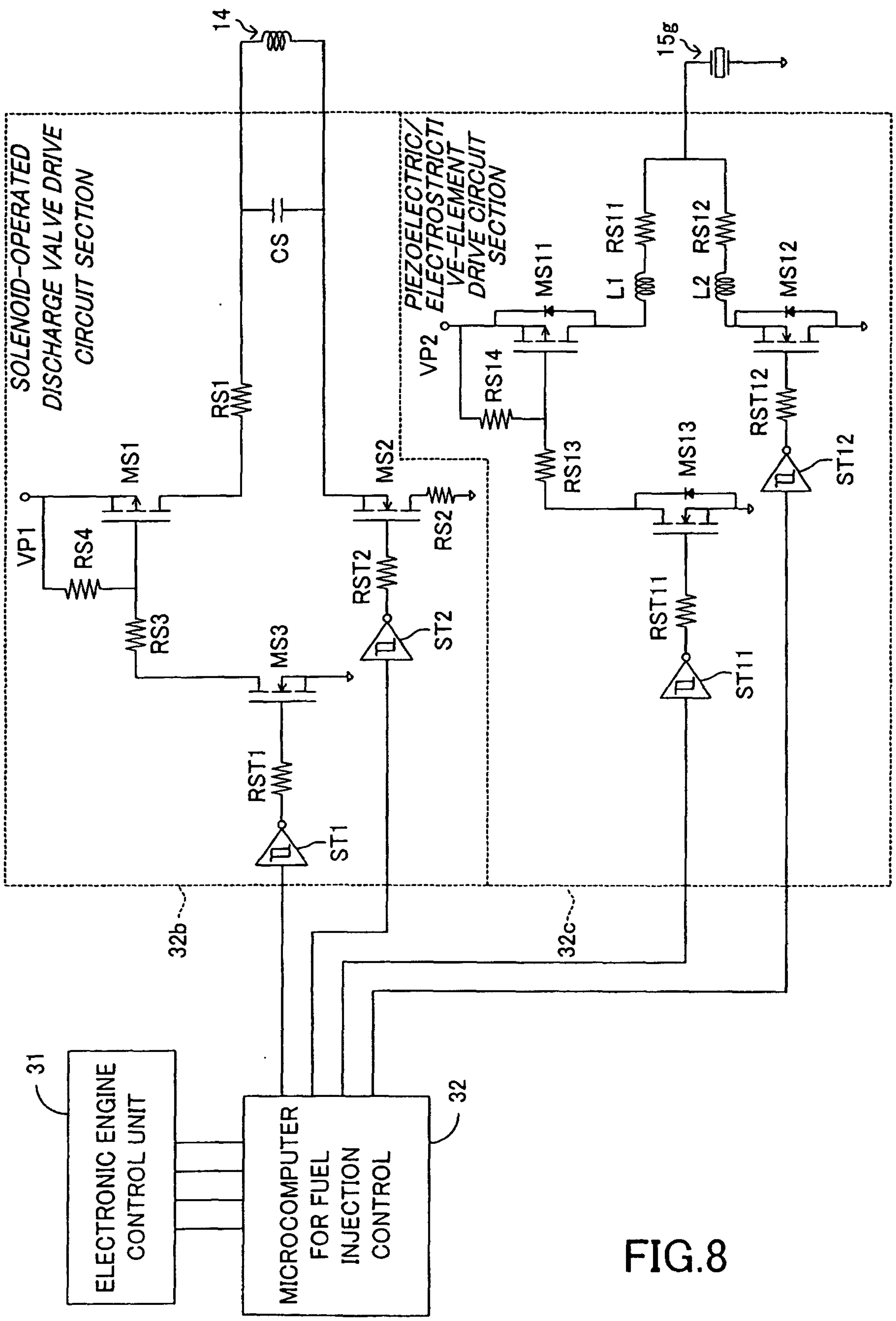
14
15g
SOLENOID-OPERATED DISCHARGE VALVE DRIVE CIRCUIT SECTION
PIEZOELECTRIC/ ELECTROSTRICTI VE-ELEMENT DRIVE CIRCUIT SECTION
CS
RS1
MS1
MS2
VP1
RS4
RS2
RST2
RS3
MS3
ST2
RST1
ST1
VP2
MS11
RS11
L1
RS12
L2
MS12
RS14
RS13
MS13
RST12
ST12
RST11
ST11
32b
32c
31
ELECTRONIC ENGINE CONTROL UNIT
MICROCOMPUTER FOR FUEL INJECTION CONTROL
32

