

[54] **FUEL INJECTION SYSTEM FOR INTERNAL COMBUSTION ENGINES**

[75] Inventor: **Cormac G. O'Neill**, Lafayette, Calif.

[73] Assignee: **Physics International Company**, San Leandro, Calif.

[22] Filed: **June 29, 1972**

[21] Appl. No.: **267,550**

3,036,564	5/1962	Guiot.....	123/32 EA
3,319,613	5/1967	Begley et al.....	123/32 EA
3,575,145	4/1971	Steiger	123/139 E
3,587,547	6/1971	Hussey et al.....	123/139 E
3,596,640	8/1971	Bloomfield	123/139 E

Primary Examiner—Laurence M. Goodridge
Attorney, Agent, or Firm—Lindenberg, Freilich & Wasserman

[52] U.S. Cl. **123/32 EA, 123/119 R, 123/139 E**

[51] Int. Cl. **F02m 5/06**

[58] Field of Search..... **123/139 E, 102, 32 EA, 123/119 R**

[56] **References Cited**

UNITED STATES PATENTS

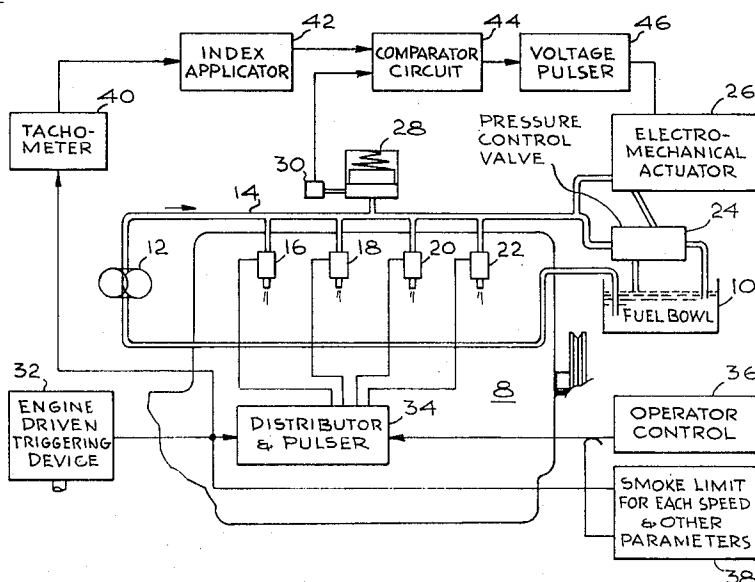
2,918,911 12/1959 Guiot..... 123/32 EA

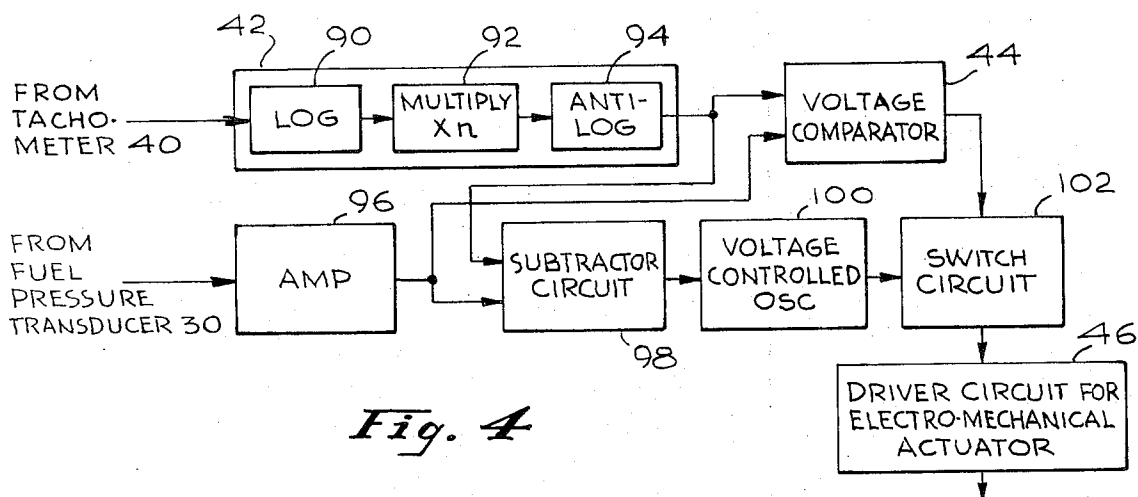
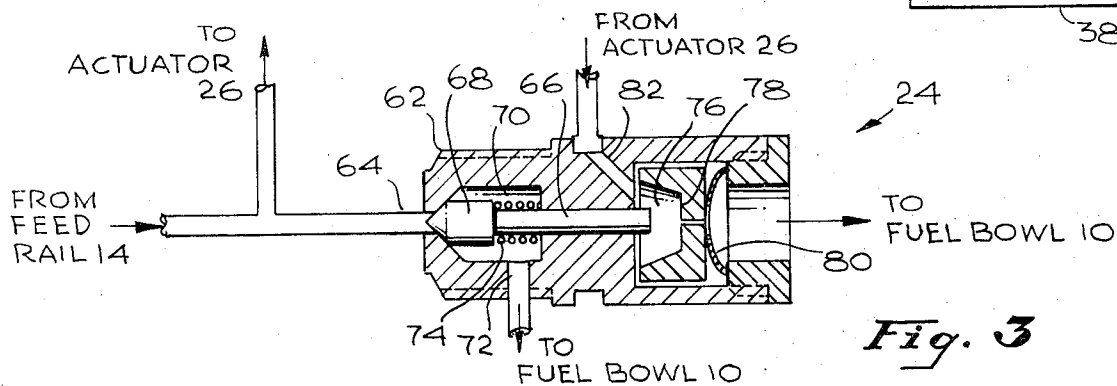
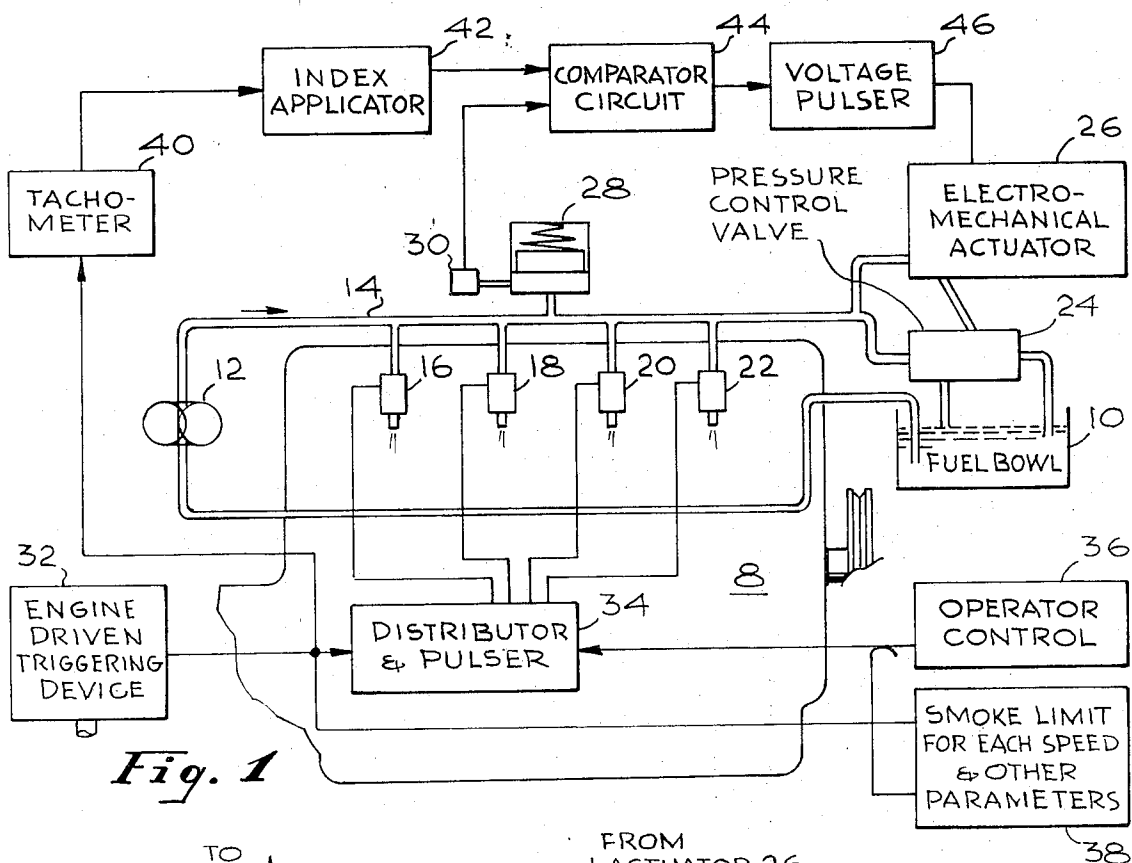
[57]

