

Sept. 15, 1970

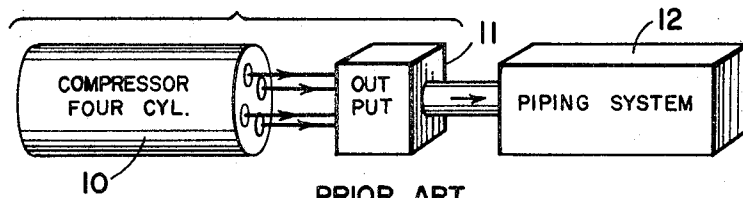
M. LE ROY PATTERSON ET AL

3,529,144

WAVEFORM GENERATOR FOR COMPRESSOR FLOW SIMULATION

Filed May 22, 1968

6 Sheets-Sheet 1



PRIOR ART

FIG. 1

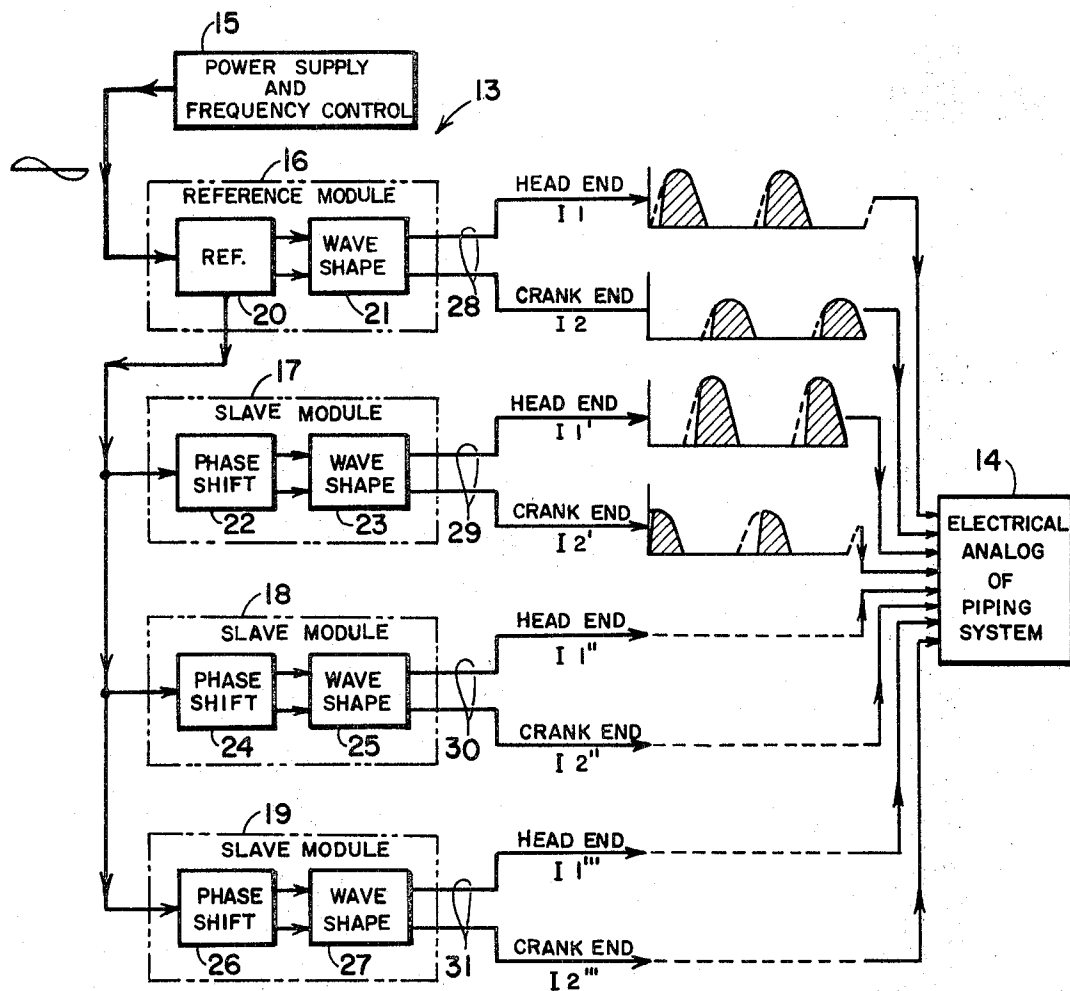


FIG. 2

INVENTORS:

MARVIN LEROY PATTERSON

ERICH KURT LAETSCH, JR.