FIG.8

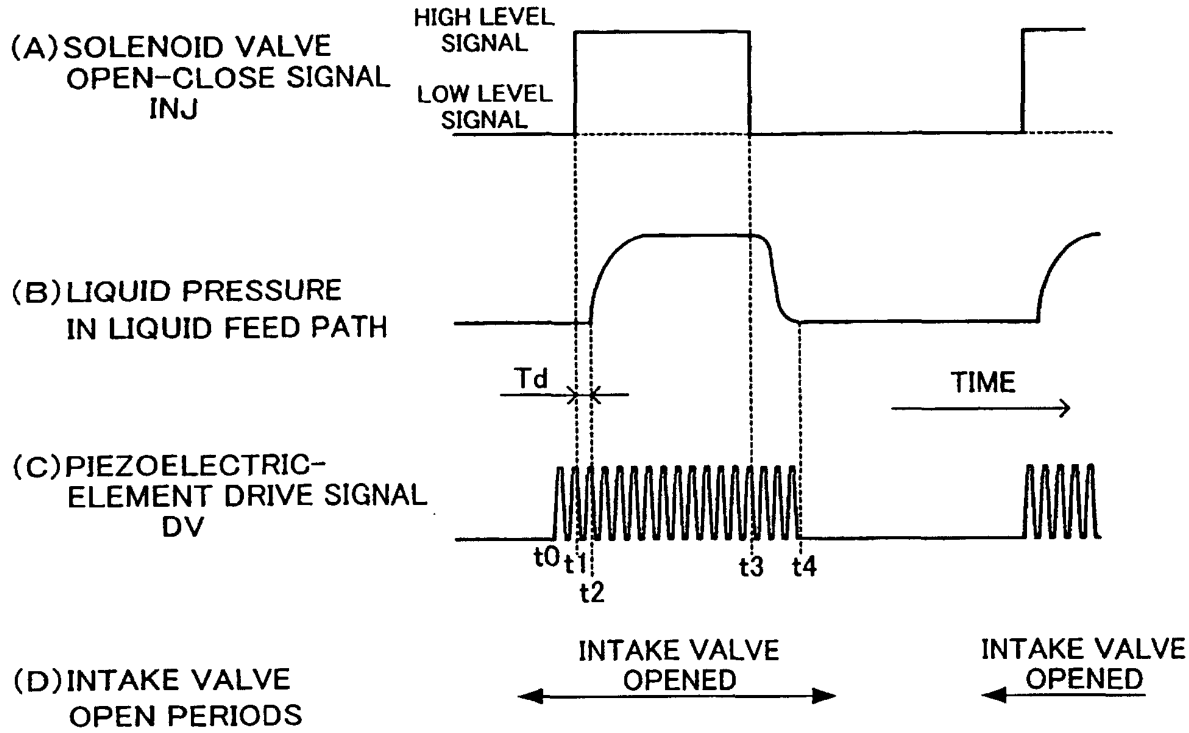
(A) SOLENOID VALVE
OPEN-CLOSE SIGNAL
INJ
HIGH LEVEL
SIGNAL
LOW LEVEL
SIGNAL
(B) LIQUID PRESSURE
IN LIQUID FEED PATH
Td
TIME
(C) PIEZOELECTRIC-
ELEMENT DRIVE SIGNAL
DV
t0
t1
t2
t3
t4
(D) INTAKE VALVE
OPEN PERIODS
INTAKE VALVE
OPENED
INTAKE VALVE
OPENED

