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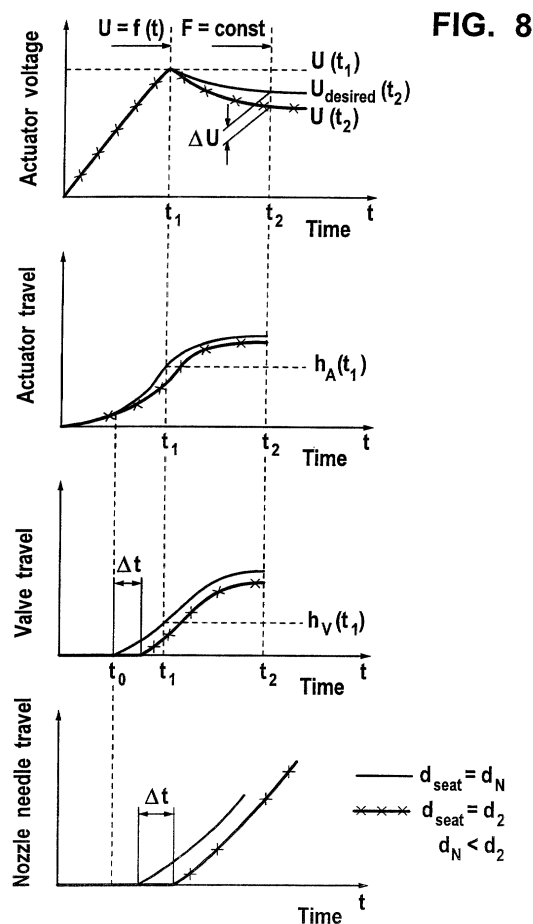
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(54) **Method and apparatus for controlling a fuel injection process**

(57) The invention describes a method and an apparatus for performing a correction to a fuel injection system for, for example, an internal combustion engine. The apparatus is characterized in that a voltage difference deviation is determined for a voltage applied to an piezoelectric element and a correction is applied to an piezoelectric element drive signal based on the voltage difference deviation.



Description

[0001] The present invention relates to an apparatus as defined in the preamble of claim 1, and a method as defined in the preamble of claim 7, i.e., a method and an apparatus for performing a correction to a fuel injection system.

[0002] The present piezoelectric elements being considered in more detail are, in particular but not exclusively, piezoelectric elements used as actuators. Piezoelectric elements can be used for such purposes because, as is known, they possess the property of contracting or expanding as a function of a voltage applied thereto or occurring therein.

[0003] The practical implementation of actuators using piezoelectric elements proves to be advantageous in particular if the actuator in question must perform rapid and/or frequent movements.

[0004] The use of piezoelectric elements as actuators proves to be advantageous, inter alia, in fuel injection nozzles for internal combustion engines. Reference is made, for example, to EP 0 371 469 B1 and to EP 0 379 182 B1 regarding the usability of piezoelectric elements in fuel injection nozzles.

[0005] Piezoelectric elements are capacitative elements which, as already partially alluded to above, contract and expand in accordance with the particular charge state or the voltage occurring therein or applied thereto. In the example of a fuel injection nozzle, expansion and contraction of piezoelectric elements is used to control valves that manipulate the linear strokes of injection needles.

[0006] In a fuel injection nozzle, for example, implemented as a double acting, double seat valve to control linear stroke of a needle for fuel injection into a cylinder of an internal combustion engine, the amount of fuel injected into a corresponding cylinder is a function of the time the valve is open, and in the case of the use of a piezoelectric element, an activation voltage applied to the piezoelectric element. If the valve plug of the valve is located in one of the two seats of the double seat valve, the nozzle needle remains or becomes closed. If the valve plug is in an intermediate position between the seats, then the nozzle needle remains or becomes open. The goal is to achieve a desired fuel injection volume with high accuracy, especially at small injection volumes, for example during pre-injection.

[0007] In the example of a double seat valve, the piezoelectric element is to be expanded or contracted by the effect of an activation voltage so that a controlled valve plug is positioned midway between the two seats of the double seat valve to position the corresponding injection needle for maximum fuel flow during a set time period. It has proven to be difficult to determine and apply an activation voltage suitable for all injection elements and during the whole lifetime of the injection system with sufficient precision such that the corresponding valve plug is accurately positioned for maximum fuel

flow.

[0008] It is therefore an object of the present invention to develop the apparatus as defined in the preamble of claim 1 and the method as defined in the preamble of claim 7 in such a way that an activation voltage level for a piezoelectric element is determined and set with sufficient precision to accurately position a valve plug for maximum fuel flow. The piezoelectric element can be one of several piezoelectric elements used as actuators in a system such as, for example, a fuel injection system.

[0009] This object is achieved, according to the present invention, by way of the features claimed in the characterizing portion of claim 1 (apparatus) and in the characterizing portion of claim 7 (method).

[0010] These provide for:

- a voltage difference deviation is determined for a voltage applied to an piezoelectric element and a correction is applied to an piezoelectric element drive signal based on the voltage difference deviation (characterizing portion of claim 1); and for
- a definition to be made as to a voltage difference deviation and for a correction for application to an piezoelectric element drive signal based on the voltage difference deviation (characterizing portion of claim 7).

[0011] The amount of force needed to move the valve needle is a function of the operating characteristics of the fuel injection system, for example, the fuel pressure applied to the control valve at the fuel injection nozzle, temperature, and so on. Thus, the load on the piezoelectric element from the corresponding valve, and the amount of displacement of the piezoelectric element in response to application of a particular activation voltage are also a function of, for example, the fuel pressure applied to the valve.

[0012] In the case of a common rail fuel injection system, the fuel pressure at any particular fuel injection nozzle for a cylinder will be approximately equal to the fuel pressure in the common rail. The common rail fuel pressure acting upon the valves of an internal combustion engine can change significantly as a function of the working point within the fuel injection system, resulting in considerable changes in the forces acting upon the valve.

[0013] Accordingly, in this example, the activation voltage level for a piezoelectric element, suitable for displacement of the element sufficient to move the injection needle to an optimum midway position for maximum fuel flow, in the example of a double acting valve, is influenced by fuel pressure levels and changes in the level.

[0014] Given an activation voltage level set as a function of an operating characteristic of the fuel injection system such as, for example, fuel pressure, the control valve can be controlled with sufficient accuracy independently of the rail pressure, and therefore of the op-

erating state of the system. The activation voltage applied to a piezoelectric element at any particular time will be appropriate relative to the rail pressure at the time of activation, so that the injection needle is properly positioned by the control valve for maximum injection volume. In this manner, a desired injection volume can be achieved with sufficient accuracy even if the injection volume is small or the injection profile complex.

[0015] Advantageous developments of the present invention are evident from the dependent claims, the description below, and the figures.

[0016] The invention will be explained below in more detail with reference to exemplary embodiments, referring to the figures in which:

Fig. 1 shows a graph depicting the relationship between activation voltage and injected fuel volume in a fixed time period for the example of a double acting control valve;

Fig. 2 shows a schematic profile of an exemplary control valve stroke and a corresponding nozzle needle lift for the example of a double control valve;

Figs. 3A,B show graphs illustrating the relationship between activation voltage and rail pressure;

Fig. 4 shows a block diagram of an exemplary embodiment of an arrangement in which the present invention may be implemented;

Fig. 5A shows a depiction to explain the conditions occurring during a first charging phase (charging switch 220 closed) in the circuit of Fig. 4;

Fig. 5B shows a depiction to explain the conditions occurring during a second charging phase (charging switch 220 open again) in the circuit of Fig. 4;

Fig. 5C shows a depiction to explain the conditions occurring during a first discharging phase (discharging switch 230 closed) in the circuit of Fig. 4;

Fig. 5D shows a depiction to explain the conditions occurring during a second discharging phase (discharging switch 230 open again) in the circuit of Fig. 4;

Fig. 6 shows a block diagram of components of the activation IC E which is also shown in Fig. 4;

Fig. 7 shows a schematic of a common rail fuel injector with a piezoelectric-actuated servo valve; and

5 Fig. 8 shows graphs of the voltage applied to the piezoelectric element versus time, the actuator travel versus time, the valve travel versus time, and the nozzle needle travel versus time.

10 **[0017]** Fig. 1 shows a graph depicting the relationship between activation voltage U and injected fuel volume Q during a preselected fixed time period, for an exemplary fuel injection system using piezoelectric elements acting upon double acting control valves. The y-axis represents volume of fuel injected into a cylinder chamber during the preselected fixed period of time. The x-axis represents the activation voltage U applied to or stored in the corresponding piezoelectric element, used to displace a valve plug of the double acting control valve.

20 **[0018]** At $x=0$, $y=0$, the activation voltage is zero, and the valve plug is seated in a first closed position to prevent the flow of fuel during the preselected fixed period of time. For values of the activation voltage U greater than zero, up to the x-axis point indicated as U_{opt} , the represented values of the activation voltage cause the displacement of the valve plug away from the first seat and towards the second seat, in a manner that results in a greater volume of injected fuel for the fixed time period, as the activation voltage approaches U_{opt} , up to the value for volume indicated on the y-axis by Q_{max} . The point Q_{max} , corresponding to the greatest volume for the injected fuel during the fixed period of time, represents the value of the activation voltage for application to or charging of the piezoelectric element, that results in an optimal displacement of the valve plug between the first and second valve seats.

35 **[0019]** As shown on the graph of Fig. 1, for values of the activation voltage greater than U_{opt} , the volume of fuel injected during the fixed period of time decrease until it reaches zero. This represents displacement of the valve plug from the optimal point and toward the second seat of the double seat valve until the valve plug is seated against the second valve seat. Thus, the graph of Fig. 1 illustrates that a maximum volume of fuel injection occurs when the activation voltage causes the piezoelectric element to displace the valve plug to the optimal point.

