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Boita

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[54] **METHOD OF AND APPARATUS FOR ELECTRONICALLY SIMULATING THE OPERATING CHARACTERISTICS OF A FUEL-INJECTION SYSTEM AND FOR DESIGNING SAME**

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[52] **U.S. Cl.** **235/184,** 235/183, 307/268, 328/36, 328/56

[51] **Int. Cl.** **G06g 7/57**

[58] **Field of Search** 235/184, 183; 328/56, 127, 34, 35, 36, 53, 58, 59; 307/268

[56] **References Cited**

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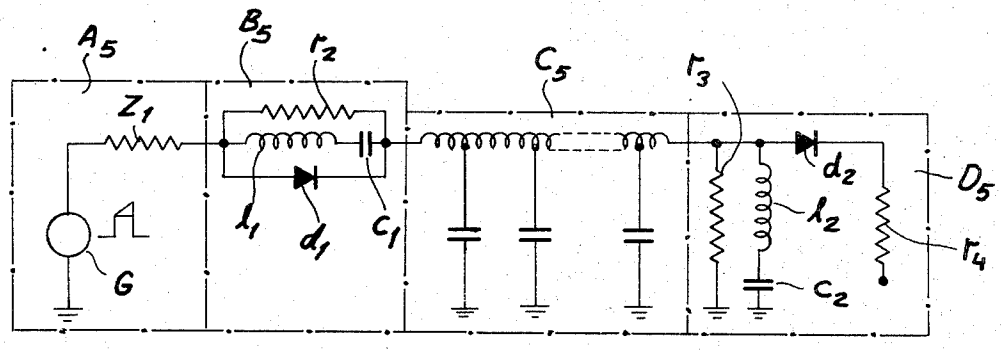
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Primary Examiner—Felix D. Gruber
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[57] **ABSTRACT**

The four major elements of a fuel-injection system for a combustion engine, i.e. the pump, metering valve, pressure line, and injector, are simulated by respective electronic analog networks whose various operating characteristics can be adjusted to electronically simulate just the operating conditions of these elements whereby the system design can be optimized by the variation-of-parameters method. The pump analog is a pulse generator. A pulse-shaping network is connected to this generator to form the pulse in analogy to the operation of the metering valve which forms the fluid pulse of the pump. An electronic delay circuit simulates the action of the pressure line and another shaping network replaces the injector. Shunt switches are provided to bypass both the first shaping network and the delay network to duplicate the performance of fuel-injection systems without a metering valve and/or pressure line.