ABSTRACT

A system is provided for varying the fuel pressure of an internal combustion engine having a common rail system as a function of an engine parameter, such as engine speed or air mass intake.

8 Claims, 7 Drawing Figures





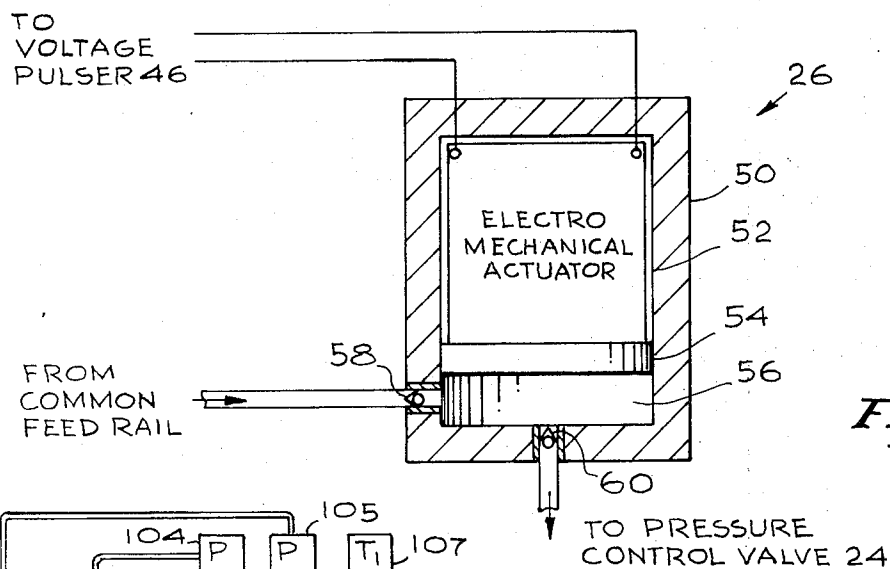


Fig. 2

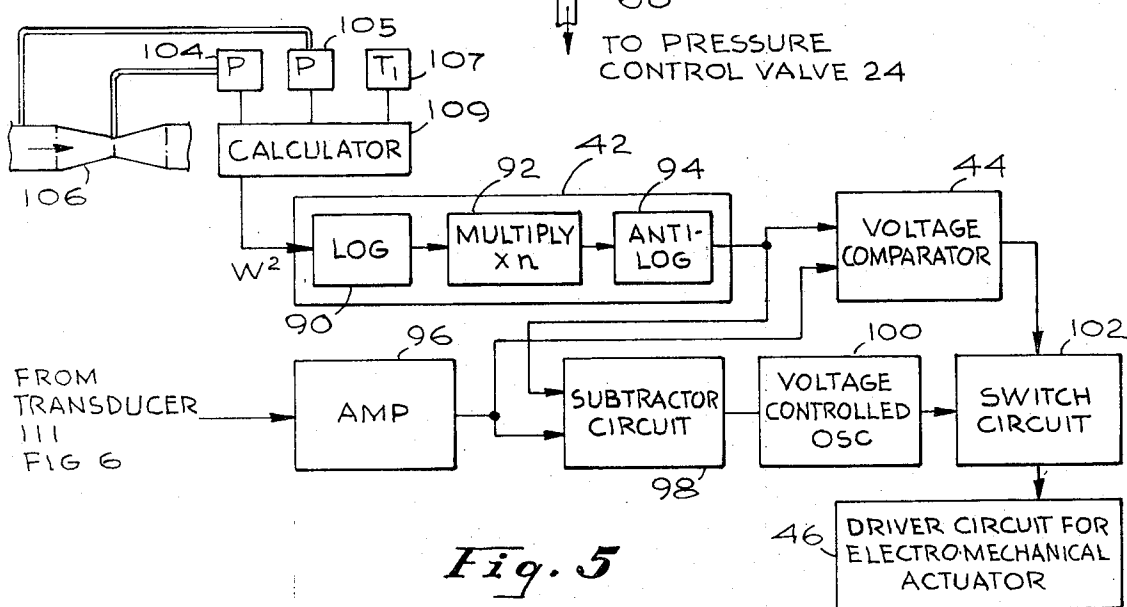


Fig. 5

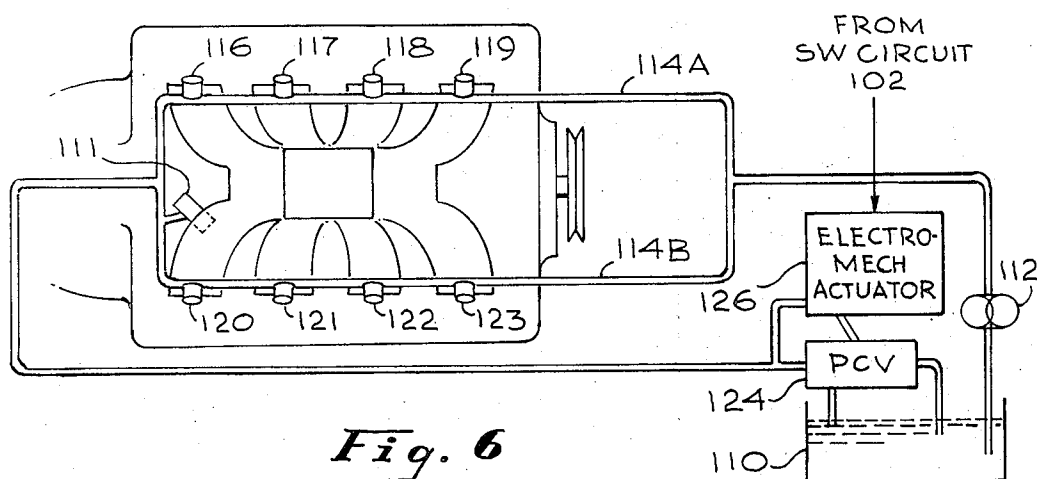


Fig. 6

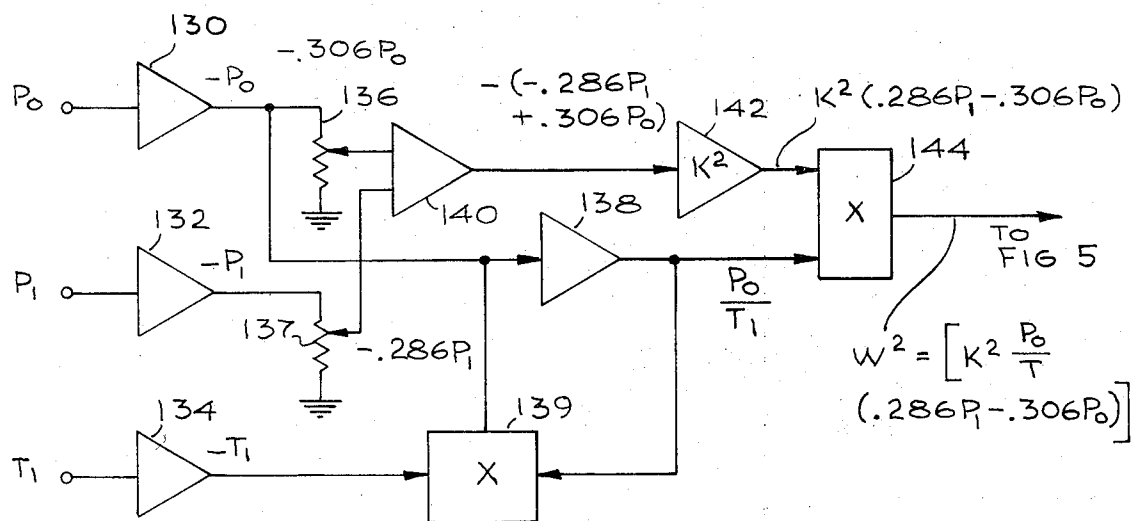


Fig. 7

FUEL INJECTION SYSTEM FOR INTERNAL COMBUSTION ENGINES

BACKGROUND OF THE INVENTION

This invention relates to fuel injection systems and more particularly, to improvements therein.