FIG.9

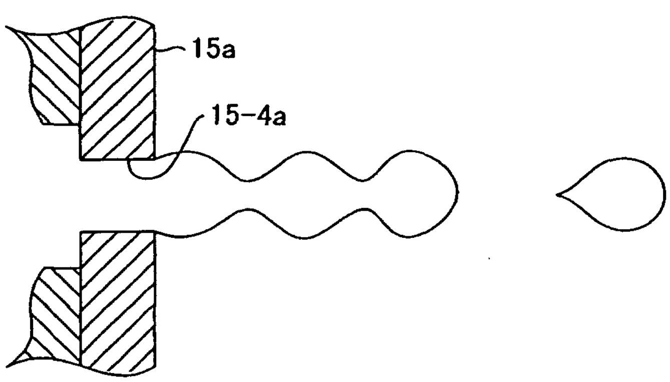
15a
15-4a

FIG.10

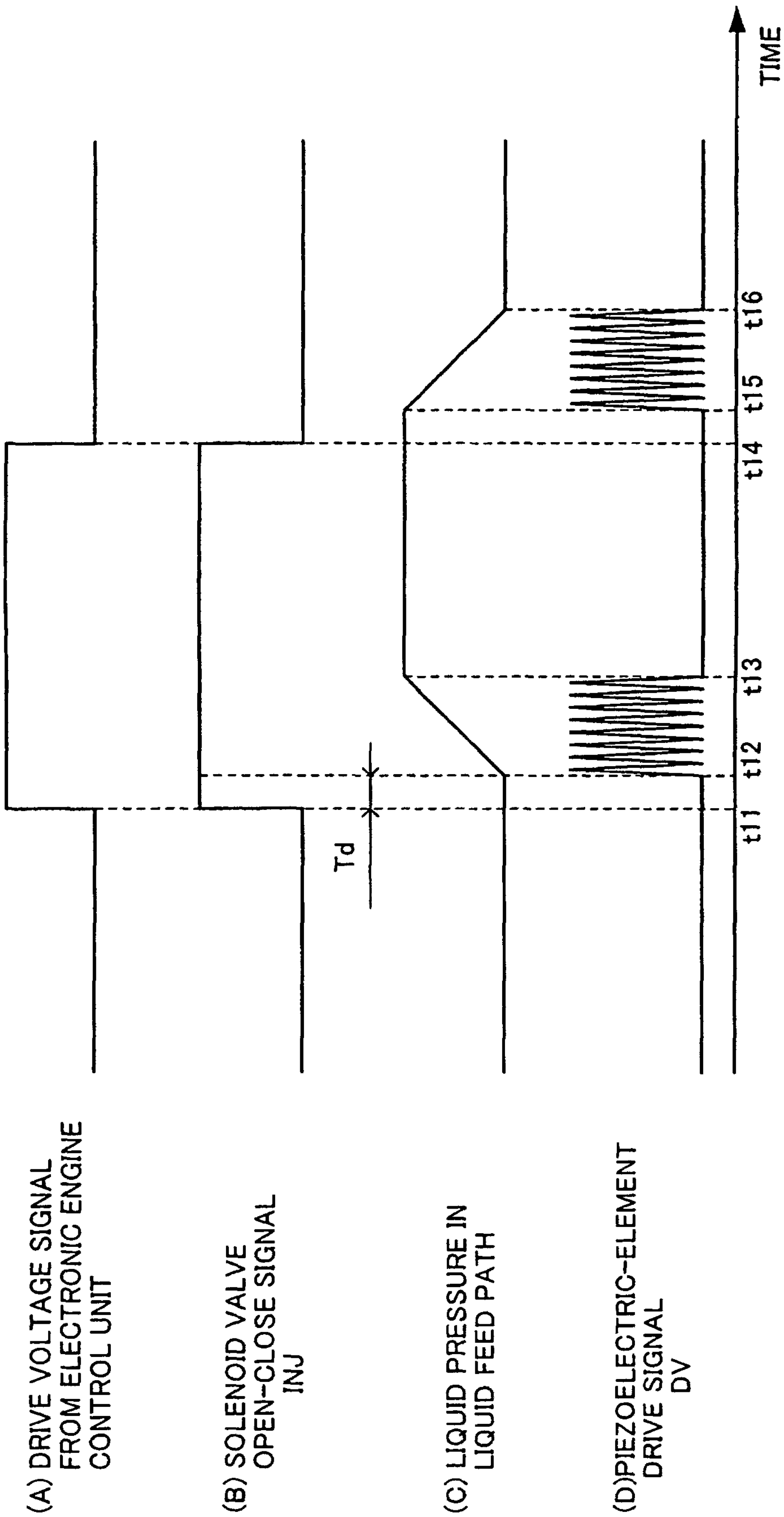
(A) DRIVE VOLTAGE SIGNAL FROM ELECTRONIC ENGINE CONTROL UNIT
(B) SOLENOID VALVE OPEN-CLOSE SIGNAL INJ
(C) LIQUID PRESSURE IN LIQUID FEED PATH
(D)PIEZOELECTRIC-ELEMENT DRIVE SIGNAL DV
Td
t11
t12
t13
t14
t15
t16
TIME