40 **[0020]** The present invention teaches that the value for U_{opt} at any given time is influenced by the operating characteristics of the fuel injection system at that time, such as for example, fuel pressure. That is, the amount of displacement caused by the piezoelectric element for a certain activation voltage varies as a function of the fuel pressure. Accordingly, in order to achieve a maximum volume of fuel injection, Q_{max} , during a given fixed period of time, the activation voltage applied to or occurring in the piezoelectric element should be set to a

value relevant to a current fuel pressure, to achieve U_{opt} .

[0021] Fig. 2 shows a double graph representing a schematic profile of an exemplary control valve stroke, to illustrate the double seat valve operation discussed above. In the upper graph of Fig. 2, the x-axis represents time, and the y-axis represents displacement of the valve plug (valve lift). In the lower graph of Fig. 2, the x-axis once again represents time, while the y-axis represents a nozzle needle lift to provide fuel flow, resulting from the valve lift of the upper graph. The upper and lower graphs are aligned with one another to coincide in time, as represented by the respective x-axes.

[0022] During an injection cycle, the piezoelectric element is charged resulting in an expansion of the piezoelectric element, as will be described in greater detail, and causing the corresponding valve plug to move from the first seat to the second seat for a pre-injection stroke, as shown in the upper graph of Fig. 2. The lower graph of Fig. 2 shows a small injection of fuel that occurs as the valve plug moves between the two seats of the double seat valve, opening and closing the valve as the plug moves between the seats. In general, the charging of the piezoelectric element can be done in two steps; the first step to charge it to a certain voltage and cause the valve to open and the second step to charge it further and cause the valve to close again at the second seat. Between both steps, in general, there may be a certain time delay.

[0023] After a preselected period of time, a discharging operation is then performed, as will be explained in greater detail below, to reduce the charge within the piezoelectric element so that it contracts, as will also be described in greater detail, causing the valve plug to move away from the second seat, and hold at a midway point between the two seats. As indicated in Fig. 1, the activation voltage within the piezoelectric element is to reach a value that equals U_{opt} to correspond to an optimal point of the valve lift, and thereby obtain a maximum fuel flow, Q_{max} , during the period of time allocated to a main injection. The upper and lower graphs of Fig. 2 show the holding of the valve lift at a midway point, resulting in a main fuel injection.

[0024] At the end of the period of time for the main injection, the piezoelectric element is discharged to an activation voltage of zero, resulting in further contraction of the piezoelectric element, to cause the valve plug to move away from the optimal position, towards the first seat, closing the valve and stopping fuel flow, as shown in the upper and lower graphs of Fig. 2. At this time, the valve plug will once again be in a position to repeat another pre-injection, main injection cycle, as just described above, for example. Of course, any other injection cycle can be performed.

[0025] Figs. 3A and B show graphs that illustrate the relationship between activation voltage levels and rail pressure, as taught by the present invention, for example, during a main injection, as shown in Fig. 2. The graphs of Figs. 3a and 3b each plot activation voltage

in percent applied to or stored in a piezoelectric element, the displacement of the nozzle needle resulting from the expansion or contraction of the piezoelectric element due to the activation voltage and the valve lift corresponding to this, and the relative fuel pressure in the common rail during the particular cycles depicted in Figs 3a and 3b, respectively. The graph in Fig. 3b differs from the graph in Fig. 3a only in that it illustrates an example for a higher relative rail pressure.

[0026] In each of the cycles shown in Figs. 3a and 3b, respectively, the valve lift is to be an amount that results in a position midway between the two valve seats, as described above. As shown in Figs. 3a and 3b, when the rail pressure peaks, the activation voltage must reach the optimum level to achieve a midway displacement.

[0027] Fig. 4 provides a block diagram of an exemplary embodiment of an arrangement in which the present invention may be implemented.

[0028] In Fig. 4 there is a detailed area A and a non-detailed area B, the separation of which is indicated by a dashed line c. The detailed area A comprises a circuit for charging and discharging piezoelectric elements 10, 20, 30, 40, 50, and 60. In the example being considered these piezoelectric elements 10, 20, 30, 40, 50, and 60 are actuators in fuel injection nozzles (in particular in so-called common rail injectors) of an internal combustion engine. Piezoelectric elements can be used for such purposes because, as is known, and as discussed above, they possess the property of contracting or expanding as a function of a voltage applied thereto or occurring therein. The reason to take six piezoelectric elements 10, 20, 30, 40, 50, and 60 in the embodiment described is to independently control six cylinders within a combustion engine; hence, any other number of piezoelectric elements might match any other purpose.

[0029] The non-detailed area B comprises a control unit D and a activation IC E by both of which the elements within the detailed area A are controlled, as well as measuring system F for measuring system operating characteristics such as, for example, rail pressure. According to the present invention, the control unit D and activation IC E are programmed to control activation voltages for piezoelectric elements as a function of measured or sensed values of operating characteristics of the fuel injection system, as for example, fuel pressure of a common rail system sensed by the measuring system F.

[0030] The following description firstly introduces the individual elements within the detailed area A. Then, the procedures of charging and discharging piezoelectric elements 10, 20, 30, 40, 50, 60 are described in general. Finally, the ways both procedures are controlled by means of control unit D and activation IC E are described in detail.

[0031] The circuit within the detailed area A comprises six piezoelectric elements 10, 20, 30, 40, 50, and 60.

[0032] The piezoelectric elements 10, 20, 30, 40, 50,

and 60 are distributed into a first group G1 and a second group G2, each comprising three piezoelectric elements (i.e., piezoelectric elements 10, 20 and 30 in the first group G1 and elements 40, 50, and 60 in the second group G2). Groups G1 and G2 are constituents of circuit parts connected in parallel with one another. Group selector switches 310, 320 can be used to establish which of the groups G1, G2 of piezoelectric elements 10, 20, and 30 and 40, 50, and 60, respectively, will be discharged in each case by a common charging and discharging apparatus (however, the group selector switches 310, 320 are meaningless for charging procedures, as is explained in further detail below).

[0033] The group selector switches 310, 320 are arranged between a coil 240 and the respective groups G1 and G2 (the coil-side terminals thereof) and are implemented as transistors. Side drivers 311, 321 are implemented which transform control signals received from the activation IC E into voltages which are eligible for closing and opening the switches as required.

[0034] Diodes 315 and 325 (referred to as group selector diodes), respectively, are provided in parallel with the group selector switches 310, 320. If the group selector switches 310, 320 are implemented as MOSFETs or IGBTs for example, these group selector diodes 315 and 325 can be constituted by the parasitic diodes themselves. The diodes 315, 325 bypass the group selector switches 310, 320 during charging procedures. Hence, the functionality of the group selector switches 310, 320 is reduced to select a group G1, G2 of piezoelectric elements 10, 20, and 30 and 40, 50, and 60, respectively, for a discharging procedure only.

[0035] Within each group G1, G2 the piezoelectric elements 10, 20, and 30 and 40, 50, and 60, respectively, are arranged as constituents of piezo branches 110, 120 and 130 (group G1) and 140, 150 and 160 (group G2) that are connected in parallel. Each piezo branch comprises a series circuit made up of a first parallel circuit comprising a piezoelectric element 10, 20, 30, 40, 50, and 60 and a resistor 13, 23, 33, 43, 53 and 63, respectively, (referred to as branch resistors) and a second parallel circuit made up of a selector switch implemented as a transistor 11, 21, 31, 41, 51, and 61 (referred to as branch selector switches) and a diode 12, 22, 32, 42, 52, 62, respectively, (referred to as branch diodes).

[0036] The branch resistors 13, 23, 33, 43, 53, and 63 cause each corresponding piezoelectric element 10, 20, 30, 40, 50, and 60 during and after a charging procedure to continuously discharge themselves, since they connect both terminals of each capacitive piezoelectric element 10, 20, 30, 40, 50, and 60 one to another.

[0037] However, the branch resistors 13, 23, 33, 43, 53, and 63 are sufficiently large to make this procedure slow compared to the controlled charging and discharging procedures as described below. Hence, it is still a reasonable assumption to consider the charge of any piezoelectric element 10, 20, 30, 40, 50 or 60 as unchanging within a relevant time after a charging procedure

(the reason to nevertheless implement the branch resistors 13, 23, 33, 43, 53 and 63 is to avoid remaining charges on the piezoelectric elements 10, 20, 30, 40, 50, and 60 in case of a breakdown of the system or other exceptional situations). Hence, the branch resistors 13, 23, 33, 43, 53 and 63 may be neglected in the following description.

[0038] The branch selector switch/branch diode pairs in the individual piezo branches 110, 120, 130, 140, 150, and 160, i.e., selector switch 11 and diode 12 in piezo branch 110, selector switch 21 and diode 22 in piezo branch 120, and so on, can be implemented using electronic switches (i.e., transistors) with parasitic diodes, for example MOSFETs or IGBTs (as stated above for the group selector switch/diode pairs 310 and 315 and 320 and 325, respectively).

[0039] The branch selector switches 11, 21, 31, 41, 51, and 61 can be used to establish which of the piezoelectric elements 10, 20, 30, 40, 50 or 60, respectively, will be charged in each case by a common charging and discharging apparatus: in each case, the piezoelectric elements 10, 20, 30, 40, 50 or 60 that are charged are all those whose branch selector switches 11, 21, 31, 41, 51 or 61 are closed during the charging procedure which is described below. Usually, at any time only one of the branch selector switches is closed.