BY

*Elliott & Pastoriza*  
ATTORNEYS

Sept. 15, 1970

M. LE ROY PATTERSON ET AL

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6 Sheets-Sheet 2

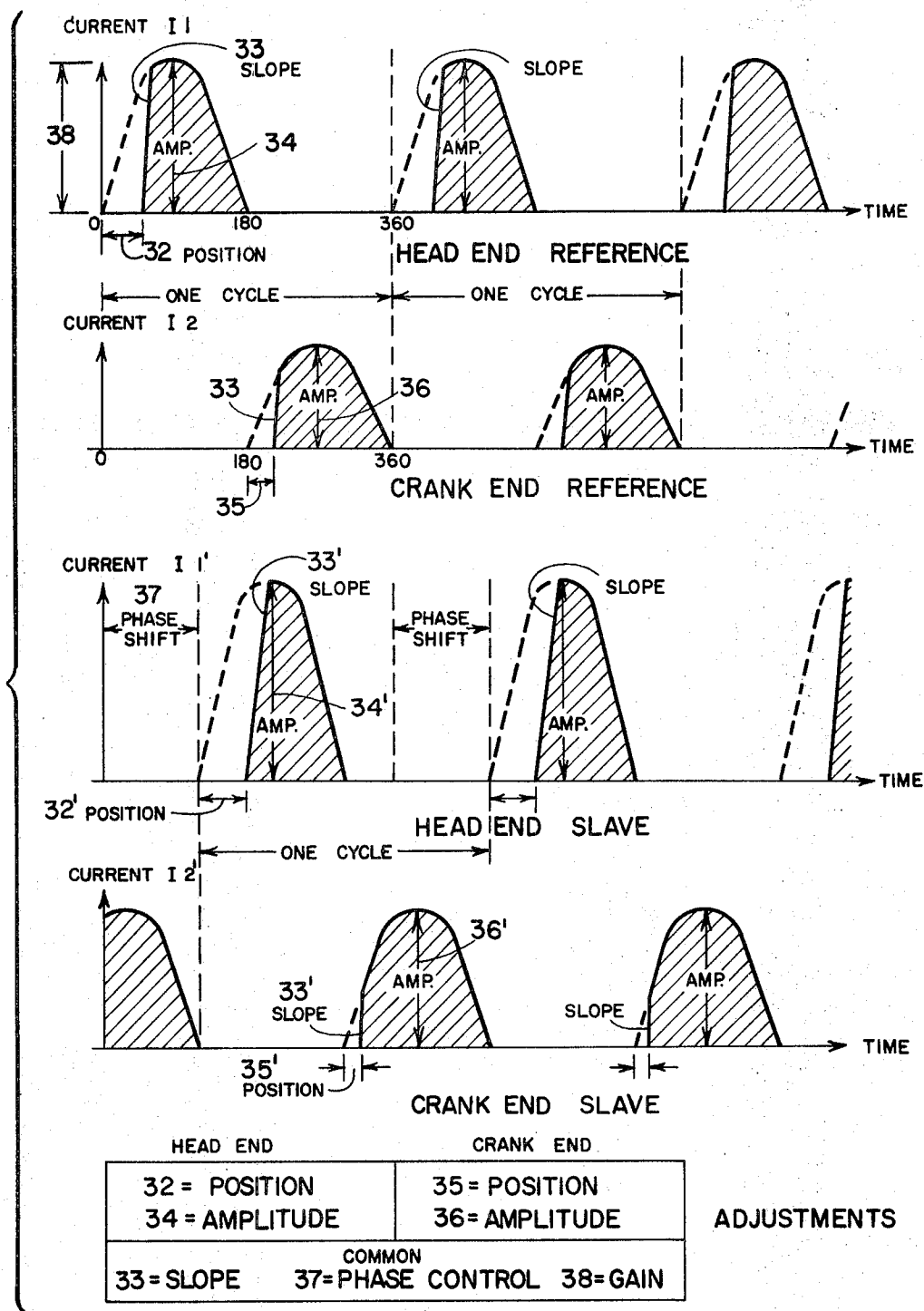


FIG. 3

INVENTORS  
MARVIN LEROY PATTERSON  
ERICH KURT LAETSCH, JR.  
BY  
*Elliott & Pastoriza*  
ATTORNEYS

Sept. 15, 1970

M. LE ROY PATTERSON ETAL

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Filed May 22, 1968

6 Sheets-Sheet 3

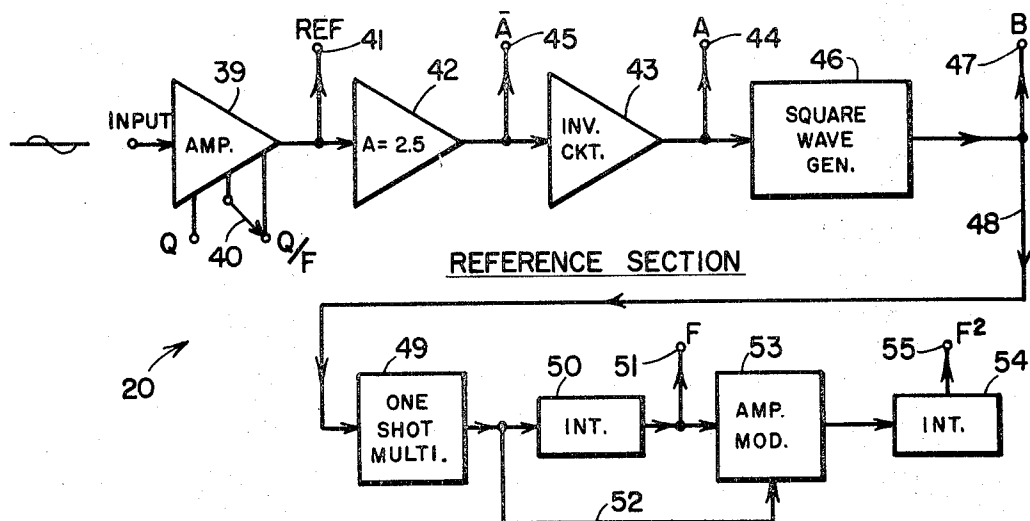


FIG. 4

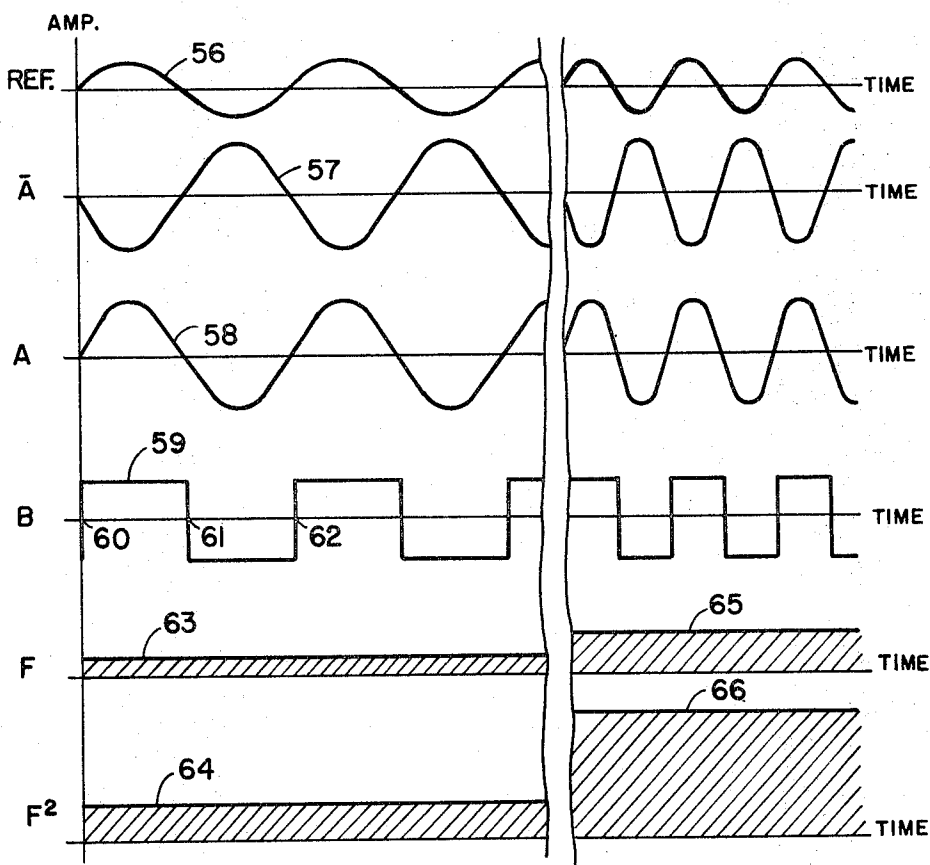


FIG. 5

INVENTORS:  
MARVIN LEROY PATTERSON  
ERICH KURT LAETSCH, JR.  
BY *Elliott & Pastoriza*  
ATTORNEYS