FIG.11

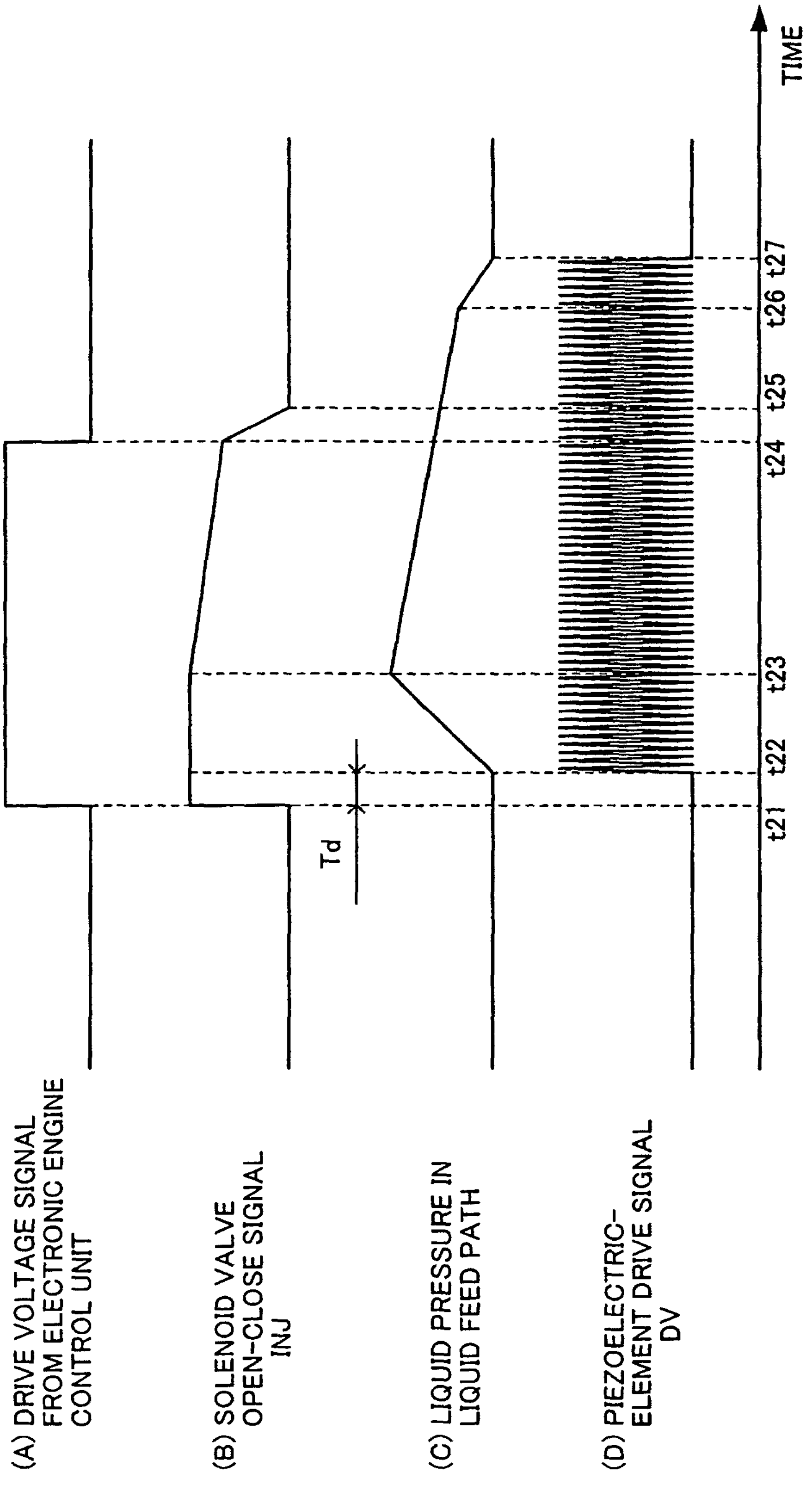
(A) DRIVE VOLTAGE SIGNAL FROM ELECTRONIC ENGINE CONTROL UNIT
(B) SOLENOID VALVE OPEN-CLOSE SIGNAL INJ
(C) LIQUID PRESSURE IN LIQUID FEED PATH
(D) PIEZOELECTRIC-ELEMENT DRIVE SIGNAL DV
Td
t21
t22
t23
t24
t25
t26
t27
TIME