[0040] The branch diodes 12, 22, 32, 42, 52 and 62 serve for bypassing the branch selector switches 11, 21, 31, 41, 51 and 61, respectively, during discharging procedures. Hence, in the example considered for charging procedures any individual piezoelectric element can be selected, whereas for discharging procedures either the first group G1 or the second group G2 of piezoelectric elements 10, 20, and 30 and 40, 50, and 60, respectively, or both have to be selected.

[0041] Returning to the piezoelectric elements 10, 20, 30, 40, 50, and 60 themselves, the branch selector piezo terminals 15, 25, 35, 45, 55, 65, respectively, may be connected to ground either through the branch selector switches 11, 21, 31, 41, 51, and 61, respectively, or through the corresponding diodes 12, 22, 32, 42, 52, and 62, respectively, and in both cases additionally through resistor 300.

[0042] The purpose of resistor 300 is to measure the currents that flow during charging and discharging of the piezoelectric elements 10, 20, 30, 40, 50, and 60 between the branch selector piezo terminals 15, 25, 35, 45, 55, and 65, respectively, and the ground. A knowledge of these currents allows a controlled charging and discharging of the piezoelectric elements 10, 20, 30, 40, 50, and 60. In particular, by closing and opening charging switch 220 and discharging switch 230 in a manner dependent on the magnitude of the currents, it is possible to set the charging current and discharging current to predefined average values and/or to keep them from exceeding or falling below predefined maximum and/or minimum values as is explained in further detail below.

[0043] In the example considered, the measurement

itself further requires a voltage source 621 which supplies a voltage of 5V DC, for example, and a voltage divider implemented as two resistors 622 and 623. This is in order to prevent the activation IC E (by which the measurements are performed) from negative voltages which might otherwise occur on measuring point 620 and which cannot be handled by means of activation IC E: such negative voltages are changed into positive voltages by means of addition with a positive voltage setup which is supplied by said voltage source 621 and voltage divider resistors 622 and 623.

[0044] The other terminal of each piezoelectric element 10, 20, 30, 40, 50, and 60, i.e., the group selector piezo terminal 14, 24, 34, 44, 54, and 64, respectively, may be connected to the plus pole of a voltage source via the group selector switch 310, 320, respectively, or via the group selector diode 315, 325, respectively, as well as via a coil 240 and a parallel circuit made up of a charging switch 220 and a charging diode 221, and alternatively or additionally connected to ground via the group selector switch 310, 320, respectively, or via diode 315, 325, respectively, as well as via the coil 240 and a parallel circuit made up of a discharging switch 230 or a discharging diode 231. Charging switch 220 and discharging switch 230 are implemented as transistors, for example, which are controlled via side drivers 222, 232, respectively.

[0045] The voltage source comprises an element having capacitive properties which, in the example being considered, is the (buffer) capacitor 210. Capacitor 210 is charged by a battery 200 (for example a motor vehicle battery) and a DC voltage converter 201 downstream therefrom. DC voltage converter 201 converts the battery voltage (for example, 12V) into substantially any other DC voltage (for example 250V), and charges capacitor 210 to that voltage. DC voltage converter 201 is controlled by means of transistor switch 202 and resistor 203 which is utilized for current measurements taken from a measuring point 630.

[0046] For cross-check purposes, a further current measurement at a measuring point 650 is allowed by activation IC E as well as by resistors 651, 652 and 653 and a 5V DC voltage source, for example, 654; moreover, a voltage measurement at a measuring point 640 is allowed by activation IC E as well as by voltage dividing resistors 641 and 642.

[0047] Finally, a resistor 330 (referred to as total discharging resistor), a stop switch implemented as a transistor 331 (referred to as stop switch), and a diode 332 (referred to as total discharging diode) serve to discharge the piezoelectric elements 10, 20, 30, 40, 50, and 60 (if they happen to be not discharged by the "normal" discharging operation as described further below). Stop switch 331 is preferably closed after "normal" discharging procedures (cycled discharging via discharge switch 230). It thereby connects piezoelectric elements 10, 20, 30, 40, 50, and 60 to ground through resistors 330 and 300, and thus removes any residual charges

that might remain in piezoelectric elements 10, 20, 30, 40, 50, and 60. The total discharging diode 332 prevents negative voltages from occurring at the piezoelectric elements 10, 20, 30, 40, 50, and 60, which might in some circumstances be damaged thereby.

[0048] Charging and discharging of all the piezoelectric elements 10, 20, 30, 40, 50, and 60 or any particular one is accomplished by way of a single charging and discharging apparatus (common to all the groups and their piezoelectric elements). In the example being considered, the common charging and discharging apparatus comprises battery 200, DC voltage converter 201, capacitor 210, charging switch 220 and discharging switch 230, charging diode 221 and discharging diode 231 and coil 240.

[0049] The charging and discharging of each piezoelectric element works the same way and is explained in the following while referring to the first piezoelectric element 10 only.

[0050] The conditions occurring during the charging and discharging procedures are explained with reference to Figs. 5A through 5D, of which Figs. 5A and 5B illustrate the charging of piezoelectric element 10, and Figs. 5C and 5D the discharging of piezoelectric element 10.

[0051] The selection of one or more particular piezoelectric elements 10, 20, 30, 40, 50 or 60 to be charged or discharged, the charging procedure as described in the following as well as the discharging procedure are driven by activation IC E and control unit D by means of opening or closing one or more of the above introduced switches 11, 21, 31, 41, 51, 61; 310, 320; 220, 230 and 331. The interactions between the elements within the detailed area A on the one hand and activation IC E and control unit D on the other hand are described in detail further below.

[0052] Concerning the charging procedure, firstly any particular piezoelectric element 10, 20, 30, 40, 50 or 60 which is to be charged has to be selected. In order to exclusively charge the first piezoelectric element 10, the branch selector switch 11 of the first branch 110 is closed, whereas all other branch selector switches 21, 31, 41, 51 and 61 remain opened. In order to exclusively charge any other piezoelectric element 20, 30, 40, 50, 60 or in order to charge several ones at the same time they would be selected by closing the corresponding branch selector switches 21, 31, 41, 51 and/or 61.

[0053] Then, the charging procedure itself may take place:

[0054] Generally, within the example considered, the charging procedure requires a positive potential difference between capacitor 210 and the group selector piezo terminal 14 of the first piezoelectric element 10. However, as long as charging switch 220 and discharging switch 230 are open no charging or discharging of piezoelectric element 10 occurs: In this state, the circuit shown in Fig. 4 is in a steady-state condition, i.e., piezoelectric element 10 retains its charge state in substan-

tially unchanged fashion, and no currents flow.

[0055] In order to charge the first piezoelectric element 10, charging switch 220 is closed. Theoretically, the first piezoelectric element 10 could become charged just by doing so. However, this would produce large currents which might damage the elements involved. Therefore, the occurring currents are measured at measuring point 620 and switch 220 is opened again as soon as the detected currents exceed a certain limit. Hence, in order to achieve any desired charge on the first piezoelectric element 10, charging switch 220 is repeatedly closed and opened whereas discharging switch 230 remains open.

[0056] In more detail, when charging switch 220 is closed, the conditions shown in Fig. 5A occur, i.e., a closed circuit comprising a series circuit made up of piezoelectric element 10, capacitor 210, and coil 240 is formed, in which a current $i_{LE}(t)$ flows as indicated by arrows in Fig. 5A. As a result of this current flow both positive charges are brought to the group selector piezo terminal 14 of the first piezoelectric element 10 and energy is stored in coil 240.

[0057] When charging switch 220 opens shortly (for example, a few μs) after it has closed, the conditions shown in Fig. 5B occur: a closed circuit comprising a series circuit made up of piezoelectric element 10, charging diode 221, and coil 240 is formed, in which a current $i_{LA}(t)$ flows as indicated by arrows in Fig. 5B. The result of this current flow is that energy stored in coil 240 flows into piezoelectric element 10. Corresponding to the energy delivery to the piezoelectric element 10, the voltage occurring in the latter, and its external dimensions, increase. Once energy transport has taken place from coil 240 to piezoelectric element 10, the steady-state condition of the circuit, as shown in Fig. 4 and already described, is once again attained.

[0058] At that time, or earlier or later (depending on the desired time profile of the charging operation), charging switch 220 is once again closed and opened again, so that the processes described above are repeated. As a result of the re-closing and re-opening of charging switch 220, the energy stored in piezoelectric element 10 increases (the energy already stored in the piezoelectric element 10 and the newly delivered energy are added together), and the voltage occurring at the piezoelectric element 10, and its external dimensions, accordingly increase.

[0059] If the aforementioned closing and opening of charging switch 220 are repeated numerous times, the voltage occurring at the piezoelectric element 10, and the expansion of the piezoelectric element 10, rise in steps.

[0060] Once charging switch 220 has closed and opened a predefined number of times, and/or once piezoelectric element 10 has reached the desired charge state, charging of the piezoelectric element is terminated by leaving charging switch 220 open.

[0061] Concerning the discharging procedure, in the

example considered, the piezoelectric elements 10, 20, 30, 40, 50, and 60 are discharged in groups (G1 and/or G2) as follows:

[0062] Firstly, the group selector switch(es) 310 and/or 320 of the group or groups G1 and/or G2 the piezoelectric elements of which are to be discharged are closed (the branch selector switches 11, 21, 31, 41, 51, 61 do not affect the selection of piezoelectric elements 10, 20, 30, 40, 50, 60 for the discharging procedure, since in this case they are bypassed by the branch diodes 12, 22, 32, 42, 52 and 62). Hence, in order to discharge piezoelectric element 10 as a part of the first group G1, the first group selector switch 310 is closed.