6 Claims, 6 Drawing Figures



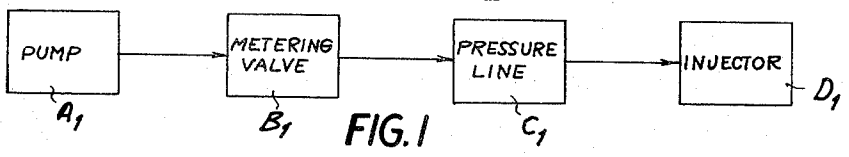


FIG. 1

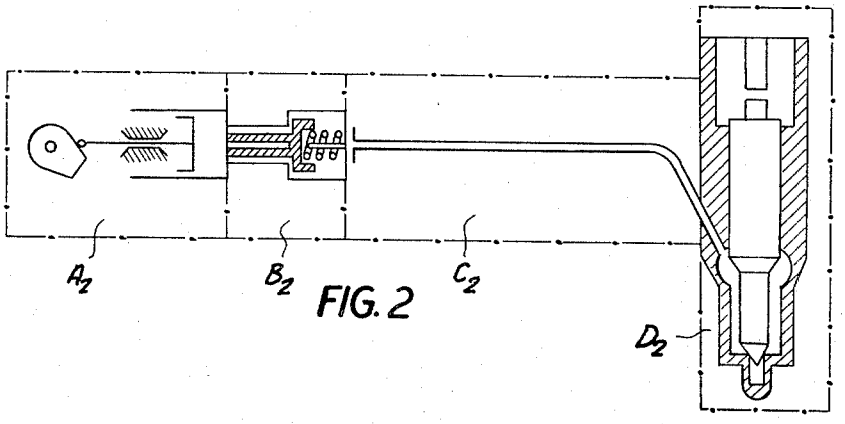


FIG. 2

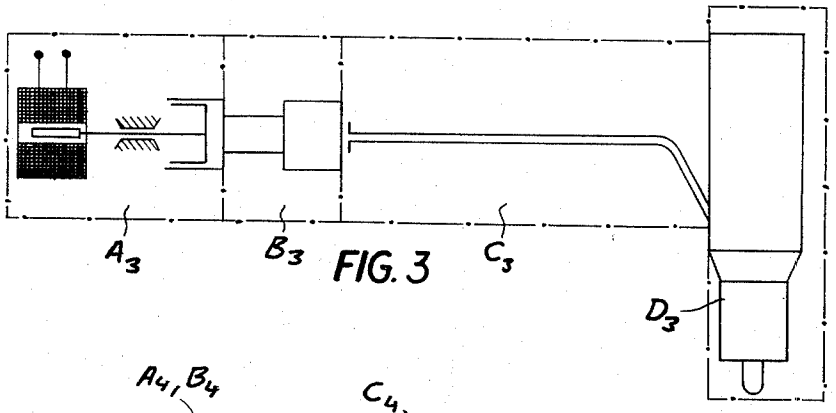


FIG. 3

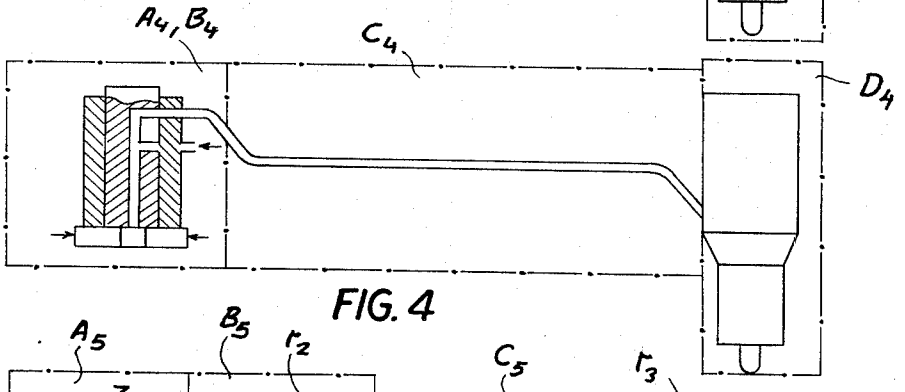


FIG. 4

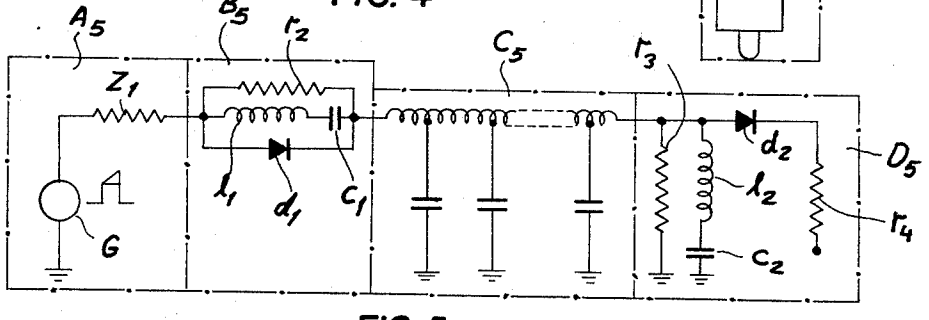


FIG. 5

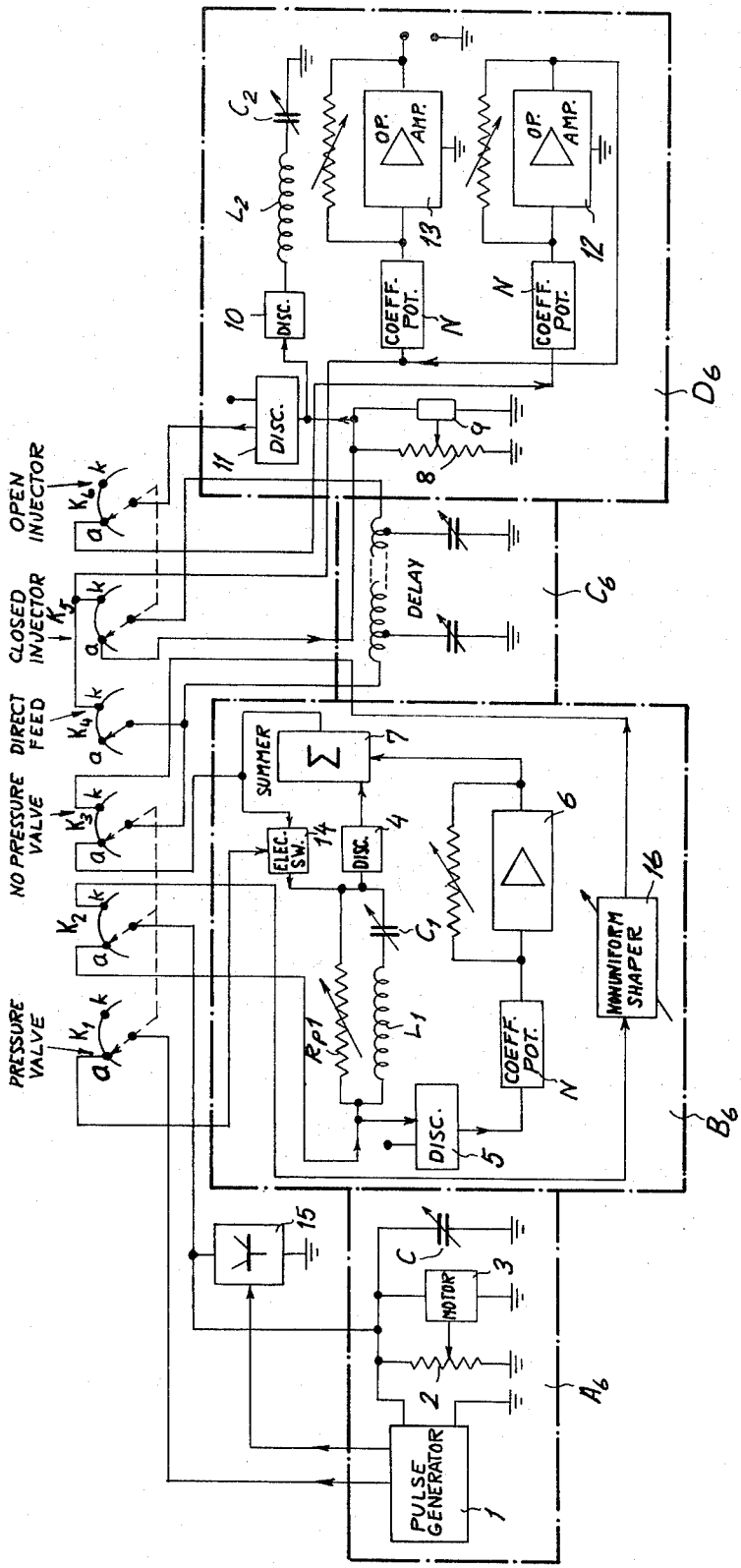

OPEN INJECTOR
CLOSED INJECTOR
DIRECT FEED
NO PRESSURE VALVE
PRESSURE VALVE
K1
K2
K3
K4
K5
K6
a
k
SUMMER
ELEC. SW.
DISC.
OP. AMP.
COEFF. POT.
DELAY
MONUNIFORM SHAPER
MOTOR
PULSE GENERATOR
C1
C2
C
L1
L2
Rp1
N
A6
B6
C6
D6

FIG. 6

METHOD OF AND APPARATUS FOR ELECTRONICALLY SIMULATING THE OPERATING CHARACTERISTICS OF A FUEL-INJECTION SYSTEM AND FOR DESIGNING SAME

FIELD OF THE INVENTION

The present invention relates to a method of and an apparatus for simulating the operating conditions of a fuel-injection system for an internal-combustion engine. More particularly this invention concerns an electronic analog simulation apparatus and method which can be made to electronically duplicate all the principal operating characteristcs of such a fuel-injection system to enable design of such systems by variation of the respective parameters to optimize the efficiency of the system.

BACKGROUND OF THE INVENTION

A fuel-injection system generally consists of a pump or the like which delivers a fluid pulse to a control or pressure valve that in turn meters out a charge of fuel through a pressure line to an injector. In some arrangements the pump directly feeds the fuel through the line to the injector in which case the pump can be thought of as also acting as the valve.

In order to design such systems it is necessary to take a multitude of operating characteristcs of the various components into account. Specifically the size and frequency of the fluid pulses must be tuned to th e reaction characteristics of the metering valve which in turn must be related to the fluid-transmission characteristics of the pressure line. Finally the reaction characteristics of the injector must be taken into account. Clearly this makes it difficult to calculate, for instance, just how much time lag will take place between the initial pulse formation at the pump and the final spurt of the fuel into the cylinder or swirl chamber. Simularly it is difficult to calculate just how much of a pulse must be delivered by the pump to produce a given fuel-combustion response in the engine cylinders.