FIG.12

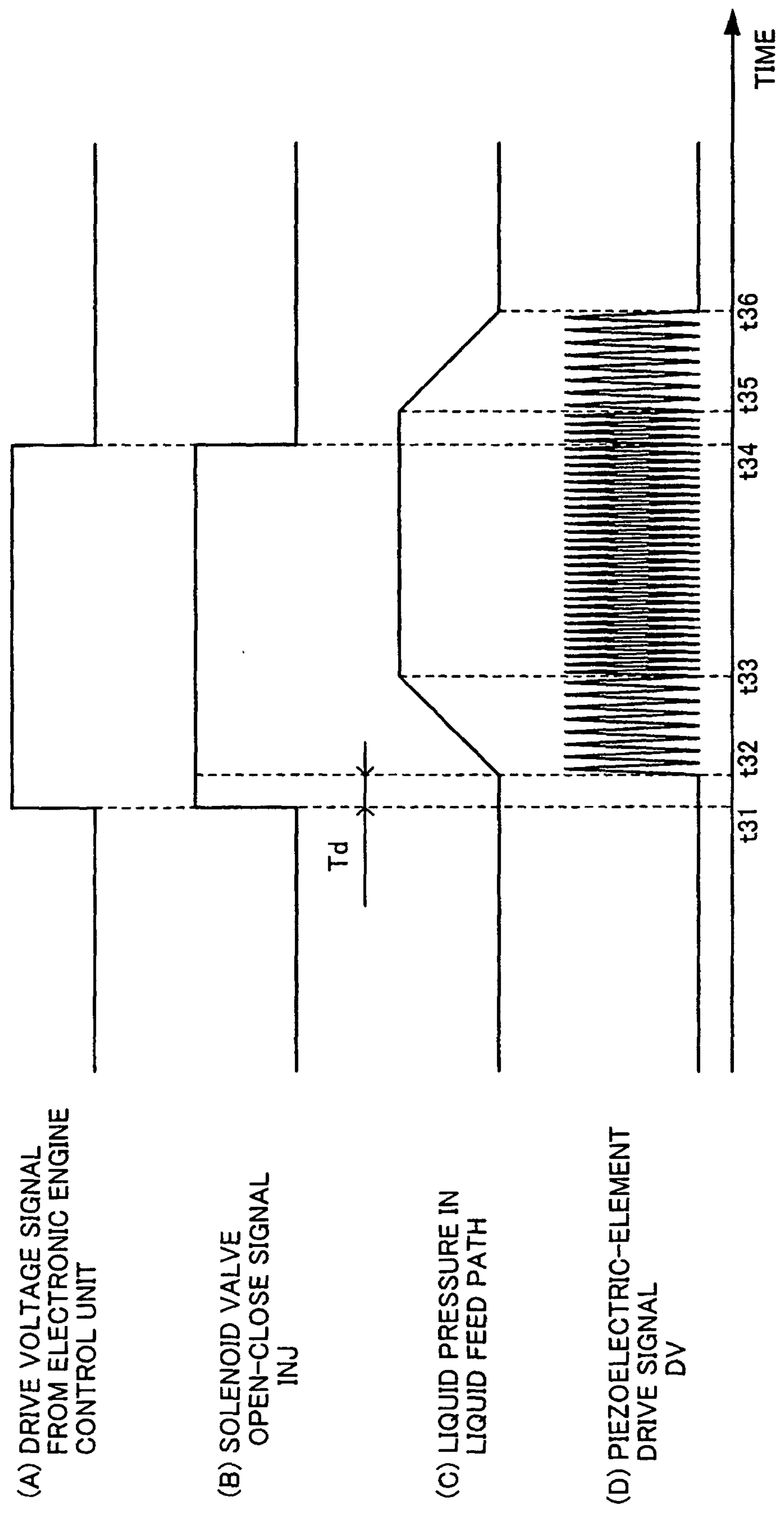
(A) DRIVE VOLTAGE SIGNAL FROM ELECTRONIC ENGINE CONTROL UNIT
(B) SOLENOID VALVE OPEN-CLOSE SIGNAL INJ
(C) LIQUID PRESSURE IN LIQUID FEED PATH
(D) PIEZOELECTRIC-ELEMENT DRIVE SIGNAL DV
Td
t31
t32
t33
t34
t35
t36
TIME