Sept. 15, 1970

M. LE ROY PATTERSON ET AL

3,529,144

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6 Sheets-Sheet 4

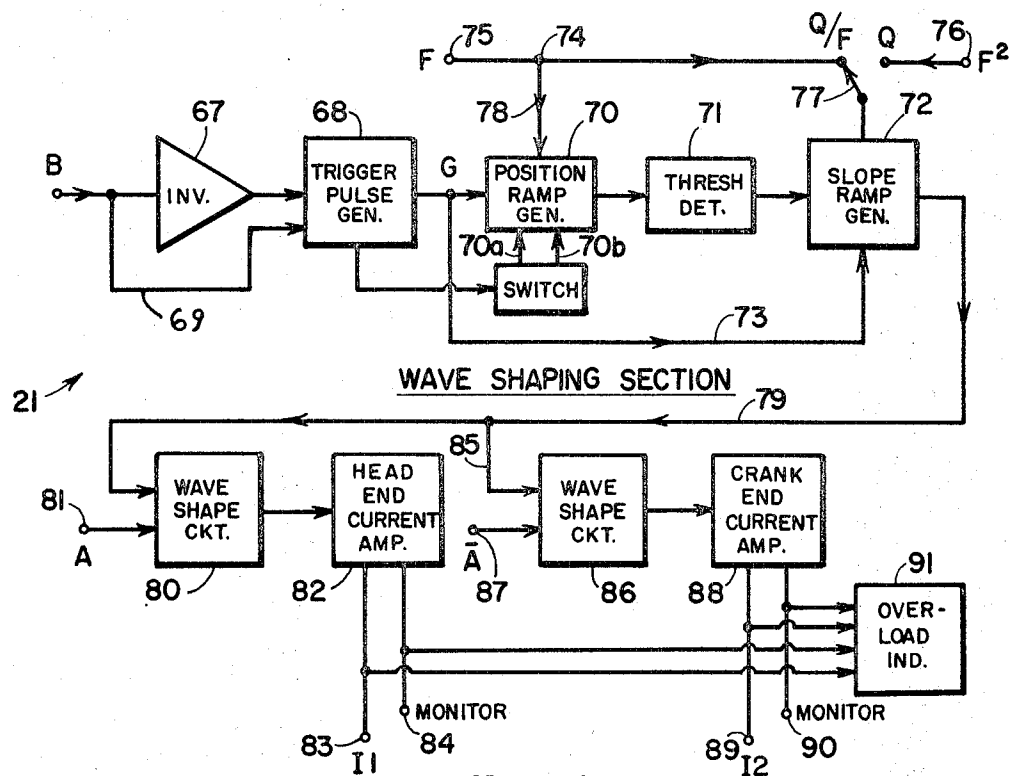


FIG. 6

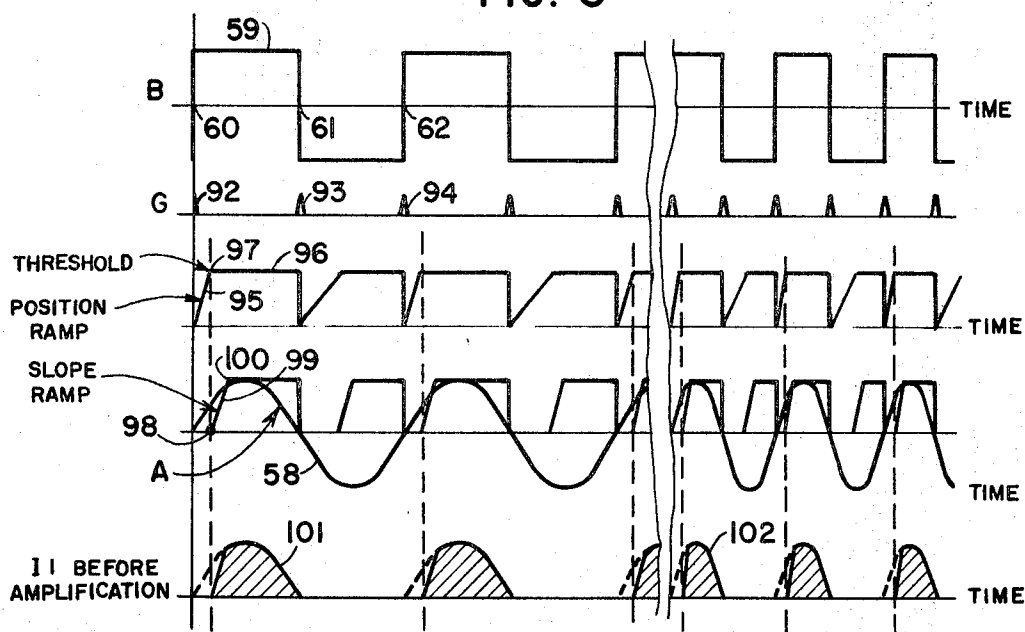


FIG. 7

INVENTORS:

MARVIN LEROY PATTERSON  
ERICH KURT LAETSCH, JR.

BY

*Elliott & Pastoriza*  
ATTORNEYS

Sept. 15, 1970

M. LE ROY PATTERSON ET AL

3,529,144

WAVEFORM GENERATOR FOR COMPRESSOR FLOW SIMULATION

Filed May 22, 1968

6 Sheets-Sheet 5

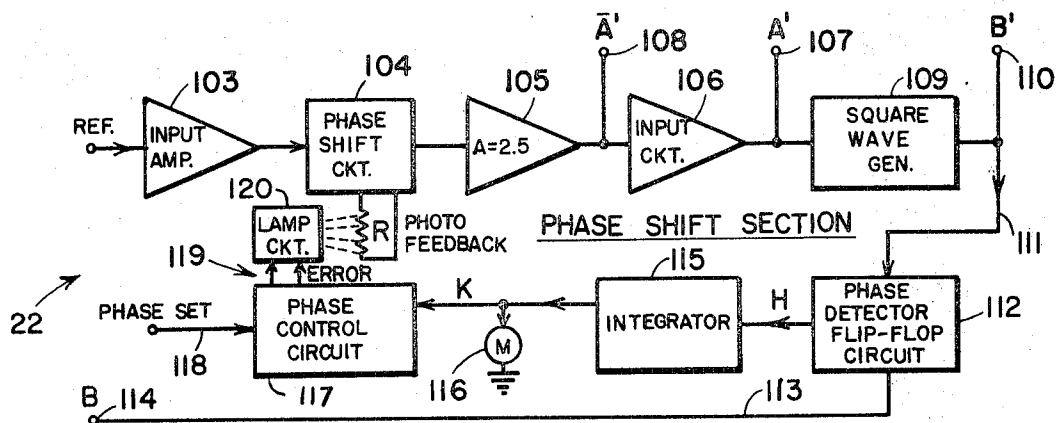


FIG. 8

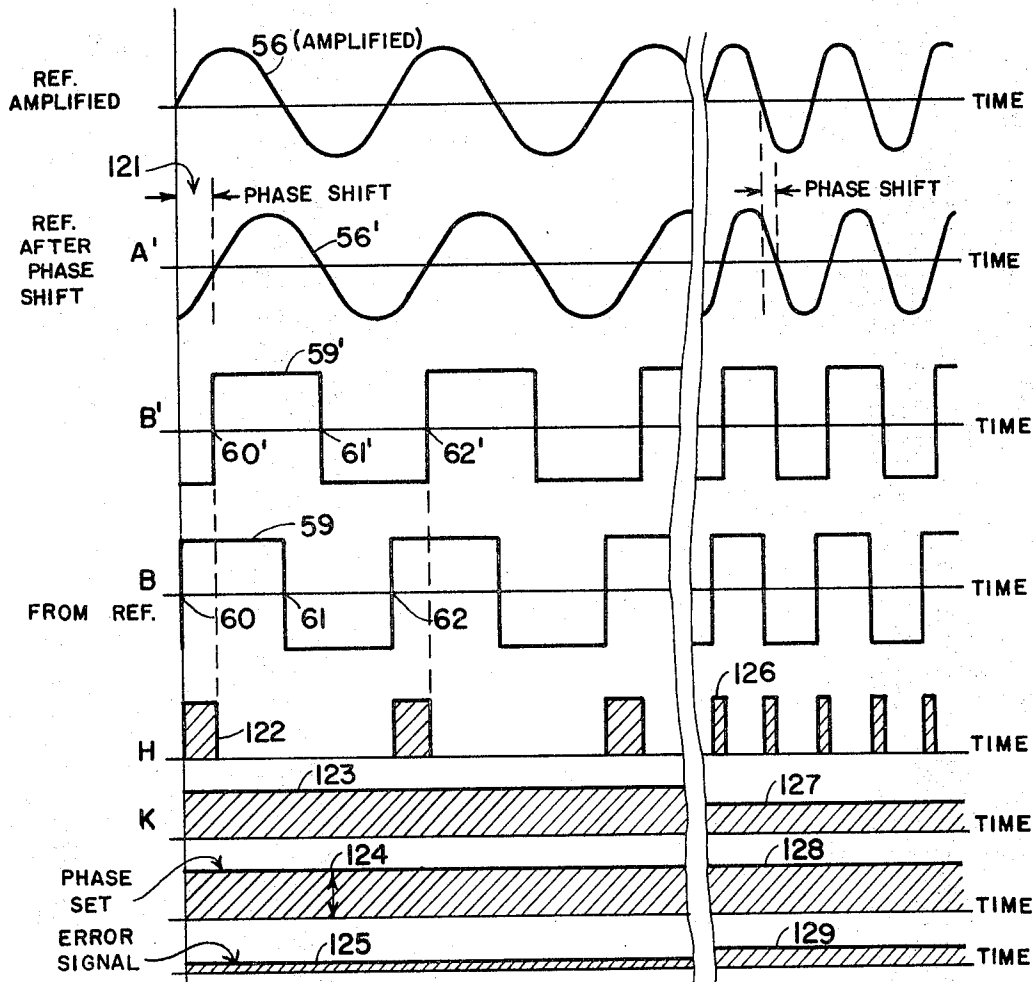


FIG. 9

INVENTORS:

MERVYN LEROY PATTERSON  
ERICH KURT LAETSCH, JR.