As a matter of fact the calculation of the above characteristics have proven to be such an error-fraught and time-consuming process that fuel-injection systems have merely been designed by empirically replacing mechanical components until the overall operating characteristics have been optimized. Such method of designing is far from ideal, making an examination of a new fuel-injection system so much trouble as not to be worth the effort. In addition such a method rarely gives the optimum results.

While I have mentioned that a basic fuel-injection system for an internal-combustion engine generally comprises a source of fuel under pressure, a transmission path for the fuel and a fuel outlet at the end of this transmission path opening into the combustion or engine chamber, and that the parameters of such systems have hitherto been designed by trial-and-error replacement of the parts of the tramsission line, fuel source and fuel outlet, I should also mention a problem which arises in electronic fuel injection. Electronic fuel-injection systems control the timing of the fuel pulses, i.e. the triggering of the fuel source or a control valve along the transmission line, in accordance with cylinder operation modes and must be designed in accordance with the response characteristics of the mechanical system. The term "mechanical system" is used herein to

refer to the mechanical components of the fuel-injection system, namely, the pump or other source of fuel under pressure, the transmission line or path including any valve means provided therealong, and the outlet device or nozzle. At any point along this system, electronic controls may be provided in accorddance with conventional practice to trigger, throttle or terminate the flow of fuel in accordance with the response characteristics of the fuel-injection system and the timing requirements of the other parts of the engine. In many cases, the electronic control of fuel injection establishes the parameters of one of the mechanical components of the system. e.g. a pump or valve. In this case, it is important to determine which parameters of the other components are necessary to obtain optimum efficiency of the fuel-injection system. Here again, designers of fuel-injection systems and especially electronic fuel-injection systems were required to operate by trial-and-error methods, using replacement of the several components with respect to the fixed components, to establish the optimum characteristics.

I should also like to mention that I am aware that it has been proposed to provide analog systems for simulating mechanical operations and, for example, electronic analogs of damping and oscillation systems are well known. As far as I am aware, however, it has not been possible heretofore to apply similar principles in the design of fuel-injection systems because of the particular responses of the various components of such systems. Hence the automatic or convenient variations of parameters of components of a fuel-injection system or analogs thereto have not been possible heretofore.

OBJECTS OF THE INVENTION

It is therefore an object of the present invention to provide an apparatus which allows the simulation of a fuel-injection system in order to assist in the design and building of actual systems.

A further object is to provide a method of and apparatus for simulating all of the operating characteristics of a fuel-injection system.

SUMMARY OF THE INVENTION

I attain the above and other objects with an electronic device having four major networks which can be regulated to simulate the various characteristics of the four elements, i.e. the pump, metering valve, pressure line, and injector, of a fuel-injection system. According to features of the present invention numerous possibilities of adjustment are provided so that all of the principal kinds of fuel-injection systems can be simulated in an analog apparatus in order that the output can be read on, for instance, an oscilloscope and the various parameters can be changed until the desired result is obtained.

The analog network simulating the pump of the fuel-injection system includes a pulse generator and an impedance. The pulse output of such a generator can be varied by providing adjustable reactive elements connected to the generator output. According to another feature of the present invention the shaping network that simulates the valve in the fuel-injection system is basically an integrator comprising a tuned circuit across which a diode and a load resistor are connected. Instead of a diode an operational amplifier, which inherently has diodic properties, with a variable feedback loop, can be provided. Of course to simulate fuel-

injection systems wherein the pump effectively includes the valve, this shaping network is bypassed by a shunting switch.

An electronic delay circuit constitutes the network simulating the pressure line. Finally a differentiating network is provided to take the place of the injector. Once again the delay circuit can be shunted to simulate systems wherein the pump is provided directly at the cylinder, or wherein the metering valve is located at this point.

From the foregoing, it is apparent that my invention resides in the use of an analog reproduction of the mechanical components of a fuel-injection system to enable the parameters of an actual fuel-injection system to be ascertained with an optimum output and thereby allow improved electronic fuel-injection systems to be developed using these parameters. Of course, the parameters of interest include the input parameters, namely, the pulse shape, frequency, timing and amplitude of the electronic signals which are the analogs of the input fuel pulses generated by the source of a fuel-injection chain.