FIG.13

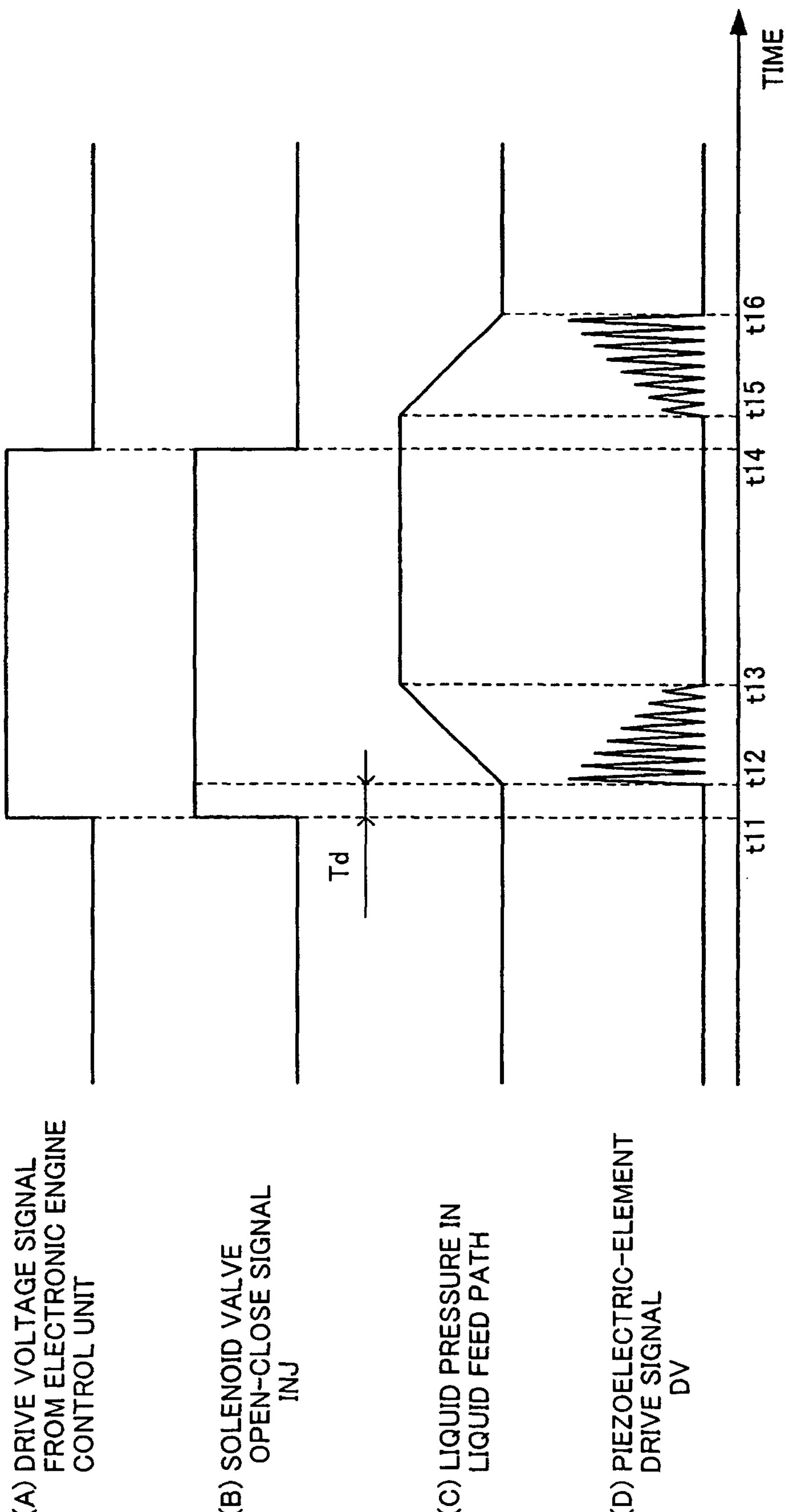
(A) DRIVE VOLTAGE SIGNAL FROM ELECTRONIC ENGINE CONTROL UNIT
(B) SOLENOID VALVE OPEN-CLOSE SIGNAL INJ
(C) LIQUID PRESSURE IN LIQUID FEED PATH
(D) PIEZOELECTRIC-ELEMENT DRIVE SIGNAL DV
Td
t11
t12
t13
t14
t15
t16
TIME