BY

*Elliott & Pastoriza*  
ATTORNEYS

Sept. 15, 1970

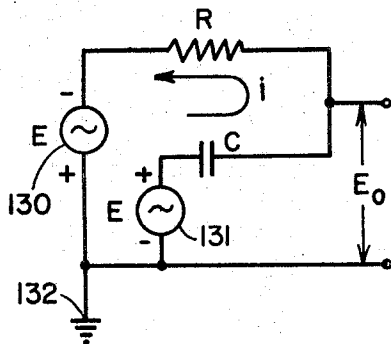
M. LE ROY PATTERSON ET AL

3,529,144

WAVEFORM GENERATOR FOR COMPRESSOR FLOW SIMULATION

Filed May 22, 1968

6 Sheets-Sheet 6



$$(1) \quad i = \frac{+E - (-E)}{R + \frac{1}{j\omega C}} = \frac{2j\omega CE}{j\omega C R + 1}$$

$$(2) \quad E_0 = -E + Ri = -E + \frac{2j\omega CE}{j\omega C R + 1} R$$

$$(3) \quad \frac{E_0}{E} = \frac{2j\omega RC - j\omega RC - 1}{j\omega RC + 1}$$

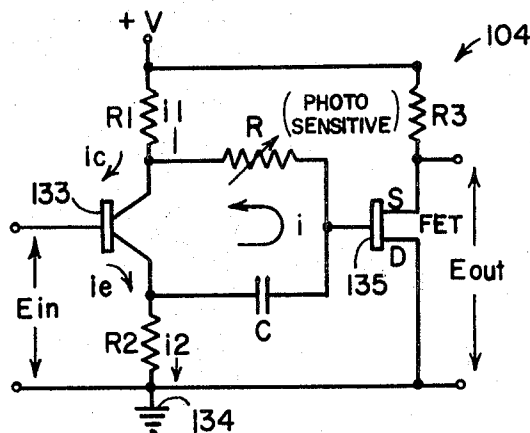
$$(4) \quad \frac{E_0}{E} = -\frac{1 - j\omega RC}{1 + j\omega RC}$$

$$(5) \quad \frac{E_0}{E} = \frac{-\sqrt{1 + \omega^2 R^2 C^2} \angle \tan^{-1}(-\omega RC)}{\sqrt{1 + \omega^2 R^2 C^2} \angle \tan^{-1}(\omega RC)}$$

$$(6) \quad \frac{E_0}{E} = -1 \angle -2 \tan^{-1}(\omega RC) ; \quad (7) \quad \left| \frac{E_0}{E} \right| = 1$$

$$(8) \quad \text{PHASE ANGLE OF } \frac{E_0}{E} = 180^\circ - 2 \tan^{-1}(\omega RC)$$

FIG. 10



$$(1) \quad i_c = i_1 + i_2 = i_e = i_2 + i_3$$

$$(2) \quad i_1 = i_2 = \frac{E_{in}}{R_2}$$

$$(3) \quad R_1 = R_2$$

$$(4) \quad \text{PHASE SHIFT OF } \frac{E_0}{E_{in}} = 360^\circ - 4 \tan^{-1}(\omega RC)$$

(FOR TWO CIRCUITS IN CASCADE)

FIG. 11

INVENTORS

MARVIN LEROY PATTERSON

ERICH KURT LAETSCH, JR.

BY

*Elliott & Pastoriza*

ATTORNEYS

1

2

3,529,144

## WAVEFORM GENERATOR FOR COMPRESSOR FLOW SIMULATION

Marvin LeRoy Patterson, 3975 Vincente St., and Erich Kurt Laetsch, Jr., 703 Acosta Drive, both of Camarillo, Calif. 93010

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U.S. Cl. 235—197

11 Claims

### ABSTRACT OF THE DISCLOSURE

An electrical waveform generator provides a plurality of electrical output signals having wave shapes simulating given fluid flow patterns such as might appear at the outlet valves of a multi-cylinder compressor. These waveforms are utilized with an electrical analog of a piping system where they will induce a response analogous to that caused by an actual compressor in an actual piping system. The electrical output signals themselves can be adjusted in relative phase relationship to simulate the phasing output of fluid flow patterns from the various cylinders in the compressor. Further, the waveform of the various electrical output signals can be shaped by varying their cyclic starting positions in time, the slopes of their leading edges, and their amplitudes so that an accurate presentation of fluid flow conditions from the compressor is realized. Suitable internal circuitry monitors the frequency of operation and adjusts both the position in time and the slope or rate of change of the leading waveform edge to represent accurately the time and rate of valve opening for the compressor, all in such a manner that the relative shaping of the waveform is maintained throughout all frequencies of operation. Finally, an amplitude-frequency switch control is provided to increase the amplitude of the electrical output signals with increasing frequency when in one switched condition and to maintain constant the amplitude of the electrical output signals with increasing frequency when in a second switched position. These first and second conditions represent, respectively, increasing flow rate or volume of fluid per unit time from an actual compressor, and a normalized flow or volume of fluid per cycle.

This invention relates generally to electrical circuits for generating waveforms and more particularly to a waveform generator for providing a plurality of electrical output signals of wave shapes simulating given fluid flow patterns from a multi-cylinder compressor for use with electrical analogs of piping systems.

### BACKGROUND OF THE INVENTION

It is well known to employ electrical analog computers for the purposes of analyzing fluid piping systems. The assembly and necessary adjustments and modifications of electrical components simulating actual piping systems can be accomplished far easier and less expensively than the fabrication and modification of actual hardware. Further, the operation and response of an electrical analog system can be measured much more easily than that of actual equipment. It is therefore common practice to do as much as possible of the preliminary analysis and design of fluid piping systems by means of electrical analog methods before actually fabricating and testing hardware.

A large number of situations using compressors require a prior analysis by electrical analog means. It is therefore necessary that an electrical simulation of the compressor itself be provided to generate the necessary signals for use in the electrical analog of the piping system. If these signals simulating the compressor are accurate,

they will induce a response in the analog piping system analogous to that caused by the actual compressor in an actual piping system.

Heretofore, electrical analog methods used to determine an analog compressor induced response in a piping system usually relied on the analysis of the frequency response of the analog system over a frequency range corresponding to the r.p.m. of the compressor. Thus, a single sinusoidal input signal was applied to an electrical analog of a piping system and the frequency of this sinusoidal input signal varied over the frequency range involved. Since, however, the actual output waveform of a compressor is not sinusoidal but rather a composite of many harmonics, accurate results could not be obtained except after much tedious calculation.

Other systems for providing a generated electrical signal for use with an electrical analog of a piping system provide only one signal and thus simulate only the output of one cylinder. This system is not adequate, of course, for a multi-cylinder compressor. Still other systems have been provided which can simulate the action of a number of cylinders in a compressor. However, these systems require a separate set of adjustments for each frequency used in the measurements. In other words, the output signals simulating the compressor operation would change whenever the frequency was changed and therefore in taking measurements at any one frequency various parameters had to be adjusted for that one frequency. As a matter of expediency, such analysis was carried on by taking only spot frequency measurements to thus minimize the number of readjustments that would have to be made. With such a system, significant response data could be overlooked for frequencies between those at which spot measurements were made.

### BRIEF SUMMARY OF THE INVENTION

In accord with the present invention, a waveform generator for simulating a multi-cylinder compressor is designed to provide a plurality of electrical output signals which duplicate in wave shape the fluid flow patterns present at the valve outputs of the multi-cylinder compressor. These output electrical signals can be adjusted to simulate a large variety of compressor configurations. When applied to an electrical analog of a piping system, they will induce a response analogous to that caused by the actual compressor in the actual piping system in a manner much more accurately than has been possible heretofore so that more accurate correlation can be achieved between simulated and actual piping system responses.

More particularly, the waveform generator for simulating the multi-cylinder compressor includes a power supply providing a sine wave the frequency of which may be varied over a desired range. This sine wave is received in a reference module including, in turn, a reference section connected to the power supply means for deriving from the sine wave a reference signal, a first A-C signal, a second A-C signal 180° out of phase with the first A-C signal, and a control signal. The reference module also includes a wave shaping section connected to the reference to receive the first A-C signal, second A-C signal, and control signal. This wave shaping section includes position means, slope means, and amplitude means responsive to the control signal for changing the starting position, the leading edge slope, and the amplitude of each waveform cycle of the first and second A-C signals respectively to provide output signals constituting electrical current signals simulating the head end and crank end output of one of the cylinders of the compressor. The position means, slope means, and amplitude means may be individually adjusted so that the shape of the

output electrical signal properly simulates the time of opening of the cylinder valves, the rate of opening of the cylinder valves, and the volume of fluid from the cylinder valves, respectively. Since the actual flow patterns from the head end and crank end of a compressor are 180° out of phase, the two A-C signals utilized in the wave shaping section properly simulate this condition.