It is next important to establish the signal-transmission and signal modification parameters of the transmission line or path between the source and the outlet of the system and any attenuation, losses or system-response or transfer-function characteristics of the transmission line.

Finally, it is essential to establish the response and corresponding characteristics of the outlet or nozzle.

In the system of the present invention, at least three, but preferably more, quadripoles or bocks are provided in sequence to constitute an electronic analog of the mechanical system. These blocks include a signal generator block producing an electronic output which is an analog of the time-rate-of change of a parameter of fuel pulse transmitted to the system, and includes any pulse-shaping means (preferably adjustable) between a pulse generator and the output of this block which may be necessary to provide a transfer function analogous to that of the pump or other fuel source of the mechanical system. While the signal is generally a stop upon which a sawtooth has been superimposed, corresponding to the output of a pulse-generating pump, various attenuators may be provided within the block to more closely represent the fuel signal and even to enable design of an optimum elecronic signal to serve as a guide for design of the pump which will produce the corresponding fuel signal.

The next block or quadripole of the chain comprises an electronic circuit having a transfer function which is variable to determine optimum operating characteristics, but which represents the transmission path of the fuel pulse. This transmission line or block may consist of two or more subblocks, at least one of which represents a resistance or throttle by its transfer function, corresponding to the pressurized line along which the fuel is to flow. Another component of the path representing the transmission portion of the system may be a block or quadripole representing a metering or other valve. It will be apparent, however, that the control valve may also be incorporated in the source. Since the nozzle generally comprises a valve which is pressure-responsive, i.e. allows a buildup of pressure at a certain level and then discharges a fuel spurt or jet into the engine, the final block is a quadripole whose electronic components present the transfer function of a storage and threshold device.

DESCRIPTION OF THE DRAWING

The above and other objects, features, and advantages will become apparent from the following, reference being made to the accompanying drawing in which:

FIG. **1** is a block diagram illustrating a fuel-injection system;

FIGS. **2, 3,** and **4** are diagrammatic views of three types of fuel-injection systems;

FIG. **5** is a schematic diagram of a simplified embodiment of the apparatus according to the present invention; and

FIG. **6** is a schematic diagram of a more complicated embodiment of the apparatus according to this invention.

SPECIFIC DESCRIPTION

As shown in FIG. **1** a fuel-injection system consists of a pump A_1 connected through a metering valve B_1 and a pressure line C_1 to an injector D_1.

Such a system can take many forms. In FIG. **2** a cam-and-tappet pump A_2 actuates a conventional metering valve B_2 which feeds a charge of fuel through a small-diameter conduit C_2 to an ijector D_2. FIG. **3** shows how an electromagentically actuated pump A_3 can be used, and in FIG. **4** a rotary pump-valve A_4, B_4 is used. Systems are also known in which, for instance, a small electromagnetically actuated self-priming pump is mounted directly on the injector, so that elements corresponding to B_{1-4} and C_{1-4} are omitted.

FIG. **5** shows the circuit of an apparatus whose four networks A_5, B_5, C_5, and D_5 correspond to the above-described elements. The network A_5 corresponds to the pump or fluid-pulse generator and consists of a generaor G of pulses of trapezoidal shape in series with which is connected an impedance Z_1 reproducing the inherent lag or backflow resistance. Since a fluid pulse is a surge of fluid of a given volume, pressure and duration, the represented parameter may be either the pressure or volume. The network B_5 corresponding to the metering valve comprises a diode *d*shunted by a series tuned circuit l_1, c_1 and by a load resistor r_2. The pressure line is simulated by a conventional electronic delay circuit C_5. Finally the injector equivalent network D_5 is formed of a series tuned circuit l_2, c_2 damped by a resistor r_3 with a series diode d_2 and a resistor r_4 acting as load.