FIG.14

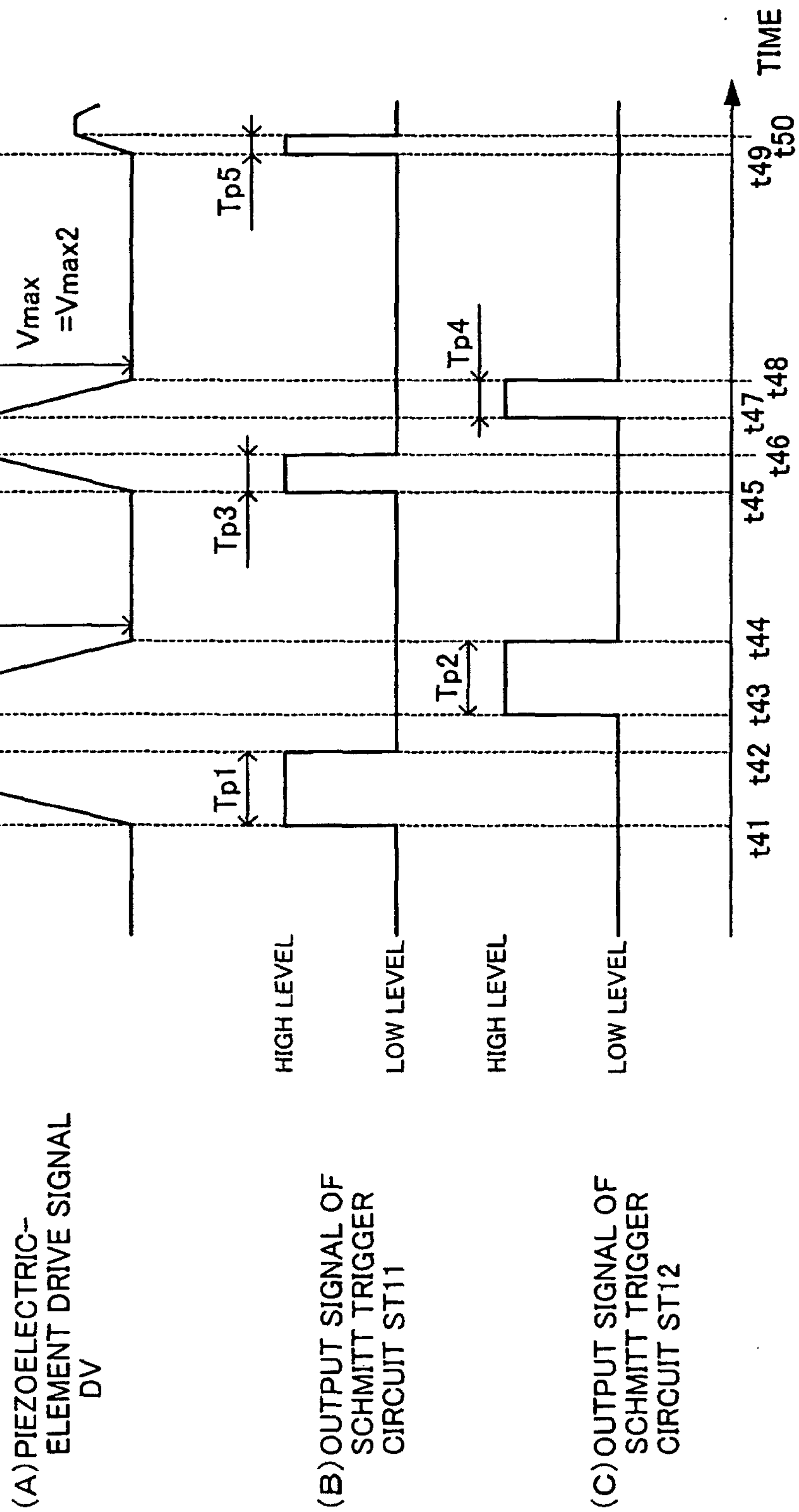
(A) PIEZOELECTRIC-ELEMENT DRIVE SIGNAL DV
(B) OUTPUT SIGNAL OF SCHMITT TRIGGER CIRCUIT ST11
(C) OUTPUT SIGNAL OF SCHMITT TRIGGER CIRCUIT ST12
HIGH LEVEL
LOW LEVEL
HIGH LEVEL
LOW LEVEL
T
T
Vmax =Vmax1
Vmax =Vmax2
Tp1
Tp2
Tp3
Tp4
Tp5
t41 t42 t43 t44 t45 t46 t47 t48 t49 t50
TIME