In addition to the reference module, there is provided a plurality of slave modules connected to receive the reference signal from the reference section of the reference module. These slave modules represent respectively additional cylinders. Since the signals simulating the head end and crank end conditions of the additional cylinders are respectively shifted in phase from the first cylinder represented by the reference module, the slave modules each include a phase shift section connected to the reference section to receive the reference signal and shift the phase thereof a proper number of degrees corresponding to the phase relationship of the actual additional compressor cylinder to the first-mentioned cylinder. This phase shifted signal in turn is utilized to provide phase shifted first and second A-C signals 180° out of phase with each other together with a phase shifted control signal. These signals in turn are then fed to a wave shaping section in each of the slave modules substantially identical to the wave shaping section described in the reference module so that there result output electrical signals from the slave modules corresponding to the head end and crank end flow patterns of the additional cylinders.

From the foregoing, it will be evident that for a double acting four cylinder compressor the waveform generator must include the reference module for one of the cylinders and three slave modules to represent respectively the three remaining cylinders. Further, it will be evident that the reference module need only include the reference section to provide the basic reference signal and a wave shaping section as described. Each of the slave modules in turn need only include a phase shift section and a wave shaping section. There are thus involved only three basic circuits, to wit: the reference section, the wave shaping section, and the phase shift section and these respective circuits may be formed on integral printed circuit boards, respectively, so that the entire generator can be economically constructed and maintained.

Internal circuitry in the reference and slave modules functions to adjust both the position in time and the slope of the leading edge of each waveform corresponding to the time and rate of a valve opening so that the relative shape of the output electrical signal is maintained for all frequencies of operation. This situation thus correctly simulates the action of an actual compressor and facilitates enormously the analysis of responses in an electrical analog piping system since once the proper adjustments have been effected, no readjustment is necessary when the frequency changes.

An additional feature of the invention contemplates the provision of an amplitude-frequency control switch. When this switch is in a first position, the output amplitudes from all of the modules increases with frequency to correspond to the normal increase in flow rate or volume of fluid per unit time from an actual compressor. When in a second switched position, the amplitude of the output electrical signals is maintained constant for all operating frequencies and thus represents a normalized flow condition or volume of fluid per cycle.

#### BRIEF DESCRIPTION OF THE DRAWINGS

A preferred embodiment of the invention for use in simulating output fluid flow patterns from a multi-cylinder compressor will now be described in conjunction with the attached drawings, in which:

FIG. 1 is a schematic block diagram of an actual compressor and piping system existing in the prior art for which an electrical analog is to be constructed for facilitating analysis thereof;

FIG. 2 is a basic block diagram of the waveform generator of this invention for providing a plurality of electrical output signals of wave shapes simulating the fluid flow patterns from the actual compressor of FIG. 1 for use in an electrical analog of the piping system of FIG. 1;

FIG. 3 is an enlarged view of various waveforms constituting some of the output electrical signals provided by the system of FIG. 2;

FIG. 4 is a block diagram of the electrical circuit making up the reference section of the reference module of FIG. 2;

FIG. 5 illustrates a series of waveforms useful in explaining the operation of the circuit of FIG. 4;

FIG. 6 is a block diagram of the electrical circuit for the wave shaping section in the reference module of FIG. 2. This same diagram also applies to the wave shaping sections in each of the slave modules of FIG. 2;

FIG. 7 illustrates a series of waveforms useful in explaining the operation of the circuit of FIG. 6;

FIG. 8 is a block diagram of the electrical circuit for the phase shift section utilized in each of the slave modules of FIG. 2;

FIG. 9 illustrates a series of waveforms useful in explaining the operation of the circuit of FIG. 8;

FIG. 10 is a simplified circuit diagram for explaining the basic operation of the phase shift circuit in the phase shift section of FIG. 8 together with various equations useful in explaining the operation of the circuit; and

FIG. 11 illustrates part of the actual phase shift circuit together with explanatory equations utilized in the phase shift section of FIG. 8.

#### DETAILED DESCRIPTION

Referring first to FIG. 1 there is illustrated schematically at 10 a four cylinder compressor having the head end and crank end fluid flow outlets from each cylinder passing to the output portion of the compressor itself as indicated at 11 and thence feeding into a piping system 12.

As described heretofore, it is conventional practice to provide an electrical analog circuit corresponding to a proposed actual piping system. By then feeding into the system electrical signals which simulate the actual flow patterns from the compressor, an analysis of the piping system can be much more economically made as compared to actually fabricating the system and making measurements.

FIG. 2 represents such an electrical analog for the system of FIG. 1. In FIG. 2, there is represented generally by the numeral 13 a waveform generator for providing output electrical signals of wave shape simulating the fluid flow patterns from the compressor 10 of FIG. 1. As shown, these signals are fed into a block 14 representing the electrical analog of the piping system 12 of FIG. 1. The particular type of electrical analog circuit for the piping system as indicated at 14 forms no part of the present invention. Rather, this invention is concerned solely with the provision of a waveform generator for simulating the output flow patterns by means of output electrical signals for use with such an electrical analog of the piping system.

For the particular compressor under consideration, the waveform generator 13 includes basically a power supply 15 for providing an input electrical sine wave. The frequency of this sine wave may be manually adjusted by any conventional means.

The remaining portion of the waveform generator comprises a reference module 16 and three slave modules 17, 18, and 19. The reference module includes a reference section 20 connected to receive the sine wave from the power supply 15 and provide signals to a wave shaping section 21 and also provide a reference signal to the slave modules 17, 18, and 19 all as indicated by the connecting lines and arrows.

The reference module 16 of FIG. 2 represents one cylinder of the compressor while the slave modules 17,

5

18, and 19 represent the remaining three cylinders. The output electrical signals from the reference module are, by definition, always at zero phase. Therefore, only phase controls need be provided for the remaining three cylinders as represented by the three slave modules. Thus, the slave module 17 includes a phase shift section 22 passing its output into a wave shaping circuit 23 which may be the same as the circuit 21 in the reference module. Similarly, the slave module 18 includes a phase shift section 24 and wave shaping section 25, and the slave module 19 includes a phase shift section 26 and wave shaping section 27.

The head end and crank end electrical output signals for the reference module appear on leads 28 and are designated I1 and I2. Similarly, the head end and crank end outputs for each of the slave modules are respectively shown at 29, 30, and 31. The respective electrical output signals are designated I1', I2' for slave module 17, I1'' and I2'' for slave module 18, and I1''' and I2''' for slave module 19.

In FIG. 2, there is schematically represented the actual waveforms for the output electrical signals I1 and I2 from the reference module and the phase shifted output signals I1' and I2' for the slave module 17. Similar waveforms would be provided by the slave modules 18 and 19 but would have different phase relationships to correspond to the actual physical phasing of the compressor cylinder outputs.

The adjustability of the phase as well as the shaping of each cyclic waveform is accomplished by suitable circuits in the phase shift and wave shape sections. Essentially, adjustments are provided to vary the time position of starting of each cyclic waveform, the slope of the leading edge of each waveform, and the amplitude of the waveform. These variations permit the waveforms to properly reflect the time of valve opening, the rate of valve opening, and the magnitude of fluid flow respectively for the valves at the head end and crank end of each of the cylinders of the compressor.

With reference now to FIG. 3, a better understanding of each of these adjustments will be had. Thus referring first to the two top waveforms representing the output from the reference module, the time positioning of each cycle of the current I1 is indicated at 32 and is measured from a zero phase angle since these waveforms constitute the references for which phase angle measurements are made for the remaining waveforms in the various slave modules. The dotted line portion of each waveform represents its appearance in the absence of any position adjustment. The slope adjustment is indicated at 33 and by varying this slope, the waveform is shaped to properly reflect the rate of the head end valving action. In most compressors, the rate of valve action is the same at the head end as at the crank end and therefore the same slope 33 when once adjusted also characterizes the crank end waveforms as indicated by the current I2 in FIG. 3.

Finally, the amplitude of the waveform as indicated at 34 may be adjusted for the head end current I1.