Fuel injection systems are used in normal practice to affect the introductions of liquid fuel to the induction ports or cylinders or internal combustion engines. In one system, a mechanically driven pump is used to raise fuel to injection pressure. A pressure regulating valve is employed to control the fuel pressure in a common feedrail so that it is maintained at a constant value, with excess fuel being spilled back to the pump inlet. Injection valves which are fed from the common rail, are then opened sequentially for a duration responsive to the operating needs of the engine to regulate the amount of fuel that is injected at a constant injection rate. In spark ignition engines, a turndown ratio of approximately 4 to 1 is required between maximum load and minimum load fuel at any speed. It has been found advantageous in the reduction of toxic emissions from gasoline engine exhaust to effect injection during the time that the engine's inlet valve is open. Since only 5 to 6 milliseconds are typically available for injection within the intake period at maximum speed, a minimum injection duration of 1.25 to 1.5 milliseconds becomes mandatory for minimum load at all speeds, since time duration is the only control parameter available. Such short injection duration is difficult to achieve with electromagnetic or mechanically operated injection valves. Very short injection intervals with these valves give inconsistent fuel control, which might be tolerated at high speed, but is not acceptable at idle and off-idle conditions.

In diesel engines, a constant pressure in the common rail applies a constant rate of fuel injection. The rate of injection required to inject maximum fuel at high RPM must also be accepted at low RPM. Excessive diesel knock then occurs for the following reasons. Diesel fuel has an injection delay period which is approximately constant and independent of engine speed. If fuel is injected at an excessive rate, the entire fuel charge will be within the cylinder undergoing the ignition delay phase. Upon heat release, the full charge will combust almost instantaneously causing rapid pressure rise and heavy knock. It would be more desirable to inject fuel at a slow rate during slow running, so that only a small proportion of the charge will complete the ignition delay phase and the bulk of the fuel will burn at a rate controlled by the injection rate. Fuel injected after the release of heat from the first fuel injected will then combust almost immediately as it is injected, due to the greater reaction rate at higher temperature, as described by the Arrhenius relationship, and pressure rise rate may be controlled by injection rate.

Consequently, even when pilot injection is employed, a variable injection rate of the main injection is desirable to control pressure rise, peak pressure, noise, formation of nitrogen oxides and other effects related to high cylinder pressure and temperature.

OBJECTS AND SUMMARY OF THE INVENTION

An object of this invention is to provide a system for controlling the pressure of fuel in a common feed rail for an internal combustion engine, in accordance with changes in engine speed or air mass intake.

Another object of the present invention is the provision of a novel fuel pressure control system in an internal combustion engine having a common feed rail.

Still another object of the present invention is the provision of a common feed rail fuel pressure control system that can rapidly increase or decrease pressure in response to predetermined engine variables.

These and other objects of the invention may be achieved in an arrangement wherein the pressure in a common rail is determined by a pressure control valve. The pressure control valve is operated to enable the pressure in the common rail to increase or decrease in response to the output of a pump. The pump is operated in response to an engine parameter, such as engine speed. This is calculated as $p \propto (\text{RPM})^n$ where RPM is engine speed, n is an index (exponent) established by tuning, and p is the calculated fuel pressure. The index n may be considered to be that applicable to the Bernoulli relationship $p \propto v^2$ where v is the velocity of flow through an orifice under pressure p . However, in practical systems departures occur from this theoretical relationship due to viscous effects at low Reynolds numbers and due to eddy losses and other irreversible processes. The Bernoulli index of 2 is consequently seldom achieved precisely in practice and adjustment for this departure must be provided by practical calibration tests.

With an increase in engine speed the pump is operated in a manner to cause the pressure control valve to allow less and less of the fuel in the common rail to circulate thus building up the pressure, and with a decrease in engine speed to allow more fuel to circulate thus decreasing the pressure. Engine speed is converted to an analog form and then is used to calculate a theoretically correct pressure. The actual common rail fuel pressure is measured and compared with the computed pressure. Any difference is used to control an electromechanical actuator in a manner to control the pressure control valve to bring the common rail fuel pressure up to or down to the calculated value. By adjusting fuel pressure, for example, in proportion to $(\text{RPM})^2$ the time of valve opening for constant fuel per engine stroke will vary inversely with engine speed (equivalent to a constant crankshaft degree interval) and longer periods of opening are permitted at low speed giving more accuracy in fuel regulation.

The novel features of the invention are set forth with particularity in the appended claims. The invention will best be understood from the following description when read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a digrammatic lay out of a system in accordance with this invention which may be employed with diesel engines.

FIG. 2 illustrates an electromechanical actuator of a type suitable for use as a pump in this invention.

FIG. 3 shows a pressure control valve suitable for use with this invention.

FIG. 4 is a block schematic diagram illustrating a computing circuit for a diesel engine suitable to control a pump for this invention.

FIG. 5 is a block schematic diagram illustrating details of a computer circuit, suitable for use with a gasoline engine, which may be employed for controlling the pump which is used in this invention.

FIG. 7 is a block schematic diagram of an analog calculator exemplary of one which may be employed to calculate (air mass flow rate)².

DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 represents a diagrammatic lay out of a system for diesel engines, in accordance with this invention. The engine, 8, has a fuel holding bowl, 10, and a fuel feed pump, 12, which pumps fuel from the fuel bowl through a common feed fuel line 14. The pump, 12, is capable of raising the fuel pressure through the common feed line to a value exceeding the maximum pressure required for injection. The common feed line is also known as a common rail. A plurality of injection valves, 16, 18, 20, 22, which may be of the type, for example, which are actuated in response to an electrical signal, are connected for the purpose of injecting fuel from the common rail into the cylinders of the engine.

The common feed rail 14 returns fuel to the fuel bowl 10 by way of a pressure control valve 24, the details of which are shown in FIG. 3. The pressure control valve operates both in response to the pressure of the fuel in the feed rail as well as under the control of an electromechanical actuator 26, which may be a solenoid operated pump, or a magnetostrictive pump or a piezoelectric pump, of the general type represented in FIG. 2.