The circuit of FIG. **6** represents an operational model of the present invention having four networks A_6–D_6 corresponding to the similarly identified elements described above. Network A_6 comprises an adjustable pulse generator **1** which forms trapezoidal pulses with parallel flanks, an impedance **2** (e.g. a potentiometer) whose value depends on signal level and which is controlled by a reactive element **3** (e.g. a servomotor — see pp. 47 ff. *Servomechanism Practice*, McGraw-Hill Book Co., N.Y., 1960), and a variable capacitor C whose value determines the accumulating volume of the pump. All of the characteristics of the above-described pumps can be simulated with this network. Thus the height of the pulse (amplitude) will represent pressure and the charge on the capacitor will represent volume as a function of time. The network B_6 includes an inductance L_1 connected in series with a capacitor

C to form a tuned circuit shunted by an adjustable resistor Rp_1, level discriminators **4** and **5** which pass a signal when the amplitude thereof exceeds a predetermined level as with the threshold detector of U.S. Pat. No. 3,529,144) an operational amplifier **6** with adjustable feedback resistor, and an adder **7.** The network C_6 comprises a conventional choke-capacitor type of delay line (see U.S. Pat. No. 2,830,179) type cells. Finally the fourth network D_6 comprises an impedance whose value depends on the pulse level as controlled by a reactive element **9,** a series tuned circuit L_2, C_2, level discriminators **10, 11** (which pass a signal when the level thereof exceeds a predetermined value as with the threshold detector of U.S. Pat. No. 3,529,144), and operational amplifiers **12, 13** with nonlinear feedback. Coefficient potentiometers are shown at N. The devices **5** and **11** have additional inputs for the reference signal.

In operation the device functions as follows:

A parallel-flank trapezoidal impulse is delivered and as it appears at the outut terminals (represented by arrowheads) of the pulse generator **1** the impedance of element **15** (e.g. as described for impedance Z_1) becomes infinite to simulate the throttling effect of the pump inlet. Part of the originally formed pulse is drained to ground through the impedance **2** controlled by the feedback elements **3** (responding to the potential capacitor) and C which are set according to the accumulating volume of the pump simulated. In the simulation of injection systems as shown in FIGS. **2** and **3** with metering valves the switches K_1, K_2, and K_3 are moved into the left-hand, *a* position.

Since the pressure valve does not form a direct and immediate communication link in the fuel-injection system the pulse then travels through the passive elements L_1, C_1, and Rp_1 (delay network), then through the discriminator **4,** and the adder **7.** One input to the latter (derived from amplifier **6**) represents the component of direct build up in pressure of the fuel at the inlet to the transmission line while the other input (from discriminator **4**) represents the lag produced at the valve, the summer **7** forming a composite signal representing the slug of fuel entering the transmission tube. Thence the signal (from summer **7**) is fed through the delay circuit C_6 whose delaying properties are tuned to simulate those of the pressure line, depending on this element's length and cross-sectional area. To simulate systems with closed injectors the switches K_5 and K_6 are thrown into their left-hand, *a* positions. Initially the injector is not open so that the delay line effectively terminates at the impedance **8** whose value is great because the signal is small to start with. The impulse is reflected to the other end since the line there has also a large impedance, and this reflecting back and forth oscillation continues.

As the signal amplitude increases in a fuel-injection system the valve lifts off its seat and direct communication between pump and pipe starts. To simulate this, the signal no longer passes through tuned circuit L_1, C since thediscriminator **4** is blocked. Then the impulse takes a path through the amplitude discriminator **5,** and the operational amplifier **6** whose feedback circuit can be adjusted to simulate various flow rates through different size valve orifices, and then through the high-output-impedance adder **7,** and thence through the delay line C_6 which is ineffective until a condition corresponding to valve opening comes into being.

The rise of the injector's needle is simulated by passage of the pulse through the discriminator and L_2 and C_2 to ground and through the discriminator **11,** and operational amplifiers **12** and **13** whose feedbacks can be adjusted to simulate flow resistance in the valve orifice. In the injection system being simulated the needle would now reach the limit of its passage, a condition simulated by the tuned circuit L_2, C_2 whose time constant is adjusted to correspond to the rise time of such an injector needle. The discriminator **10** blocks this tuned circuit off so that the pulse only goes through discriminator **11** and amplifiers **12** and **13.**

On completion of the pulse at the generator **1,** the pulse length being of course adjusted to correspond to that of the pump being simulated, the impedance of element **15** drops to zero to discharge the condenser C and the element **14** is triggered by the trailing pulse flank to couple the tuned circuit L_1, C_1, and Rp_1 with the delay line for precise determination of the extent of discharge of this element, which corresponds to the pressure remaining in the pressure pipe after firing of the injector. An impulse is obtained at the output terminal of amplifier **13** whose waveform corresponds to that of the fuel-injection the cicuit was programmed to simulate, regardless of scale.