FIG.15

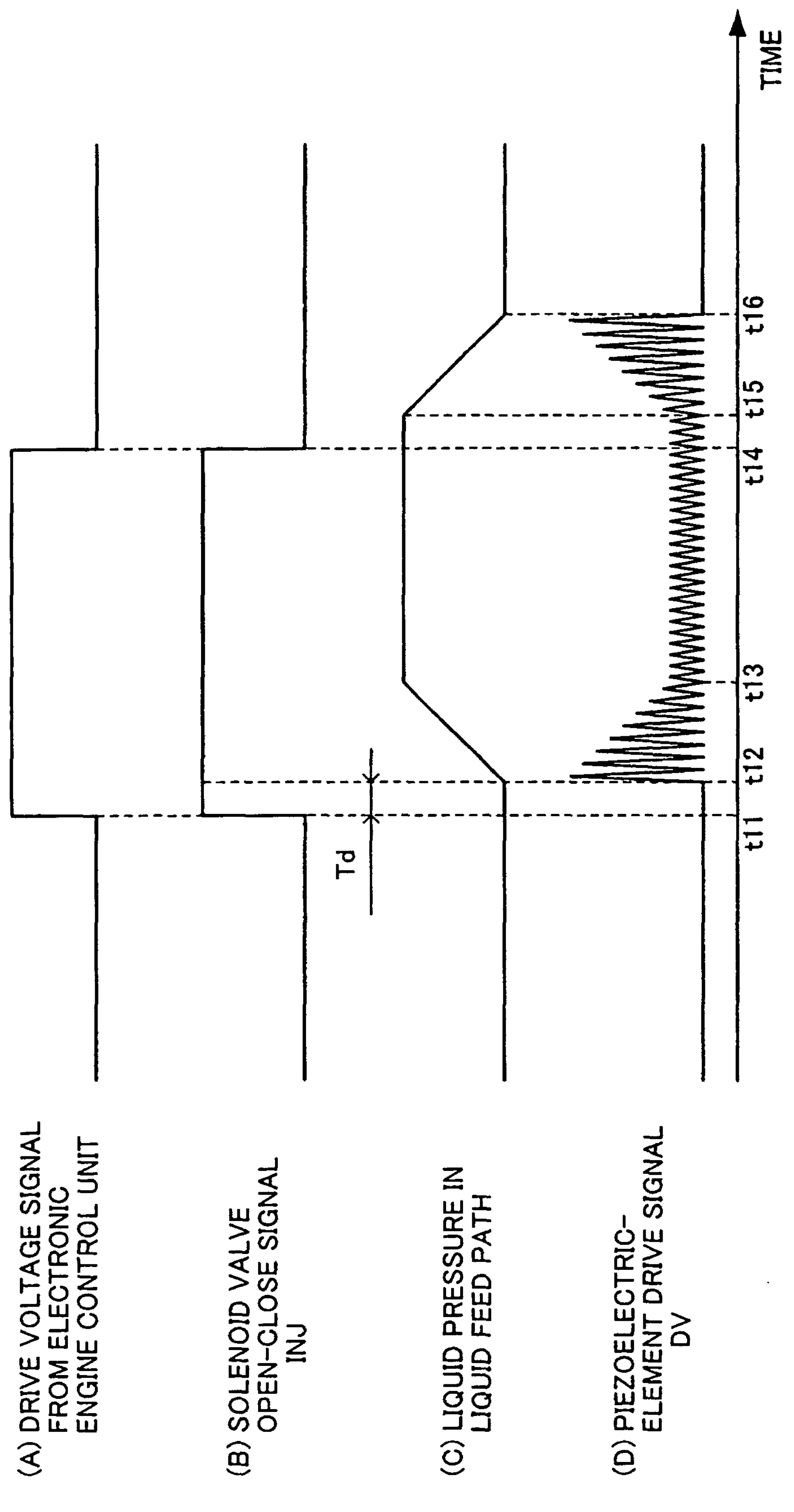
(A) DRIVE VOLTAGE SIGNAL FROM ELECTRONIC ENGINE CONTROL UNIT
(B) SOLENOID VALVE OPEN-CLOSE SIGNAL INJ
(C) LIQUID PRESSURE IN LIQUID FEED PATH
(D) PIEZOELECTRIC-ELEMENT DRIVE SIGNAL DV
Td
t11
t12
t13
t14
t15
t16
TIME

FIG.16

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP03/01619

A. CLASSIFICATION OF SUBJECT MATTER
Int.Cl[7] F02M51/06, F02M61/18, B05B17/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
Int.Cl[7] F02M51/06, F02M61/18, B05B17/04

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Jitsuyo Shinan Koho	1922-1996	Toroku Jitsuyo Shinan Koho	1994-2003
Kokai Jitsuyo Shinan Koho	1971-2003	Jitsuyo Shinan Toroku Koho	1996-2003

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 3-77665 A (TDK Corp.), 03 April, 1991 (03.04.91), Full text; all drawings (Family: none)	1-8
A	EP 1093857 A1 (NGK INSULATORS, LTD.), 25 April, 2001 (25.04.01), Full text; all drawings & WO 00/01491 A & JP 2000-15144 A	1-8
A	JP 4-134176 A (Mazda Motor Corp.), 08 May, 1992 (08.05.92), Full text; all drawings (Family: none)	1-8

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
06 June, 2003 (06.06.03)	17 June, 2003 (17.06.03)
Name and mailing address of the ISA/ Japanese Patent Office	Authorized officer
Facsimile No.	Telephone No.

Form PCT/ISA/210 (second sheet) (July 1998)