[0063] When discharging switch 230 is closed, the conditions shown in Fig. 5C occur: a closed circuit comprising a series circuit made up of piezoelectric element 10 and coil 240 is formed, in which a current $i_{EE}(t)$ flows as indicated by arrows in Fig. 5C. The result of this current flow is that the energy (a portion thereof) stored in the piezoelectric element is transported into coil 240. Corresponding to the energy transfer from piezoelectric element 10 to coil 240, the voltage occurring at the piezoelectric element 10, and its external dimensions, decrease.

[0064] When discharging switch 230 opens shortly (for example, a few μs) after it has closed, the conditions shown in Fig. 5D occur: a closed circuit comprising a series circuit made up of piezoelectric element 10, capacitor 210, discharging diode 231, and coil 240 is formed, in which a current $i_{EA}(t)$ flows as indicated by arrows in Fig. 5D. The result of this current flow is that energy stored in coil 240 is fed back into capacitor 210. Once energy transport has taken place from coil 240 to capacitor 210, the steady-state condition of the circuit, as shown in Fig. 4 and already described, is once again attained.

[0065] At that time, or earlier, or later (depending on the desired time profile of the discharging operation), discharging switch 230 is once again closed and opened again, so that the processes described above are repeated. As a result of the re-closing and re-opening of discharging switch 230, the energy stored in piezoelectric element 10 decreases further, and the voltage occurring at the piezoelectric element, and its external dimensions, also accordingly decrease.

[0066] If the aforementioned closing and opening of discharging switch 230 are repeated numerous times, the voltage occurring at the piezoelectric element 10, and the expansion of the piezoelectric element 10, decrease in steps.

[0067] Once discharging switch 230 has closed and opened a predefined number of times, and/or once the piezoelectric element has reached the desired discharge state, discharging of the piezoelectric element 10 is terminated by leaving discharging switch 230 open.

[0068] The interaction between activation IC E and control unit D on the one hand and the elements within

the detailed area A on the other hand is performed by control signals sent from activation IC E to elements within the detailed area A via branch selector control lines 410, 420, 430, 440, 450, 460, group selector control lines 510, 520, stop switch control line 530, charging switch control line 540 and discharging switch control line 550 and control line 560. On the other hand, there are sensor signals obtained on measuring points 600, 610, 620, 630, 640, 650 within the detailed area A which are transmitted to activation IC E via sensor lines 700, 710, 720, 730, 740, 750.

[0069] The control lines are used to apply or not to apply voltages to the transistor bases in order to select piezoelectric elements 10, 20, 30, 40, 50, or 60 to perform charging or discharging procedures of single or several piezoelectric elements 10, 20, 30, 40, 50, 60 by means of opening and closing the corresponding switches as described above. The sensor signals are particularly used to determine the resulting voltage of the piezoelectric elements 10, 20, and 30 and 40, 50, and 60 from measuring points 600, 610, respectively, and the charging and discharging currents from measuring point 620. The control unit D and the activation IC E are used to combine both kinds of signals in order to perform an interaction of both as will be described in detail now while referring to Figs. 4 and 6.

[0070] As is indicated in Fig. 4, the control unit D and the activation IC E are connected to each other by means of a parallel bus 840 and additionally by means of a serial bus 850. The parallel bus 840 is particularly used for fast transmission of control signals from control unit D to the activation IC E, whereas the serial bus 850 is used for slower data transfer.

[0071] In Fig. 6 some components are indicated, which the activation IC E comprises: a logic circuit 800, RAM memory 810, digital to analog converter system 820 and comparator system 830. Furthermore, it is indicated that the fast parallel bus 840 (used for control signals) is connected to the logic circuit 800 of the activation IC E, whereas the slower serial bus 850 is connected to the RAM memory 810. The logic circuit 800 is connected to the RAM memory 810, to the comparator system 830, and to the signal lines 410, 420, 430, 440, 450 and 460; 510 and 520; 530; 540, 550 and 560. The RAM memory 810 is connected to the logic circuit 800 as well as to the digital to analog converter system 820. The digital to analog converter system 820 is further connected to the comparator system 830. The comparator system 830 is further connected to the sensor lines 700 and 710; 720; 730, 740 and 750 and -as already mentioned- to the logic circuit 800.

[0072] The above listed components may be used in a charging procedure for example as follows:

[0073] By means of the control unit D a particular piezoelectric element 10, 20, 30, 40, 50 or 60 is determined which is to be charged to a certain target voltage. Hence, firstly the value of the target voltage (expressed by a digital number) is transmitted to the RAM memory

810 via the slower serial bus 850. The target voltage can be, for example, the value for U_{opt} used in a main injection, as described above with respect to Fig. 1. Later or simultaneously, a code corresponding to the particular piezoelectric element 10, 20, 30, 40, 50 or 60 which is to be selected and the address of the desired voltage within the RAM memory 810 is transmitted to the logic circuit 800 via the parallel bus 840. Later on, a strobe signal is sent to the logic circuit 800 via the parallel bus 840 which gives the start signal for the charging procedure.

[0074] The start signal firstly causes the logic circuit 800 to pick up the digital value of the target voltage from the RAM memory 810 and to put it on the digital to analog converter system 820 whereby at one analog exit of the converters 820 the desired voltage occurs. Moreover, said analog exit (not shown) is connected to the comparator system 830. In addition hereto, the logic circuit 800 selects either measuring point 600 (for any of the piezoelectric elements 10, 20, or 30 of the first group G1) or measuring point 610 (for any of the piezoelectric elements 40, 50, or 60 of the second group G2) to the comparator system 830. Resulting thereof, the target voltage and the present voltage at the selected piezoelectric element 10, 20, 30, 40, 50 or 60 are compared by the comparator system 830. The results of the comparison, i.e., the differences between the target voltage and the present voltage, are transmitted to the logic circuit 800. Thereby, the logic circuit 800 can stop the procedure as soon as the target voltage and the present voltage are equal to one another.

[0075] Secondly, the logic circuit 800 applies a control signal to the branch selector switch 11, 21, 31, 41, 51 or 61 which corresponds to any selected piezoelectric element 10, 20, 30, 40, 50 or 60 so that the switch becomes closed (all branch selector switches 11, 21, 31, 41, 51 and 61 are considered to be in an open state before the onset of the charging procedure within the example described). Then, the logic circuit 800 applies a control signal to the charging switch 220 so that the switch becomes closed. Furthermore, the logic circuit 800 starts (or continues) measuring any currents occurring on measuring point 620. Hereto, the measured currents are compared to any predefined maximum value by the comparator system 830. As soon as the predefined maximum value is achieved by the detected currents, the logic circuit 800 causes the charging switch 220 to open again.

[0076] Again, the remaining currents at measuring point 620 are detected and compared to any predefined minimum value. As soon as said predefined minimum value is achieved, the logic circuit 800 causes the charging switch 220 to close again and the procedure starts once again.

[0077] The closing and opening of the charging switch is repeated as long as the detected voltage at measuring point 600 or 610 is below the target voltage. As soon as the target voltage is achieved, the logic circuit stops the

continuation of the procedure.

[0078] The discharging procedure takes place in a corresponding way: Now the selection of the piezoelectric element 10, 20, 30, 40, 50, or 60 is obtained by means of the group selector switches 310, 320. The discharging switch 230 instead of the charging switch 220 is opened and closed and a predefined minimum target voltage is to be achieved.

[0079] The timing of the charging and discharging operations and the holding of voltage levels in the piezoelectric elements 10, 20, 30, 40, 50, or 60 depends on the corresponding valve stroke to realize a certain injection, as shown, for example, in Fig. 2.

[0080] It is to be understood that the above given description of the way charging or discharging procedures take place are exemplary only. Hence, any other procedure which utilizes the above described circuits or other circuits might match any desired purpose and any corresponding procedure may be used in place of the above described example.

[0081] As stated previously, it has proven to be difficult to determine and apply an activation voltage suitable for all injection elements and during the whole lifetime of the injection system with sufficient precision such that a corresponding valve plug is accurately positioned for maximum fuel flow. To be able to meter the quantity of fuel to be injected with as much precision as possible, it is required to switch the servo valve exactly. One of the difficulties that can be encountered in switching the valve exactly is due to the physical differences in the sizes of the valve seats in the multiple injectors that are used in any one control system. These physical differences may be due to manufacturing inaccuracies. Since manufacturing tolerances, among other factors, play a significant role in being able to provide the exact quantity of fuel required, it is desired to be able to account for these manufacturing inaccuracies in the control system and to modify the operation of the control system accordingly. One approach for monitoring the movement of the valve could be to provide additional travel sensors on the servo valve, however, this approach would be costly. Therefore, the present invention provides an apparatus and method for performing a correction to the drive system based on the voltage that can be measured at the piezoelectric element and using this correction to compensate for manufacturing inaccuracies. Specifically, the invention compensates for manufacturing inaccuracies in the servo valve.

[0082] Fig. 7 shows a schematic of a common rail injector 1000 with a piezoelectric-actuated servo valve 1030. The operation of the injector 1000 will also be discussed in connection with Fig. 8. Fig. 8 provides graphs of the voltage applied to the piezoelectric element versus time, the actuator travel versus time, the valve travel versus time, and the nozzle needle travel versus time. Each of the graphs in Fig. 8 is positioned with respect to each of the other graphs in Fig. 8 such that the points of interest on the time axes of each graph (the x axes)

are aligned for each graph.