The crank end current I2 is shown 180° out of phase which properly simulates actual conditions. As mentioned, the leading edge slope 33 is the same as that for the head end current I1. However, the position of each waveform may be adjusted as indicated at 35 independently of the position adjustment 32 for the head end current. Also, the amplitude of the crank end current I2 may be varied independently of the head end current as indicated at 36.

With reference now to the lower two waveform diagrams representing the head end and crank end electrical output signals I1' and I2' for the slave module, there is indicated at 32' the positioning of the head end current I1'. Similarly, there is illustrated at 33' and 34' the slope adjustment and amplitude adjustment, these adjustments being independent of the position, slope, and amplitude adjustments for the various current outputs in the reference section.

6

For the crank end output current I2' of the slave module, the slope is again designated 33' and is the same as that for the head end as was also the case in the reference module. However, the position and amplitude of the crank end current I2' as indicated at 35' and 36' may be independently adjusted relative to the head end current adjustments.

For the particular slave module output depicted, the degree of phase shift is indicated at 37 in FIG. 3. As described heretofore the remaining slave modules provide similar waveforms except that they would normally be at yet different phase positions and each would include independent adjustments similar to those already described.

At the lower end of FIG. 3 there is illustrated in the box the various adjustments discussed. Thus it will be clear that the head end and crank end include independent adjustments for position and amplitude while both head end and crank end are simultaneously adjusted for slope and phase control. In addition, there may be provided a common gain control indicated at 38 which will vary the amplitude of both the head and crank end waveforms simultaneously and in proper proportion.

As mentioned in conjunction with the block diagram of FIG. 2, there are involved only three basic circuits in the waveform generator. First, the reference section in the reference module and in the various slave modules, and third the phase shift section in the various slave modules. The desired electrical output signals described in FIG. 3 are derived from these basic circuits and accordingly the manner in which these waveforms are generated and adjusted will be better understood by a detailed description of each section respectively.

#### REFERENCE SECTION

FIG. 4 illustrates the reference section 20 in the reference module. As shown, this circuit includes an input amplifier 39 receiving an input sine wave from the power supply. This amplifier incorporates an amplitude-frequency switch control means schematically indicated at 40 and arranged to be switched between first and second positions to engage first and second terminals Q/F and Q. When in the Q/F position as shown, the amplifier 39 has a gain at about 1.0 for all frequencies of the input sine wave. When switched to the Q position, the gain of amplifier 39 varies directly with the frequency from about .2 to about 1.0 over a frequency range of perhaps 40 to 200 cycles per second. Amplifiers with such characteristics are well known to those skilled in the art and are fully described in "Analysis and Design of Electronic Circuits" by Paul M. Chirlian, McGraw-Hill Book Company, New York, published 1965, chapter 6, sections 5 and 6, pp. 218 through 226.

When the switch 40 of the amplifier 39 is in the Q position, the various final output electrical signals described in FIG. 3 will increase in amplitude with increasing frequency of the input sine wave to thereby represent the frequency dependent output level characteristic of the compressor. For purposes of the present description, in regard to FIG. 4 and the remaining figures, the switch 40 will be assumed to be in the Q/F position wherein the output signals are of constant amplitude over the contemplated frequency range.

From the amplifier 39 there is derived a reference signal from a terminal 41. This reference signal feeds into a further amplifier 42 providing an amplification of approximately 2.5. By passing the output from the amplifier 42 through an inverting circuit 43, there may be provided at terminals 44 and 45 first and second A-C signals 180° out of phase with each other. The first signal which is in phase with the reference signal 41 appears on terminal 44 and is designated A. The second A-C signal which is 180° out of phase with the reference signal as a result of inversion in the amplifier 42 appears on

terminal 45 and is designated  $\bar{A}$ . The reference signal on terminal 41, and the first and second A-C signals on terminals 44 and 45 are passed to the wave shaping section of the reference module. The reference signal itself is also passed to the various phase shift sections in the slave modules all as will become clearer as the description proceeds.

In addition to the provision of the reference and first and second A-C signals, there is provided a control signal for utilization in the reference module wave shaping section. This control signal is derived by passing the output from the inverting circuit 43 into a square wave generator 46 and takes the form of a square wave having zero cross-over transition points corresponding exactly in time to those of the reference signal. This control signal is provided on an output terminal 47 designated by the letter B and is utilized in the phase shift circuit of the slave modules. The same control signal is also passed through a lead 48 to a one shot multi-vibrator circuit 49 which serves to generate a waveform having a duty cycle directly proportional to frequency. This waveform is averaged by a first integrator 50 and appears as a D-C voltage on an output terminal 51. This D-C voltage level is thus proportional to the input frequency and is designated F. The output from the multivibrator 49 is also applied through lead 52 to an amplitude modulator 53 where its amplitude is varied directly by the F voltage. When the output waveform of modulator 53 is averaged by a second integrator 54, the resulting voltage appears on a terminal 55 and is proportional to the square of the input frequency. This second D-C voltage level is designated  $F^2$ .

The first and second D-C voltage levels F and  $F^2$  are utilized in conjunction with the amplitude-frequency switch control described in the reference section in a manner to be subsequently described with respect to the wave shaping section.

The various waveforms discussed with respect to the reference section of FIG. 4 are shown in FIG. 5. These waveforms are depicted in FIG. 5 under first and second frequency conditions separated by the broken lines as shown.

The reference sine wave is indicated at 56 and after passing through the amplifier 42 provides the second A-C signal  $\bar{A}$  shown at 57 and after reinverting by the inverter circuit 43 the first A-C signal A shown at 58.

The output control signal B from the square wave generator 46 is shown at 59 and defines zero cross-over points at 60, 61, and 62, by way of example. These cross-over points correspond exactly in time to the sine wave cross-over transition points of the reference signal 56.

Below the waveform B there are illustrated the first and second D-C voltage levels F and  $F^2$  respectively as at 63 and 64. When the frequency of the various signals is increased as shown in the right-hand portion of FIG. 5, the first and second D-C voltage levels F and  $F^2$  increase directly and with the square of the frequency as indicated respectively at 65 and 66.

The manner in which the various signals generated in the reference section are used in the wave shaping section of the reference module and the various slave modules will now be described in conjunction with FIG. 6.

#### WAVE SHAPING SECTION

In FIG. 6, the wave shaping section corresponds to the wave shaping section 21 in the reference module. As indicated, the control signal B from terminal 47 of FIG. 4 is applied to the input of an inverter amplifier 67 to a trigger pulse generator 68. This same signal is also directly applied through lead 69 to the trigger pulse generator. The output from the trigger pulse generator passes to a position ramp generator 70. The position ramp generator provides a linearly rising voltage which starts at each crossover or transition of the B control signal applied to the trigger pulse generator. The slope of this

position ramp generator output signal can be adjusted to one value when the ramp is initiated by an upgoing transition of the B waveform and to a second value when the ramp is initiated by a downgoing transition of the B voltage. This alternate changing of the slope is accomplished by a switch arrangement schematically indicated at 70a and 79b and enables a series of cyclic position ramp signals of one slope to be generated only during positive cycles of the control signal B and a series of cyclic position ramp voltages of a different slope to be generated during the negative cycles of the control signal B.

The position ramp voltages are compared with a given threshold voltage in a threshold detector 71. The output of this threshold detector 71 passes to a slope ramp generator 72. The arrangement is such that initiation of a slope ramp voltage is effected at the time that the position ramp voltage crosses over or intersects the given threshold voltage level established in the threshold detector 71. The ramp voltage signals in both the position ramp generator 70 and the slope ramp generator 72 are returned to zero at each cross-over or transition point of the B voltage and in this respect, there is provided a lead 73 between the output of the trigger pulse generator 68 and the slope ramp generator 72.

The position in time relative to the control signal B at which the slope ramp generator starts to generate a linear ramp voltage can be controlled by changing the slope of the position ramp generator and thus the time at which it intersects the threshold voltage level in the threshold detector. Further, the value of the slope of the slope ramp generated from the slope ramp generator 72 may be varied as desired.