In the case of systems with an open injector the switches K_5 and K_6 are placed in the right-hand, *b* positions in which case the pulse is fed directly from the delay line C_6 to the input of amplifier **13.**

For systems in which the pressure valve is part of the pump or not present at all the switches K_{1-3} are switched into the right-hand, *b* position and the network B_6 is replaced with a simple nonlinear element **16** which shapes the pulse according to the size of the communication orifice between pressure pipe and pump.

Finally in circuits without a pressure pipe the switch K_4 is switched from the left-hand, *a* positon to the right-hand, *b* position to short out the delay line C_6 and allow for direct and immediate communication between networks B_6 and D_6.

Such an arrangement can be embodied as a conventional oscilloscope-type of equipment having a multiplicity of adjustments for all of the parameters of a fuel-injection system. Say, for instance, that a given pump, metering valve, and injector are to be used. With the apparatus according to the present invention the adjustments of the delay line can be changed until the optimum output is achieved, then the readings noted and a pressure pipe of those characteristics used. Furthermore the elements which wear and the parameters which change with time or varying temperature conditions are known and can be tested on such a device before even building a fuel-injection system in order to best gauge tolerances.

The system described above has numerous advantages which will be readily apparent. Firstly, it insures the rapid and precise determination of geometric dimensions of the elements of the injection system to be designed, and which will then perform the given function. Secondly it is no longer necessary to produce a large numer of mechanical devices at considerable cost for trial-and-error determination of optimum conditions, thereby reducing comsumption of materials and labor to bring about practical realization of the system. Thridly, it enables the electronic triggering of the system to be coordinated with the operation of the heat

enegine and thus provides an optimum utilization of the latter, especially when it is operated by electronic fuel injection. Fourthly, thesystem allows calculation and visualization of the influence of practically every element on the shape of the fuel pulse injected into the engine. Finally, it enables the influence of wear of the elements upon the injection and of the determination of critical wear in a convenient and economical manner.

I claim:

1. A method of simulating the operating characteristics of a fuel-injection system in which a slug of fuel is produced and supplied to a fuel injector, said method comprising the steps of:

generating an electrical pulse having a waveform analogous to the build up of the fuel slug with time;

electronically shaping said electrical pulse by passing same through a nonlinear network to represent the change in character of said fuel slug as the latter is fed to said fuel injector;

electronically delaying the shaped electrical pulse in accordance with fluid-transmission characteristics between the production of said fuel slug and the delivery thereof to said fuel injector;

reshaping the delayed electrical pulse in accordance with the operating characteristics of said injector;

displaying the reshaped electrical pulse as a function of time; and

varying at least one parameter of said generated electrical pulse, the shaping of said electrical pulse, the delay of said electrical pulse and the reshaping of said electrical pulse to obtain an optimum waveform thereof afer reshaping.

2. An apparatus for simulating the operating characteristics of a fuel-injection system in which a fuel slug is fed to a fuel injector, said apparatus comprising:

means for generating an electrical pulse havng a waveform analogous to the build up of said fuel with time;

first elecronic means including a nonlinear network connected to the generating means for shaping said electrical pulse for simulating the temporary blockage of flow of said fuel slug by a valve of the fuel-injection system;

second electronic means including a delay line connected to the first electronic means for delaying the shaped elecrical pulse in accordance with transmission characteristics for said slug of a pressure line between said valve and said fuel injector; and

third electronic means connected to said delay line for reshaping the delayed electrical pulse in accordance with the operating characteristics of said injector upon said fuel slug.

3. The apparatus defined in claim **2** wherein said generating means includes a variable-level square-pulse generator and a reactive impedance connected in series therewith and connected to said nonlinear network.

4. The apparatus defined in claim **3** wherein said first elecronic means includes a variable circuit including an inductor in series with a capacitor to form a tuned network, a resistor ridged across said network in parallel to the series-connected inductor and capacitor, and a diode conductive in the direction of said delay line bridged across said network in parallel to the series-connectd inductor and capacitor.

5. The apparatus defined in claim **4** wherein the third electronic means includes a variable circuit including an inductor connected in series with a capacitor, a diode connected in series with a further resistor and connected to the series-connected inductor and capacitor of the third electronic means and conductive away therefrom, and yet another resistor in parallel with the series-connected inductor and capacitor of said third electronic means.

6. The apparatus defined in claim **2**, further comprising switch means connectable across said first electronic means for connecting said generating means directly to said delay line for simulating a fuel-injection system without a valve.

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