[0083] As discussed previously, the piezoelectric element 1010 is operated in a voltage-controlled mode, i.e., the voltage U is initially a function of time, $U = f(t)$, until time t_1 . In this operation, the piezoelectric element 1010 expands and the pressure in the coupler 1020 increases. The valve 1030 is first held closed by the rail pressure P_{CR} . In a nominal case, i.e., with a nominal size for the valve seat 1035 as will be further discussed below, the valve 1030 does not open until time t_0 when the pressure in the coupler 1020 has exceeded a specific value. If the voltage across the piezoelectric element 1010 has reached a specified value, the piezoelectric element is disconnected from the voltage source at the control unit side. Starting at this moment t_1 , the charge F on the piezoelectric element 1010 is approximately constant because of it being disconnected from the voltage source. After the servo valve 1030 has opened, the pressure in the control chamber 1050 is released and the needle 1040 raises from its seat.

[0084] In the nominal case, at time t_1 , the valve 1030 has reached a specific travel $h_v(t_1)$. The piezoelectric element 1010 has also reached a specific travel $h_A(t_1)$. The charge F on the piezoelectric element is fixed with the actuator travel and the applied voltage at time t_1 . Since the valve 1030 and the piezoelectric element 1010 have not yet reached a position of equilibrium, the voltage U on the piezoelectric element drops again as the actuator travel increases. In the nominal case, i.e., with a nominal size for the valve seat 1035, a known voltage difference $U_{desired}(t_2) - U(t_1)$ is present. The travel of the piezoelectric element 1010 is also known at time t_2 and t_1 . The graphs for piezoelectric element voltage, actuator travel, valve travel, and nozzle needle travel versus time when the valve seat d_{seat} is of a nominal size, i.e., $d_{seat} = d_N$, are illustrated by the lines indicated in the legend of Fig. 8.

[0085] If there are manufacturing inaccuracies, for example, if the valve seat d_{seat} is made too large, i.e., $d_{seat} = d_2$ where $d_N < d_2$, the valve 1030 opens later than it does in the nominal case, i.e., at time of $t_0 + \Delta t$, since a higher coupler pressure must be built up. Consequently, because the nozzle needle travel also starts at a later time, i.e., at a delay of Δt from the nominal start time, the fuel injection process also starts later. In this way, the quantity of fuel injected is too small. The graphs for piezoelectric element voltage, actuator travel, valve travel, and nozzle needle travel versus time when the valve seat d_{seat} is made too large, i.e., $d_{seat} = d_2$, are also illustrated by the lines indicated in the legend of Fig. 8.

[0086] Since the valve travel starts with a time delay of Δt , the valve travel, and thus the actuator travel, at time t_1 will be less, resulting in a certain voltage difference $U(t_2) - U(t_1)$. From this, a voltage difference deviation, or error, $\Delta U = U(t_2) - U_{desired}(t_2)$ in relation to the nominal case can be determined. The actuator travel and the valve travel are closely linked to one another

and for this reason, the valve travel at time t_1 can be derived.

[0087] The voltage difference deviation is thus a measure for the time delay Δt and in turn for the seat error of the valve 1030. Since the voltage deviation ΔU is determined in the control unit D, the piezoelectric element drive signal (voltage and time of the drive signal) can be adapted for the next fuel injection process such that the valve 1030 and the nozzle needle 1040 open at the specified time.

[0088] A voltage difference deviation can also be determined by comparing voltage signals applied to different fuel injectors at a same relative time within each injector's injection cycle. So for example, for specific injectors i and j, a voltage due to the charge of the piezoelectric element at injector i, at a point t_{i2} , or $u(t_{i2})$, can be compared to a voltage due to the charge of the piezoelectric element at injector j at time t_{j2} , or $u(t_{j2})$. From this comparison, a voltage difference deviation can also be determined. The voltage difference deviation can be used to determine whether or not an error exists in one or the other injector, or, if one injector is treated as having a desired voltage $u(t_{i2}$ or $t_{j2})$ then a correction can be applied to the piezoelectric element drive signal of the other injector.

Claims

1. A fuel injection system having a piezoelectric element (10, 20, 30, 40, 50, or 60) for controlling an amount of injected fuel by charging and/or discharging the piezoelectric element (10, 20, 30, 40, 50, or 60) to a voltage, **characterized in that** a control unit (D) is provided for determining a voltage difference deviation for the voltage and applying a correction to a piezoelectric element drive signal based on the voltage difference deviation.
2. The apparatus as defined in claim 1, **characterized in that** the voltage deviation is determined by comparing the voltage to a desired voltage.
3. The apparatus as defined in claims 1 or 2, **characterized in that** the voltage difference deviation is determined by comparing voltages of piezoelectric elements (10, 20, 30, 40, 50, or 60) of different fuel injectors at a same relative time in each injector's injection cycle.
4. The apparatus as defined in claim 1, 2, or 3, **characterized in that** the voltage difference deviation is indicative of a time delay in a travel start time of a valve.
5. The apparatus as defined in claim 1, 2, 3, or 4 **characterized in that** the voltage difference deviation is indicative of a seat error of a valve.
6. The apparatus as defined in claim 1, 2, 3, 4, or 5, **characterized in that** the correction applied to the piezoelectric element drive signal includes a correction to a voltage of the drive signal and/or a time of transmitting the drive signal.
7. A method for operating a fuel injection system with a piezoelectric element (10, 20, 30, 40, 50, or 60) for controlling an amount of injected fuel by charging and/or discharging the piezoelectric element (10, 20, 30, 40, 50, or 60) to a voltage, **characterized in that** a voltage difference deviation is determined and a correction to a piezoelectric element drive signal is applied based on the voltage difference deviation.
8. The method as defined in claim 7 **characterized in that** the voltage difference deviation is indicative of a time delay in a travel start time of a valve.
9. The method as defined in claim 7 or 8 **characterized in that** the voltage difference deviation is indicative of a seat error of a valve.
10. The method as defined in claim 7, 8, or 9 **characterized in that** the correction applied to the piezoelectric element drive signal includes a correction to a voltage of the drive signal and/or a time of transmitting the drive signal.
11. The method as defined in claim 7, 8, 9, or 10, **characterized in that** the voltage deviation is determined by comparing the voltage to a desired voltage.
12. The method as defined in claims 7, 8, 9, 10, or 11, **characterized in that** the voltage difference deviation is determined by comparing voltages of piezoelectric elements of different fuel injectors at a same relative time in each injector's injection cycle.