Both the position and slope ramp voltages are created by charging a fixed capacitor with a transistor acting as a constant current generator. As the operating frequency is changed, it is important to also change the slope of each ramp in an automatic manner in order to maintain a fixed output wave shape with changing frequency. This desired frequency dependent slope generation is accomplished in accord with the invention by adjusting the charging current to each capacitor with the first and second D-C voltage levels F or  $F^2$  described heretofore from the reference section. Towards this end, there is illustrated in FIG. 6 a lead 74 receiving on one end terminal 75 the F voltage from the reference section and on its opposite end terminal 76 the  $F^2$  voltage. A switch arm 77 is provided for passing either the F signal or the  $F^2$  signal to the slope ramp generator 72. The F signal itself provides the required frequency adjustment for both ramps when the Q/F or constant output amplitude is used as indicated by the positioning of the switch arm 77 on the Q/F terminal. However when the amplitude-frequency control switch is in the Q position where the output amplitude increases with increasing frequency, the slope ramp generator 72 must be frequency corrected by the  $F^2$  voltage to maintain a consistent wave shape with changing frequency. This latter situation is readily accomplished by simply moving the switch arm 77 from the Q/F position to the Q position.

The output slope ramp from the slope ramp generator 72 is passed through lead 79 to a wave shape circuit 80 having an input terminal 81 for receiving the first A-C signal A from the reference section. Essentially, this ramp voltage is impressed on the first A-C signal by the wave shaping circuit to generate an output which is in turn passed to a head end current amplifier 82. The output of this current amplifier 82 in turn appears at output terminal 83 and constitutes the electrical output signal 11 described in FIG. 3. With reference both to FIGS. 3 and 6, the position adjustment 32 of FIG. 3 is determined by the position in time at which the slope ramp generator 72 commences generating the slope ramp voltage whereas the actual leading edge configuration of the wave form as indicated at 33 is defined by the slope itself of the slope ramp voltage. The amplitude 34 of this head end current

output 11 is adjusted by changing the gain of the head end current amplifier 82. A second output terminal 84 from the head end current amplifier 82 provides a convenient means for monitoring the output signal 11 on the terminal 83.

The same slope ramp voltage from the slope ramp generator 72 appearing on the output lead 79 in FIG. 6 is also passed by means of a branch lead 85 to a second wave shaping circuit 86. This second wave shaping circuit 86 has an input terminal 87 for receiving the second A-C signal  $\bar{A}$  from the reference section it being recalled that this second A-C signal is  $180^\circ$  out of phase with the first A-C signal. The wave shaping circuit 86 of FIG. 6 operates the same as the wave shaping circuit 80 and simply impresses the slope ramp voltage occurring during the negative cycles of the control signal B on the second A-C signal  $\bar{A}$  to provide an output signal passed to a crank end current amplifier 88. The output from the crank end current amplifier appears on a lead 89 and defines the output electrical signal 12. Again, a monitor terminal 90 may be provided for monitoring the output signal appearing on the terminal 89.

A suitable overload indicator circuit 91 may be connected to the output terminals 83, 84, and 89, and 90 as shown to provide an immediate indication of any overload condition.

The foregoing description of the various components of the wave shaping section will be better understood by now referring to the various waveforms in FIG. 7. As shown, the control signal B is reproduced in FIG. 7 at 59 with the various transition points 60, 61, and 62 previously described in FIG. 5 properly indicated. The waveform G appears at the junction between the trigger pulse generator 68 and the position ramp generator 70 and merely constitutes a series of trigger pulses 92, 93, and 94 occurring at each of the transition points of the control signal B. The output from the position ramp generator 70 is indicated at 95 and the threshold voltage level is indicated at 96. The intersection or cross-over point of the ramp 95 with the threshold voltage level 96 occurs at the point 97 and it will be evident that this point will shift to the left or right depending upon the value of the slope 95; that is, the rate of change of the linearly rising voltage.

In FIG. 7, the position ramp slope for the position ramp output occurring during the negative portions of the cyclic waveform 59 as a result of the switching action described in FIG. 6 by means of the electronic switch outputs 70a and 70b is different from the slope 95. These waveforms are shown in lighter lines and the intersection points with the threshold voltage will be different although they could be adjusted to be the same as the intersection point 97.

The superimposed waveforms shown in the next lower waveform indicate the inputs to the wave shape circuit 80 of FIG. 6. As shown, the starting of the slope ramp occurs at the point 98 which corresponds to the intersection point 97, the slope ramp voltage itself being indicated at 99. The first A-C signal A passed into the terminal 81 of the wave shape circuit 80 is indicated at 58 and the point at which the slope ramp 99 intersects this A-C signal A is indicated at 100. The wave shape circuit 80 functions to provide an output which follows the least positive of the two input voltages and to yield a zero output when either input goes negative. With these conditions, it will be evident that with the first A-C signal A connected to one input and the slope ramp voltage connected to the other, the resulting output signal will appear as indicated at 101 in the last waveform plot of FIG. 7. It will be evident by comparing the waveform 58 with the slope ramp 99 and its intersection of the A-C signal at 100, the least positive voltage constitutes the remaining portion of the A-C signal 58 and in all instances where the inputs are negative, the output is zero. When the signal 101 is amplified in the head end current

amplifier 82, the electrical output signal 11 of FIG. 3 as described heretofore is obtained.

In FIG. 7, the corresponding cooperation between the slope ramp voltage and the second A-C signal  $\bar{A}$  applied to the terminal 87 of the wave shape circuit 86 in FIG. 6 has not been shown. However, the operation is exactly the same except that the position ramp occurring during the negative portions of the control signal B may be adjusted to a different value than the position ramp 95 thereby providing the independent adjustment of the position of starting of the slope for the crank end output signal. Since the second A-C signal  $\bar{A}$  is  $180^\circ$  out of phase with the first A-C signal A shown in FIG. 7, it will be understood that the resulting crank end output signal 12 would appear between the signals 101 and the amplitude of these signals in turn may be independently controlled by varying the gain of the crank end current amplifier 88.

The maintaining of a consistent wave shape for the final output signals under an increased frequency condition is depicted to the right of FIG. 7 wherein it will be noted that with increased frequency the slopes from the respective position ramp generators and slope ramp generators are considerably greater than in the previous situation described. Again this increased slope is automatically effected by the first and second control signals F or  $F^2$  as the case may be which signals in turn constitute functions of the frequency. This automatic control of the wave shape adjustments with changes in frequency constitutes an important feature of this invention since a number of different frequencies may be utilized without requiring any changes in the initial settings for the position ramp and slope ramp.

As described, the wave shaping section of FIG. 6 corresponds to the wave shaping section 21 in the reference module. The other wave shaping sections 23, 25, and 27 shown in FIG. 2 are identical to that shown in FIG. 6 except that the input control signal constitutes a desired phase shifted control signal relative to the signal B prior to being received in the inverter amplifier 67 and the first and second A-C signals A and  $\bar{A}$  are generated from the phase shifted reference signal in the phase shift section and applied to terminals 81 and 87. The manner in which this phase shifting is accomplished will now be described.

#### PHASE SHIFT SECTION

Referring to FIG. 8 there is shown the wave shift section 22 for the slave module 17 of FIG. 2. The phase shift sections 24 and 26 for the slave modules 18 and 19 of FIG. 2 are identical except that different degrees of phase shift are set into the circuits.

As shown in FIG. 8, the reference signal REF from the terminal 41 of the reference section shown in FIG. 4 is applied to an input amplifier 103 in FIG. 8. This amplifier amplifies the signal slightly to compensate for a fixed attenuation in the phase shifter. The phase shifting circuit itself is shown at 104 and is capable of shifting the phase angle of the input signal from about zero degrees to almost  $360^\circ$  as desired. This phase shifting is accomplished with no affect on the signal amplitude.

The output from the phase shift circuit 104 passes through an amplifier 105 having a gain of about 2.5. The phase shifted signal is then passed through an inverting circuit 106 and appears as a phase shifted first A-C signal at a terminal 107. This signal corresponds to the signal A from the reference section except that it has been shifted in phase. The letter A' represents this phase shifted first A-C signal. Between the amplifier 105 and the inverter circuit 106, there is provided at terminal 108 a phase shifted second A-C signal designated  $\bar{A}'$ . This latter signal is  $180^\circ$  out of phase with the signal A' and corresponds to the second A-C signal  $\bar{A}$  except that it is phase shifted through the desired angle.