An accumulator 28 taps the common feed rail of fuel under pressure for the purpose of providing an energy source close to the injection valves to ensure good flow response. It also enables a pressure transducer 30 to measure the fuel pressure and generate a voltage whose amplitude is indicative thereof. An engine driven triggering device 32, comprises an arrangement for obtaining electrical pulses having a frequency determined by the engine speed. Such arrangements are well known and merely comprise a shaft, driven from the engine, which actuates a switch for each rotation of the shaft whereby a voltage signal having the frequency of the engine is generated. The output of the engine driven trigger device is applied to a high voltage distributor and pulser circuit 34, which comprises circuitry for properly shaping the waveform of the signal received from the engine driven trigger device and then distributing it to the proper one of the injection valves, 16 through 22, which is to inject fuel at that time. The duration of the interval over which the injection valves are maintained open is controlled by an operator control 36. The heavier the load, the longer the interval desired for the injection valves to be maintained open. This operator control can be the pedal in the operator's cab which is connected to the high voltage distributor and pulser circuit 34 for the purpose of lengthening or shortening the width of the pulse being applied to the fuel injection valves. Other engine variables which may be used for controlling the duration of the opening of the fuel injection valves, are engine speed, fuel rail pressure, engine load, smoke level, air consumption or other parameters. Such data may be converted to sig-

nals by appropriate sensors and used to modify the signal of the operator control. The circuitry representing this function is designated by the reference numeral 38. Illustrative suitable structure and techniques, for modifying or controlling the duration of the opening of fuel injection valves are shown in U. S. Pat. application Ser. No. 33,376, filed April 30, 1970.

The output of the engine driven trigger device, 32, is also applied to a tachometer, 40, whose function it is to generate a signal having a voltage representative of the engine speed. The tachometer is applied to a circuit 42, which is designated as the index applicator. The index applicator is shown in more detail in FIG. 4. It functions to convert the engine speed to a voltage whose amplitude is indicative of the pressure which the fuel in the common feed rail should have at that engine speed in order to insure proper operation of the engine, in the manner described heretofore. The signal representing the actual feed rail fuel pressure generated by the pressure transducer 30, and the signal representing the desired fuel pressure from the index applicator 42, are applied to a comparator circuit 44. When the voltages representative of the two pressures are unequal, the comparator circuit applies an output to a switch circuit 102. The voltages representing actual and desired fuel pressures are also applied to a subtractor circuit 98 from which the output represents the disparity between these voltages. This output is fed to voltage controlled oscillator 100 so that voltage pulses are fed to switch circuit 102 at a frequency proportional to the disparity. The output of the switch circuit is applied to the electromechanical actuator which operates, in a manner to be described subsequently, to cause the pressure control valve to increase or reduce the amount of fuel being returned from the common feed rail to the fuel bowl whereby the pressure in the common feed rail is brought up to or reduced to the value determined for the speed of the engine.

FIG. 2 shows an electromechanical actuator 26 of the type suitable for use in this invention. It comprises a housing 50 which contains, an electroexpansive element 52. This may be a stack of a piezoelectric discs, or a magnetostrictive actuator or a solenoid actuator, or a mechanically driven pump that can be brought into engagement with an eccentric driver by actuation of an electrically driven member or valve.

The electroexpansive element 52 actuates a piston 54 causing it to reciprocate in a chamber 56. At one end of the chamber is an inlet from the feed rail in which there is a check valve 58. At the bottom of the chamber is an outlet to the pressure control valve 24, which also contains a check valve 60.

The structure described briefly above will be recognized as a pump of the type wherein the quantity of fuel which is transmitted thereto is a function, over a given interval, of the frequency of operation of the electromechanical actuator and of the pressure at which fluid is supplied to it. A patent which describes a structure suitable for use herein is a Stec Pat. No. 3,150,592, Stevens British Pat. No. 778,962 or Benson Pat. No. 3,589,345. It should be noted that the check valves 58 and 60 are provided to allow a pressure increase of several thousand psi to occur.

FIG. 3 is a cross section of a pressure control valve 24 which may be employed with the embodiment of the invention. It comprises a housing 62 having an opening 64 which communicates with the feed rail 14. A slide-

able rod 66 is retained within the housing and carries a valve member 68 at one end which may be moved to block or partially block the opening communicating with the feed rail. The valve member 68 moves within a cavity 70, which communicates with an opening 72, which is connected to the fuel bowl. The valve member is biased by a spring 74 which urges the valve member to close the opening 64.

Fuel pressure operating on the valve member 68 overcomes the pressure of the spring 74, allowing fuel to pass the valve seating and return to the fuel bowl through the opening 72.

There is another chamber 76 which is adjacent to the end of the rod 66 which does not carry the valve member. The other end of this chamber carries a pierced plug 78 that provides an abutment for the diaphragm spring 80, and restricts but does not prevent passage of fuel that leaks past the shaft 66 and fuel that is pumped from actuator 26. The chamber 76 communicates via a passageway 82 to the output of the electromechanical actuator 26. The pierced plug 78 is displaced by pressure to deflect diaphragm spring 80 and acts as a pressure accumulator to smooth pulsations produced by actuator 26 and apply a steady pressure to the end of shaft 66.

When the fuel pressure from the feed rail 14 is applied to the valve member 68, by the opening 64, it is resisted by the pressure of spring 74 as well as the pressure applied to the end of the shaft 66 which extend into the chamber 76 by reason of the fuel being applied under pressure from actuator 26 via passageway 82. The back pressure in the feed rail increases until this back pressure, acting on the valve member 68 exceeds the pressure applied to the other end of the shaft 66 plus the spring pressure whereby fuel can flow more freely from the feed rail through the chamber 70 and the opening 72 back to the fuel bowl.

FIG. 4 is a block schematic diagram illustrating the index applicator 42, comparator circuit 44 and voltage pulser 46. The analog voltage output of the tachometer 40, representing the engine speed, is applied to a logarithmic circuit 90. This, is a well known, and commercially purchasable circuit which converts the voltage applied to its input to a voltage representative of the logarithm thereof. The output of the logarithmic circuit 90 is applied to a multiplier 92 which multiplies the logarithm by n . n may be greater or less than unity. The value of n is preset when the engine is tuned, and once so fixed remains constant. The output of the multiplier circuit 92 is applied to an antilog circuit 94. The effect of the operation by the circuits 90, 92 and 94 is to take the voltage representative of speed or RPM and raise it to the n th power or to generate the quantity $(RPM)^n$. This signal is fed to the voltage comparator 44.