FIG. 1

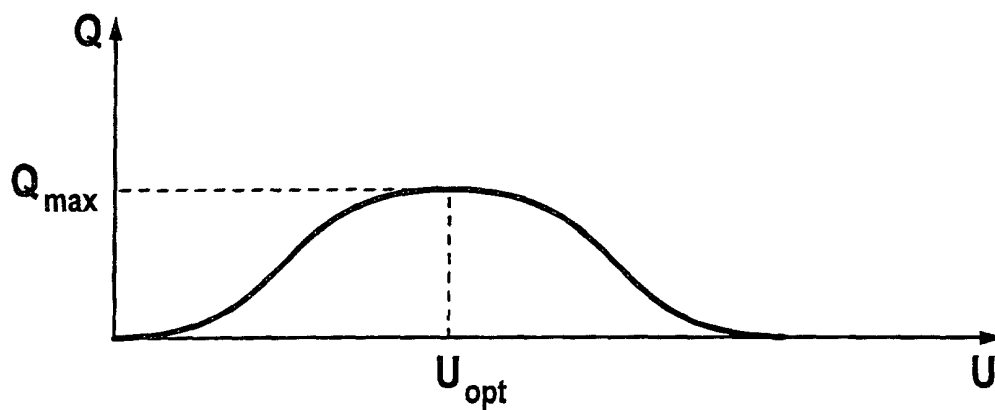
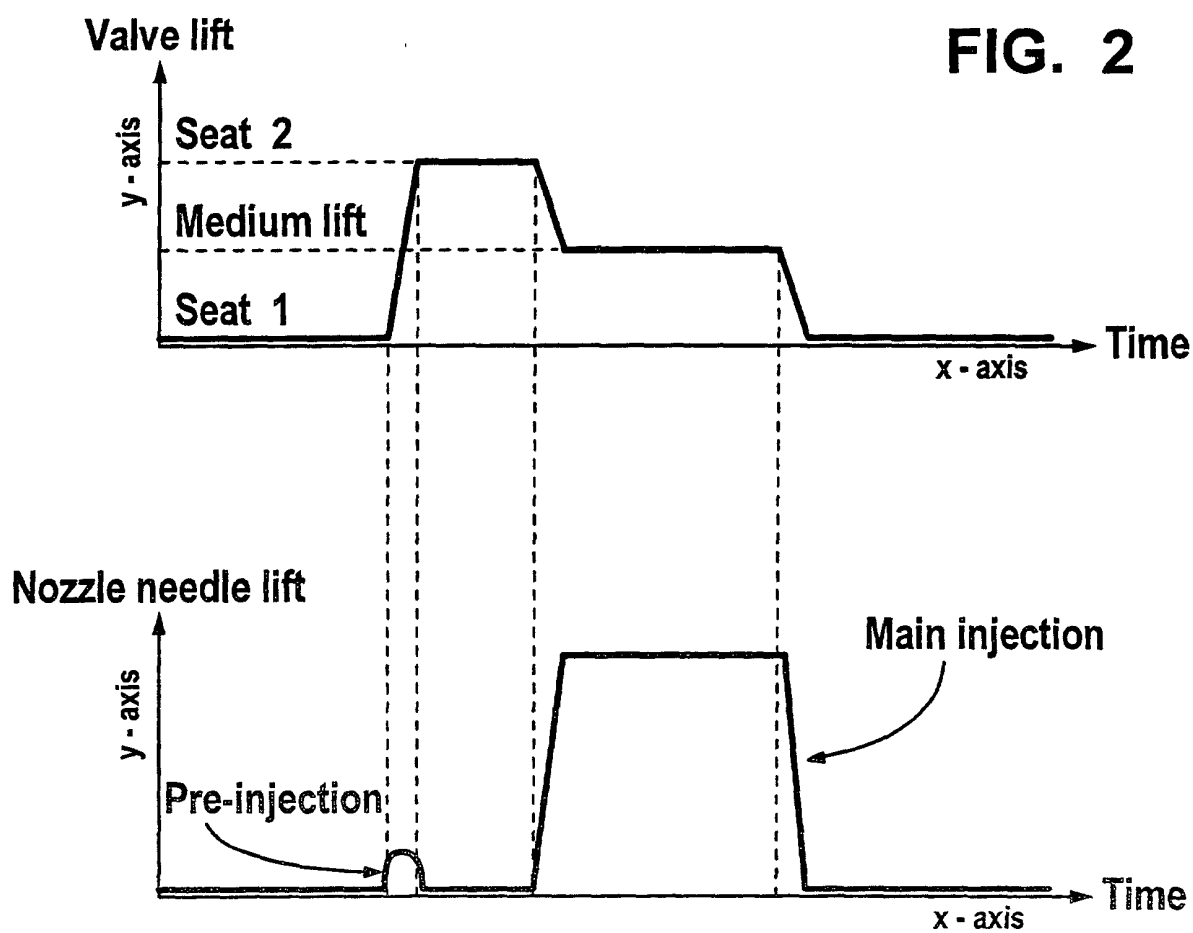
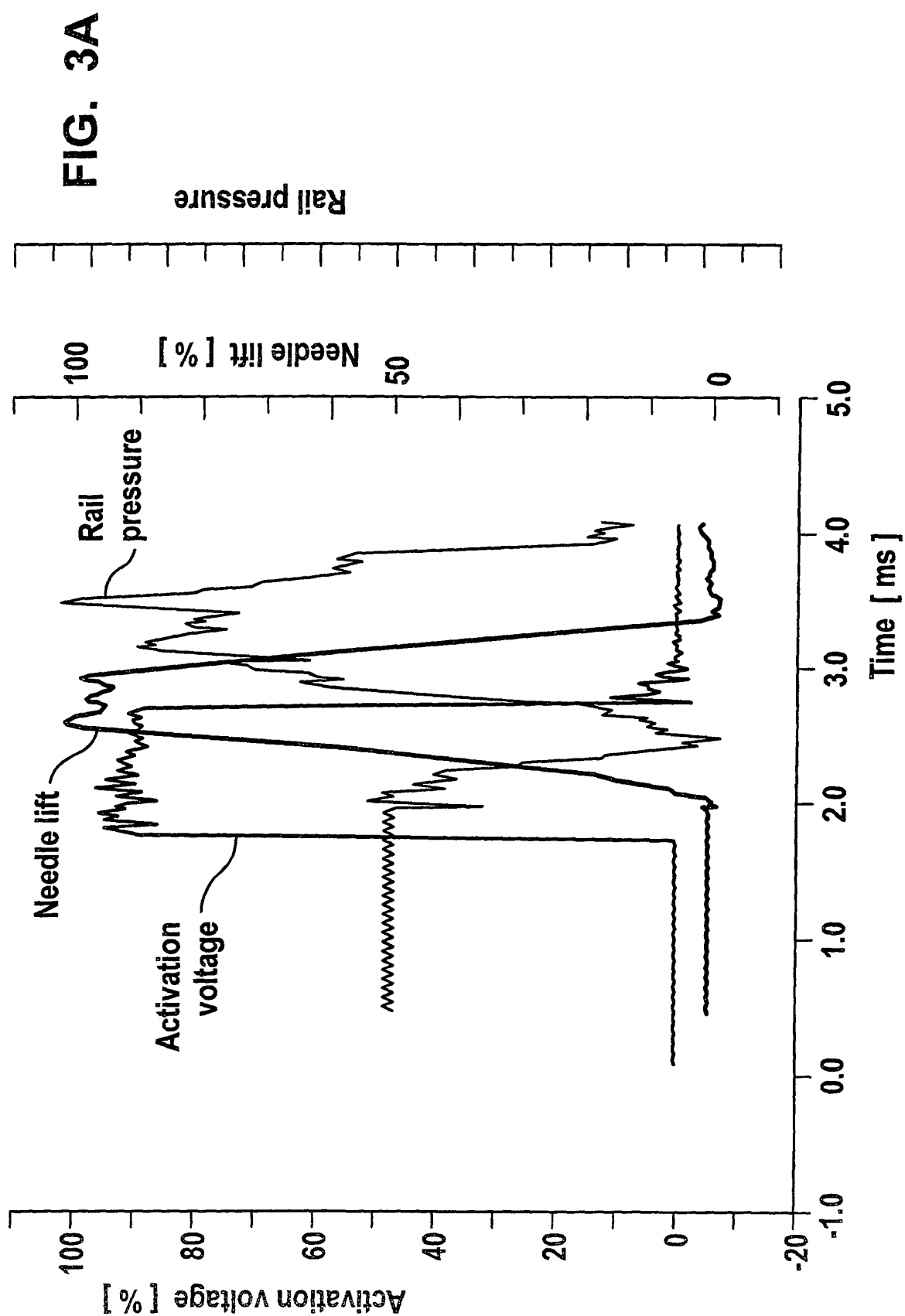
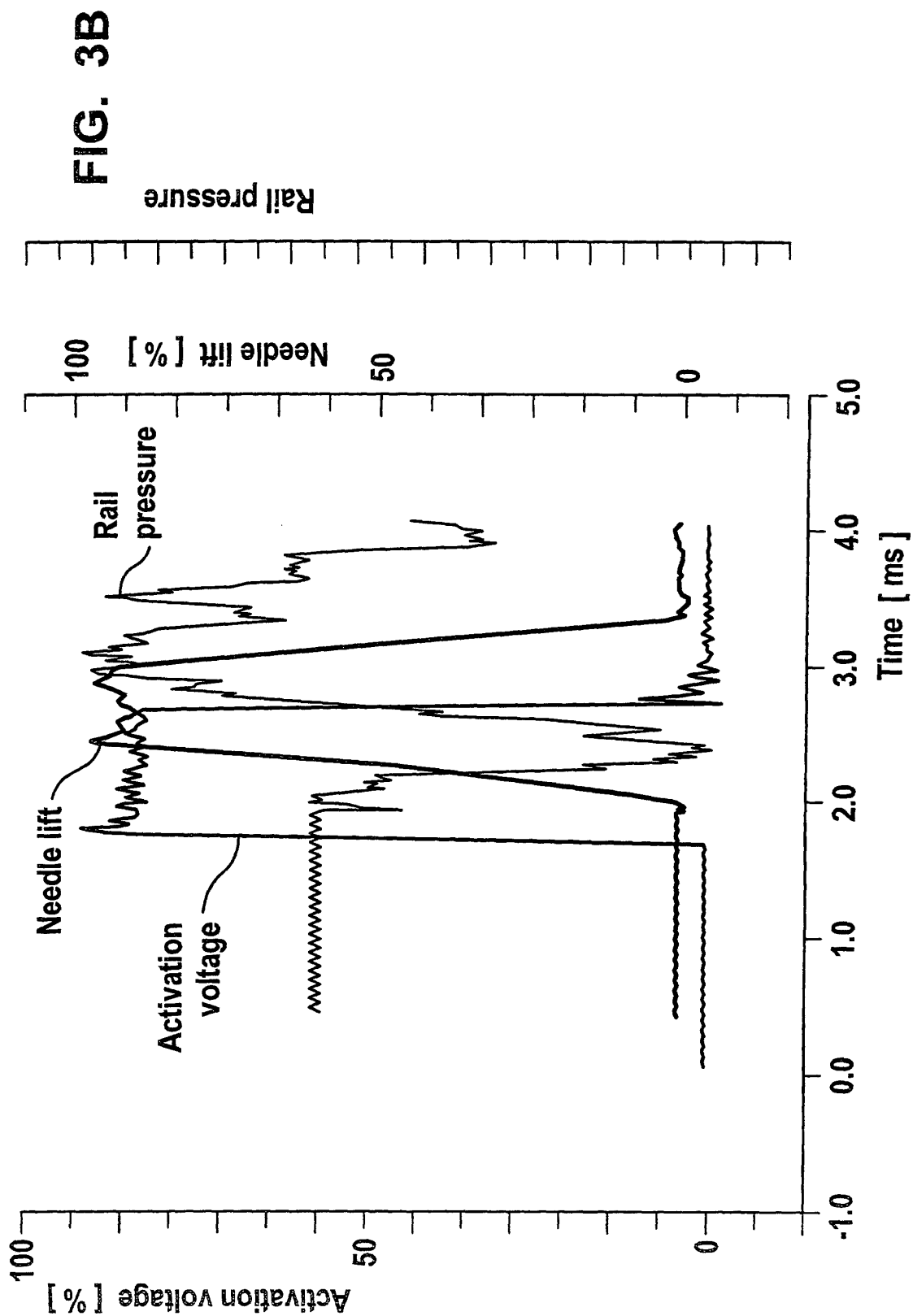


FIG. 2







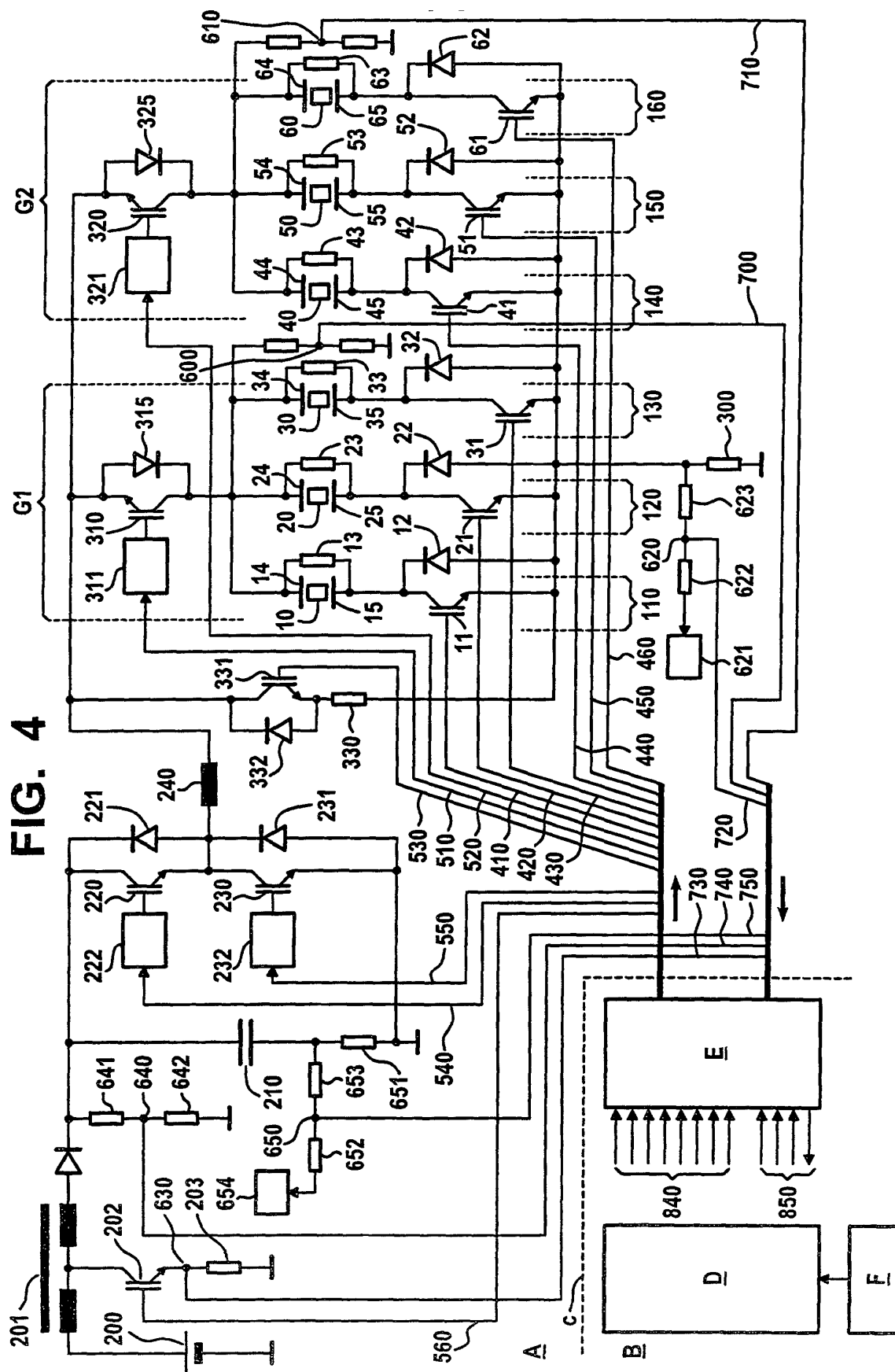


FIG. 5A

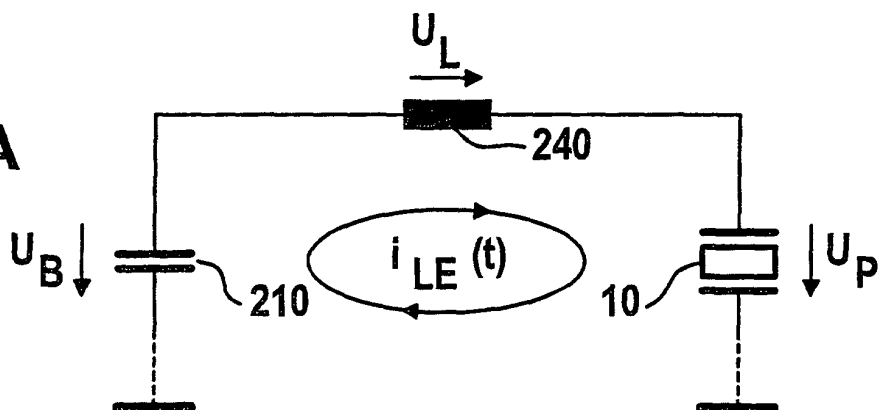


FIG. 5B

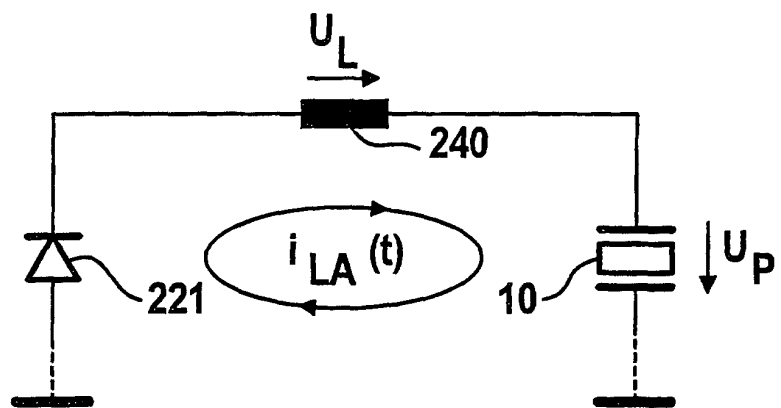


FIG. 5C

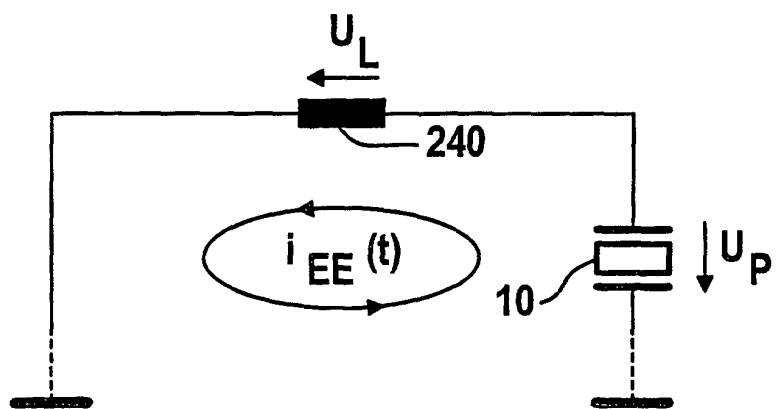
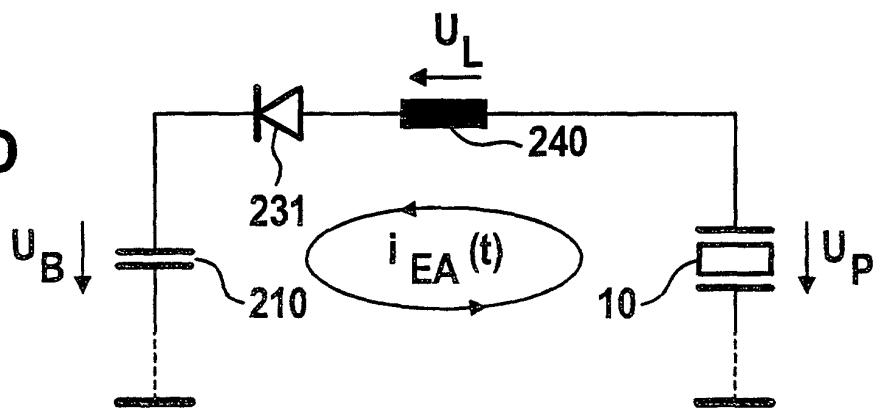