The other input to the voltage comparator 44 is derived from the pressure transducer 30 and comprises a signal representative of the pressure in the feed rail. This signal is applied to an amplifier 96 which establishes the input voltage at a suitable level. The output of the amplifier 96 is applied to the voltage comparator 44 as well as to a subtractor circuit 98. The other input to the subtractor circuit 98 comprises the signal $(RPM)^n$. The difference between the two signals, which is the difference between actual fuel pressure and computed fuel pressure, is applied to a voltage controlled oscillator 100. This circuit provides an output whose frequency is determined or controlled by the amplitude

of the input signal. The output of the comparator circuit 44 is applied to a switching circuit 102, which may include a silicon controlled rectifier. The silicon controlled rectifier, or switch 102, can be controlled by the output of the voltage comparator 44 to pass or not pass output from the voltage controlled oscillator 100.

When the actual fuel pressure is equal to or greater than the computed fuel pressure $(RPM)^n$, the voltage comparator does not enable the switch 102 to pass oscillations from the voltage controlled oscillator 100 to a driver circuit or voltage pulser 46, for the electromechanical actuator. When the feed rail pressure is less than $(RPM)^n$, the voltage comparator enables switch 102 to pass the oscillations from the voltage controlled oscillator to the driver circuit 46 which can then drive the electromechanical actuator. The magnitude of the difference between the feed rail fuel pressure representative signal and the $(RPM)^n$ representative signal is the output of the subtractor circuit 98, and is used to control the frequency of the signals which are used to operate the electromechanical actuator. Thus, the larger the difference between actual fuel rail pressure and pressure following the relationship $p = k(RPM)^n$, the greater the frequency of operation of the actuator 26 when enabled to operate by switch 102. Under repeated cycles, the actuator raises fuel pressure between the inlet 64 from the feed rail and the actuator outlet 82 so as to create an unbalanced force on the valve member 68 causing it to restrict the leakage from the feed rail to the fuel bowl. Pressure then rises in the feed rail causing a corresponding increase in pressure in the chamber 76 because the actuator 26 increases pressure by a constant increment and providing a greater sealing pressure on the valve member 68. When pressure in the rail 14 achieves the desired relationship to engine speed, the comparator circuit 44 closes switch 102 to prevent further operation of the electromechanical actuator. Leakage can then occur in the pressure control valve allowing pressure from the rail 14 to fall, until the cycle is repeated. Rod 66, in cooperation with the pierced plug 78 and diaphragm spring 80, act to damp out pulsations caused by the output of the actuator 26 and in cooperation with the adjustable leakage orifice in the diaphragm 78, provides a regulation for system hysteresis and resulting hunting.

When pressure in the feed rail 14 rises above the desired relationship, due for example to a drop in RPM, created for example, by sudden load application the actuator 26 remains inoperative and pressure control valve member 68 opens as pressure in the chamber 76 is reduced, due to fuel leakage through the control orifice in the pierced plug 78, and the leakage paths around the periphery of plug 78. This is followed by motion of the valve member 68 to further open the orifice 64 whereby pressure in the feed rail falls until the desired pressure is re-established whereupon the actuator 26 will again operate to maintain the condition.

The timing of the opening of the fuel injection valve 16, 18, 20 and 22 for a diesel engine is achieved employing a system such as that described in U. S. Pat. No. 3,575,146. The timing of valve closure is controlled by the operator who determines the load requirement. However, at each speed, a limit on maximum fuel quantity is desirable to prevent the engine from producing excessive smoke. Since each speed specifies a unique injection pressure, limits on maximum fuel will dictate a program of maximum valve open time duration ver-

speed. Thus, a control mechanism of, for example, the type described in U. S. Pat. No. 3,575,146 can adequately accommodate a smoke limit program. Speed governing can similarly be accommodated, both of these provisions overruling the operator's duration control input.

In a spark ignition internal combustion engine, the opening duration of the fuel injection valves is controlled in response to engine operating parameters, or preferably in response to air mass consumption when pressure in the fuel rail is constant. When pressure in the fuel rail is not constant, it is necessary to employ a system such as, for example, that described in Patent application No. 155,220, entitled "Fuel Injection and Control System," by Cormac G. O'Neill, and assigned to a common assignee. In the structures described in this application, the actual pressure drop across the injection valve is sensed and the signal is compared with the signal produced by air mass flow into the engine. When these signals are in a predetermined relationship, for example P_f varies as (mass air flow)² fuel is fed to the engine over a constant crank angle and a constant fuel/air ratio is maintained. When the fuel pressure departs from the desired relationship, a circuit computes the injection duration required to produce the required fuel delivery at this pressure and accordingly, adjusts the crank shaft angle over which injection is permitted in order to achieve this duration. In an arrangement of this type, a system such as that shown in FIG. 5 may be used to control the actuator.

FIG. 5, is a block schematic diagram of an arrangement for use, in accordance with this invention, with a spark type internal combustion engine. An air pressure transducer 104 generates a signal P_2 which represents pressure at the throat of a venturi meter 106, through which the air flows to the internal combustion engine. This signal together with signals P_1 and T_1 respectively generated by an ambient air pressure transducer 105 and an ambient air temperature transducer 107 are applied to a calculator 109 which calculates (corrected air mass flow rate)² from these signals. In (now allowed) U.S. Pat. application No. 33,376, entitled "Mass Flow Metered Fuel Injection System" by Cormac G. O'Neill, and assigned to a common assignee there is derived from the formula for air flow through a venturi, (which takes into consideration ambient temperature and pressure) the following approximate formula for mass air flow rate W .

$$W = C_d v \cdot A_v \sqrt{\frac{2\gamma}{\gamma-1} \cdot \frac{g}{R} \cdot \frac{P_1}{\sqrt{T_1}} \left[\frac{P_0}{P_1} \left(0.286 - 0.306 \frac{P_0}{P_1} \right) \right]^{1/2}} \quad (1)$$

where

$C_d v$ = coefficient of discharge of venturi

W = flow rate

A_v = venturi throat area (in.²)

g = units conversion factor = 32.2 ft/sec/sec

P_1 = ambient pressure

T_1 = ambient temperature

P_2 = throat pressure

R = gas constant = 96.5 ft. lbs/lb.

γ = gamma law gas factor - assumed as 1.4

$P_0 = P_1 - P_2$

The signal produced by the calculator 109 represents the corrected air mass flow rate, squared. This signal is fed to a circuit 40 which is similar to the one described

in FIG. 4. It comprises a logarithmic circuit 90 the output of which is applied to a circuit 92 for multiplying by n , the output of which is applied to an antilog circuit 94. This circuit, the input signal is raised to an index n which can range between 0.5 to 2.5. The output of the antilog circuit 94, representative of (corrected air mass flow rate) ^{n} , is applied to the voltage comparator 44 also to a subtractor circuit 98. The other input to both the voltage comparator and the subtractor circuit 98 is derived from the output of an amplifier, to whose input is applied a voltage representing the fuel pressure drop across the fuel injection valve, which is derived from a transducer 111, as shown in FIG. 6.

When the amplified fuel pressure drop signal from amplifier 134 exceeds the computed fuel pressure, the voltage comparator circuit 44 controls the switch circuit 102 so that no output from the oscillator 100 can flow to the electromechanical driver circuit 46. When the fuel pressure signal falls below the air flow signal, comparator 44 enables the switch circuit 102 to pass signals from the voltage controlled oscillator 100 to the electromechanical actuator driver circuit. Subtractor circuit 198 produces a voltage representing the difference between the two circuits applied to the voltage comparator and the difference is used to control the voltage controlled oscillator 100. The frequency of the voltage controlled oscillator is representative of the magnitude of the input signal.

Adjustment of the index n permits account to be taken of air and hydraulic flow phenomena that modify the incompressible Bernoulli relationship $p \propto v^2$, independently of whether these modifications result from fuel or air effects. Such an effect may, for example, be produced by heavy pulsations in the intake system where ram pipes or resonant chambers are employed. For such cases, the air flow produces a mean signal that is higher, since it represents the root mean square of the instantaneous flow characteristic.

It is clear that such an arrangement would hold the air mass flow and fuel pressure in the desired relationship at all times. However, the pressure range demanded between maximum fuel flow at maximum speed and minimum fuel flow at minimum speed to achieve a constant crank angle injection period can be between 1,000 and 1,500 to 1. To give acceptable fuel pump durability, maximum injection pressure should be limited to 400 psi or less and consequently the fuel pressure existing in the common rail at low engine power level would be such that vapor pockets could form due to heat absorbed from the engine enclosure. These pockets are undesirable and can cause metering errors or inconsistent running.

To avoid this problem the fuel rail pressure is not permitted to fall below a level established empirically to prevent vapor formation. The minimum pressure may be achieved by providing the spring 74 (FIG. 3) with increased strength such that a minimum pressure of satisfactory magnitude is established in the pressure rail of the spark internal combustion engine, before the pressure control valve can open.

FIG. 6 represents, very schematically, the structure in addition to that shown in FIG. 5 required with a spark internal combustion engine, in accordance with this invention. A fuel bowl 110 supplies fuel to a pump 112, which feeds this fuel to a common rail 114a, 114b, which is bifurcated to feed fuel injection valves respectively 116 through 123. The bifurcated feed rail then

joins and returns a single rail to a pressure control valve 124. The return feed rail also communicates with an electromechanical actuator 126. The structure and operation of the electromechanical actuator and a pressure control valve are the same as have been described in connection with FIG. 1 therefore will not be described here.

The pressure transducer 111 may be of a type that senses the pressure difference between the fuel pressure in the feed rail 114a, 114b, and the pressure in the engine intake manifold 128. The signal from the pressure transducer 111 may consequently be employed for regulation of fuel pressure as described above, and also for the purpose of computing the duration of injection of fuel in a control system such as that described in co-pending U. S. Pat. application No. 155,220, entitled "Fuel Injection and Control System" by Cormac G. O'Neill, and assigned to a common assignee.

In diesel engines having a common rail injection system with timed injection valves the regulation of fuel pressure in a constant relationship to speed, enables the rate of fuel injection to be adjusted in addition to the duration of the injection. As a result, the engine can be made to operate more smoothly, quietly and with lower stresses (increased durability) at light load factors.

Wear on the fuel pressure pump can be reduced to a minimum by demanding its operation at peak injection pressure only for the time that such pressure is actually needed. Known systems require this pump to operate at peak delivery pressure at all times, not only influencing durability, but also causing fuel heating, fuel aeration and power dissipation creating high specific consumption at light load.

In gasoline engines, of the type having a common rail fuel injection system with injection valves to each port or cylinder, a fixed relationship between engine speed and fuel rail pressure may be obtained of the type $p = K\omega^n$; where p is fuel pressure, ω is the engine RPM, K is a constant and n is the index that may be readily varied for tuning purposes. Pressure relationship can be accurately maintained with a system that is free from mechanical complexity and is not sensitive to vibration. Known systems employing constant fuel rail pressure are unable to achieve maximum fuel injected per stroke within the effective inlet valve opening event and to maintain a minimum valve opening duration within the capability of injection valves constructed within existing state of the art techniques.