FIG. 5D



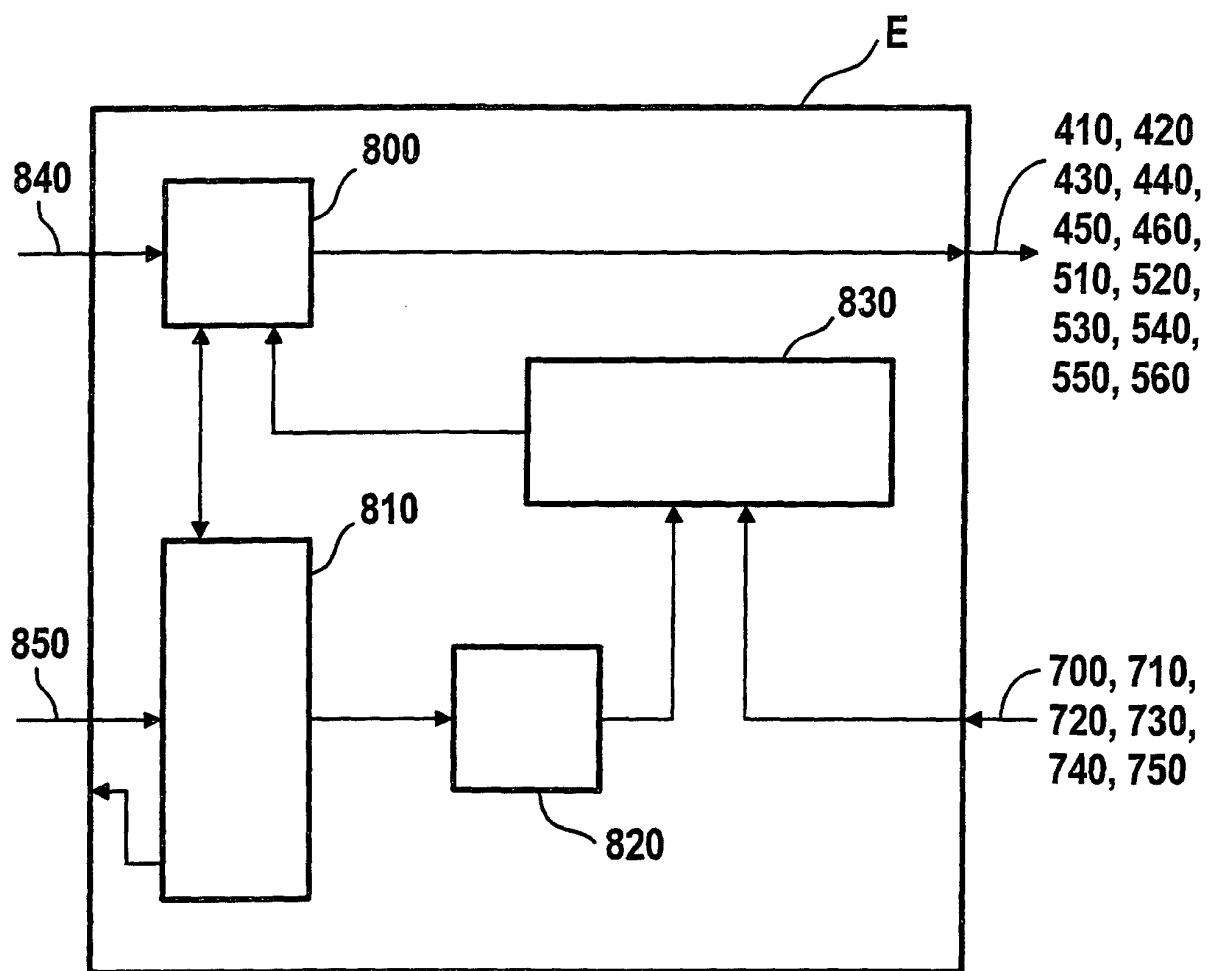


FIG. 6

FIG. 7

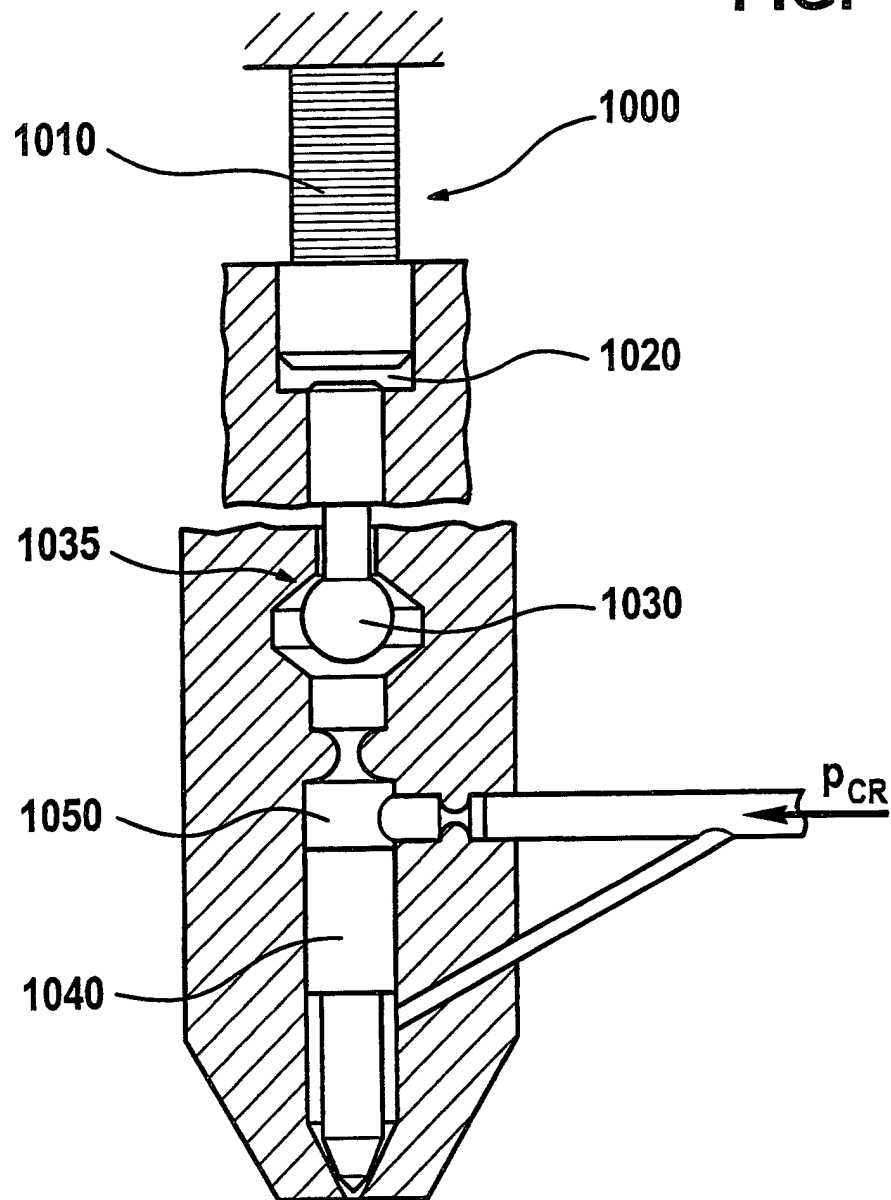
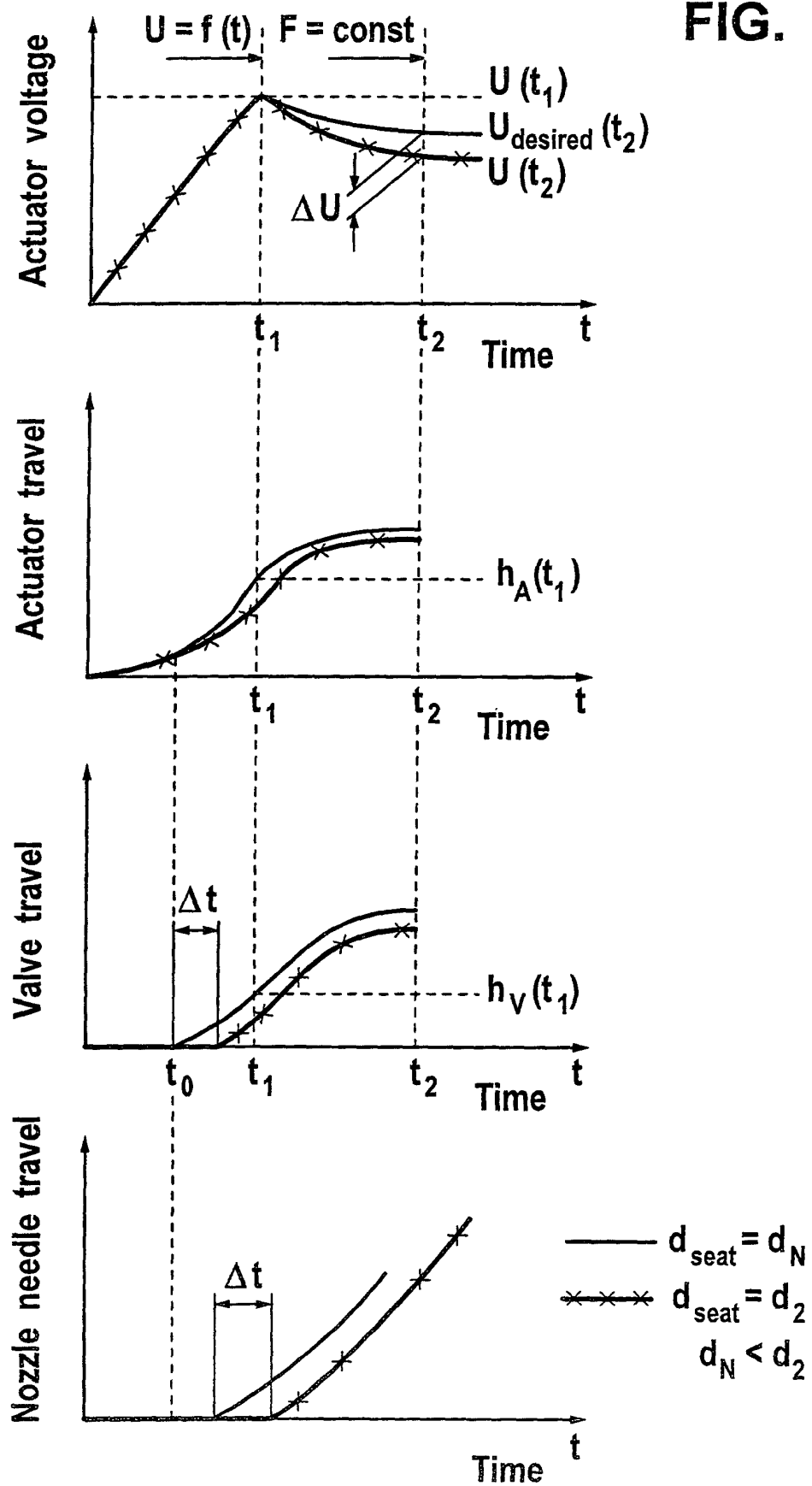


FIG. 8





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EUROPEAN SEARCH REPORT

Application Number
EP 00 10 6975

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The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 18 August 2000	Examiner Kooijman, F
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			

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18-08-2000

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