FIG. 7 is a block schematic diagram of an analog calculator 109, suitable for determining the quantity which is applied to the logarithmic circuit 90 in FIG. 5. If one looks at equation (1), one may observe that the quantity $C_d v A_v \sqrt{2\gamma/\gamma-1} \cdot g/R$ is equal to a calculatable constant K , since for any given venturi all of the values in this term are constant. The remaining part of equation (1) may be rearranged to simplify mechanization so that the entire equation may be

$$W = [K^2 \cdot P_o/T_1 (0.286P_1 - 0.306P_o)]^{1/2}$$

The signals P_o , P_1 and T_1 are all amplified and have their signs reversed by the respective amplifiers 130, 132 and 134, to respectively produce $-P_o$, $-P_1$ and $-T_1$. $-P_o$ and $-P_1$ are applied to attenuators 136 and 137 to form $-.306P_o$ and $-.286P_1$. These are applied to a two input amplifier 140 which produces the sum $-(-.286P_1 + .306P_o)$. This output is applied to an amplifier 142

whose gain is set to multiply the output by K^2 to produce the product $K^2 (.286P_1 + .306P_o)$.

The signal $-T_1$ is applied as one input to a multiplier 139 which is in the negative feedback path of an amplifier 138. The second input to multiplier 136 is the negative feedback of the amplifier. The result is that the output of amplifier 138 is the quantity P_o/T_1 . This quantity together with the output of amplifier 142 are applied to multiplier 144 to provide the output W^2 . This output is applied to the logarithmic circuit 90 in FIG. 5.

There has accordingly been described and shown herein a novel, useful and unique system for controlling the pressure of fuel in a common rail in accordance with engine speed.

What is claimed is:

1. In an internal combustion engine of the type having a fuel injection valve for each cylinder and a common feed rail for feeding fuel to said fuel injection valves, a system for varying the pressure of the fuel in accordance with a desired engine parameter comprising:

means for generating a first voltage having an amplitude representative of the fuel pressure in said common fuel rail,

means for generating a second voltage having an amplitude representative of said desired engine parameter,

means for raising said second voltage to the n th power, where n is an adjustable index whose value is established by a desired engine tuning to provide a third voltage representative of a desired fuel pressure,

means for comparing said first voltage and said third voltage to establish their difference and which is the larger, and

means responsive to the output of said means for comparing to change the pressure of the fuel in said common feed rail at a rate determined by said difference until said fuel pressure attains the value determined by said third voltage.

2. In an internal combustion engine as recited in claim 1 wherein said means for generating a second voltage having an amplitude representative of a desired engine parameter comprises tachometer means for generating a voltage representative of engine speed.

3. In an internal combustion engine as recited in claim 1 wherein said means for generating a second voltage having an amplitude representative of a desired engine parameter comprises transducer means for generating a voltage representative of the pressure differential of the air mass flowing to the engine through a venturi.

4. In an internal combustion engine as recited in claim 1 wherein said means responsive to the output of said means for comparing to change the pressure of the fuel in said common feed rail at a rate determined by said difference until said fuel pressure attains the value determined by said third voltage includes:

electromechanical pump means to which fuel from said feed rail is applied for increasing the pressure of said fuel,

control valve means to which the fuel at an increased pressure output of said electromechanical pump is applied to control the rate at which fuel in said common feed rail is permitted to circulate whereby its pressure may be controlled.

5. In an internal combustion engine of the type having a fuel injection valve for each cylinder and a common feed rail for feeding fuel to said fuel injectors, fuel being circulated by means of a pump from said common feed rail to a fuel bowl and then to a pump which pumps said fuel into said common feed rail, the improvement comprising:

means for generating a first voltage representative of engine speed,

means for generating a second voltage representative of the fuel pressure in said common rail,

means for raising said first voltage to the power n to produce a third voltage, wherein n is an adjustable index whose value is established by a desired engine tuning;

means for comparing said second and third voltages to produce a first output when said second voltage exceeds said third voltage and a second output when said third voltage exceeds said second voltage, and

control valve means connecting said common feed rail to said fuel bowl for increasing fuel flow whereby fuel pressure is reduced responsive to said first output and for decreasing fuel flow responsive to said second output whereby fuel pressure is increased.

6. In an internal combustion engine as recited in claim 5 wherein there is included a means for subtracting said second voltage from said third voltage to establish a difference voltage:

voltage controlled oscillator means to generate a pulse train whose frequency is determined by said difference voltage,

gate means rendered inoperative responsive to said first output and operative responsive to said second output to pass the pulse train from said voltage controlled oscillator, and

electromechanical actuator means connected to said gate means for controlling said control valve means responsive to said pulse train.

7. In an internal combustion engine of the type hav-

ing a fuel injection valve for each cylinder and a common feed rail for feeding fuel to said fuel injectors, fuel being circulated by means of a pump from said common feed rail to a fuel bowl and then to a pump which pumps said fuel into said common feed rail, the improvement comprising:

means for generating a first voltage representative of (air mass flow rate) into the engine,

means for generating a second voltage representative of the fuel pressure across a fuel injection valve,

means for raising said first voltage to the power n to produce a third voltage, where n is an adjustable index whose value is established by a desired engine tuning,

means for comparing said second and third voltage to produce a first output when said second voltage exceeds said third voltage and a second voltage when said third voltage exceeds said second voltage, and

control valve means connecting said common feed rail to said fuel bowl for increasing fuel flow whereby fuel pressure is reduced responsive to said first output and for decreasing fuel flow responsive to said second signal whereby fuel pressure is increased.

8. In an internal combustion engine as recited in claim 7 wherein there is included a means for subtracting said second voltage from said third voltage to establish a difference voltage,

voltage controlled oscillator means to generate a pulse train whose frequency is determined by said difference voltage,

gate means rendered inoperative responsive to said first output and operative responsive to said second output to pass the pulse train from said voltage controlled oscillator, and

electromechanical actuator means connected to said gate means for controlling said control valve means responsive to said pulse train.

* * * * *

45

50

55

60

65