The signal from the inverter circuit 106 passes into

11

a square wave generator 109 to provide a phase shifted control signal appearing on an output terminal 110 and designated B'. The components 105, 106, and 109 are the same as the components 42, 43, and 46 in the reference section and serve to provide phase shifted first and second A-C signals and a phase shifted control signal for application to the associated wave shaping section in the particular slave module involved.

The phase shifted control signal B' is also applied through lead 111 to one side of a phase detector flip-flop circuit 112. The other side of this circuit receives through lead 113 the control signal B from the reference section connected to terminal 114. The phase detector circuit 112 provides an output pulse whose width is proportional to the difference in phase between the control signal B' and control signal B which difference corresponds to the degree of phase shift effected by the phase shift circuit 104. These pulses are summed in an integrator circuit 115 to provide a D-C level proportional to the phase shift. This voltage level may be applied directly to a meter 116 to indicate the degree of phase shift. The same signal is also applied to a phase control circuit 117. The other side of the phase control circuit 117 is arranged to receive through a lead 118 a manually set D-C voltage level referred to in FIG. 8 as a phase set.

The phase control circuit 117 compares the input D-C level from the integrator 115 with the D-C voltage level received on the lead 118 and manually set. Any difference in these two voltage levels results in an error signal which is fed back through leads 119 to a feedback circuit including a lamp 120 and photosensitive resistance R, the latter element being incorporated in the phase shift circuit. The arrangement is such that the intensity of the lamp circuit 120 is a function of the error signal and will irradiate the photosensitive resistance R to change its value in such a direction as to diminish the error signal. In other words, the change in the resistance R will effect a change in the phase shift in the circuit 104 which in turn will result in a change in the input voltage level from the integrator 115 to the phase control circuit until such time as this input voltage level corresponds to the input voltage level provided by the phase set lead 118. The degree of phase shifting by the circuit 104 is thus locked to a particular value as determined by the D-C voltage input on the lead 118. This input may be manually changed to any desired value.

The foregoing operation of the phase shift section will become clearer by now referring to FIG. 9 which illustrates various waveforms appearing at correspondingly lettered points in the circuit of FIG. 8. Thus, there is illustrated in the top waveform the reference signal 56 amplified slightly by the input amplifier 103. This is the same reference signal designated 56 in FIG. 5. After this signal passes through the phase shift circuit 104, amplifier 105 where it is inverted, and inverter circuit 106 where it is reinverted, it appears as shown at 56' and corresponds to the phase shifted first A-C signal A' appearing on the terminal 107. The degree of phase shift is indicated at 121. The signal on the terminal 108 of FIG. 8 is the same as the signal 56' but is 180° out of phase therewith and as mentioned, corresponds to the phase shifted second A-C signal A'.

The output of the square wave generator 109 results in the phase shifted control signal B' and is designated 59' in FIG. 9. This control signal is the same as the B signal designated 59 in FIG. 5 but has been phase shifted so that it defines transition points 60', 61' and 62' corresponding to the transition points of the waveform 56' across the zero axis.

Below the phase shifted control signal B' there is shown the control signal B from the reference circuit designated 59 with transition points 60, 61 and 62. The phase detector flip-flop circuit 112, as mentioned, provides an output pulse or waveform 122 at the lettered point H in FIG. 8, this pulse having a width proportional to the

12

phase shift between the input signal B' and B. After passing through the integrator 115, there appears at K the output D-C voltage level 123. The magnitude of this D-C voltage is proportional to the width of the pulses 122 and when fed into the meter 116 will thus provide a reading indicating the degree of phase shift.

Below the voltage level 123 in FIG. 9 there is indicated a phase setting voltage level 124. The double headed arrow indicates that this setting may be adjusted to any desired voltage level. With the setting as shown, there is developed a small error signal 125. This error signal will control the intensity of the lamp circuit 120 as described in FIG. 8 to vary the value of the photosensitive resistance R and thus further shift the phase in a proper direction to minimize the error signal; that is, to make the input voltage level 123 as close as possible to the phase setting voltage 124. When these two voltages are equal, the error signal will be zero.

The various waveforms to the right of the broken lines in FIG. 9 correspond to those on the left except that they represent conditions under an increased frequency. As is well known to those skilled in the art, whenever the frequency of an input signal to a phase shifting circuit changes, there also will result a change in the degree of phase shifting involved. This is because the reactive elements employed in the phase shift circuit are sensitive to frequency. It is desirable, however, to have all parameters set into the waveform generator of this invention be independent of frequency in order that readjustments will not be necessary whenever the frequency is changed. The control signals and feedback circuits for the phase shift circuit described in FIG. 8 automatically compensate for the added change in phase shift as a result of frequency change.

Thus referring still to the right-hand waveforms in FIG. 9, it will be noted that the increased frequency results in a different degree of phase shift which different degree in turn will result in a different duty cycle or pulse width for the various pulses indicated at 126 which correspond to the pulses 122 for the lower frequency case.

The output from the integrator circuit 115 will thus be a different voltage level as indicated at 127. When this voltage level is compared to the phase set voltage level 128 which latter value is identical to the phase set value 124, there will result a large error signal as indicated at 129. This error signal will thus cause a change in the value of the photosensitive resistance in the phase shift circuit in a direction such as to bring the voltage level 127 up to a value corresponding to that of 128. There is thus provided automatic phase compensation for changes in frequency.

When it is desired to change the degree of phase shift, the only adjustment necessary is to change the phase set voltage level 124 applied to the phase control circuit 117 by the input lead 118. This input voltage level may be manually set by a simple potentiometer. Further, each phase shift section in each slave module may be set at a desired phase and the feedback circuitry will always assure that this desired phase is maintained.

As mentioned, the various phase shifted first and second A-C signals A', A' and phase shifted control signal B' are passed to the associated wave shaping section in the slave module to provide electrical output signals corresponding, for example, to the output signals 11' and 12' of FIG. 3. The wave shaping section operates in an identical manner as that employed in the reference section the only difference being that the wave shaping section operates at the new phase angle set by the phase shift section.

Most of the individual circuits as represented by the blocks in the various figures are individually well known to those skilled in the art. The novelty of this invention resides in the combination of these various individual circuits operating together to realize the desired end results.

One exception to the foregoing, however, is the phase shift circuit 104 described in FIG. 8. The actual circuit represented by this block is believed unique in that it provides the desired phase shift without any change in the amplitude of the phase shifted signal. Details of this circuitry will accordingly be described in conjunction with FIGS. 10 and 11.

Referring first to FIG. 10 there is illustrated a simplified schematic electrical circuit equivalent to the phase shift circuit 104 of FIG. 8. As shown, there are represented first and second A-C signal voltage generators 130 and 131 providing a voltage  $E$  with polarity as indicated. The junction between these two generators is grounded at 132 and the other ends are connected through a series resistance and capacitor circuit shown at  $R$  and  $C$ . An output voltage is taken between ground and the junction of the resistance  $R$  and the capacitor  $C$  and is indicated  $E_o$ . The assumption is made in the accompanying analysis that no current flows from the output terminal. In this case, the circulating current  $i$  will be given by Equation 1.

The value of the output voltage  $E_o$  in turn is given by Equation 2 and the transfer function or the value of  $E_o/E$  is given by Equation 3. This latter expression reduces to the expression given in Equation 4. Equation 4 may then be rewritten as Equation 5 and finally reduced to the expression set forth in Equation 6. From this last equation, it will be evident that the absolute magnitude of  $E_o/E$  equals 1 and thus is independent of the phase angle. This is expressed in Equation 7.

The phase angle itself of  $E_o/E$  is given in Equation 8. Thus while the ratio of the output amplitude to the input amplitude for this circuit is independent of frequency,  $R$ , and  $C$ , the phase shift introduced by this circuit is dependent on all three of these parameters. The phase shift circuit of this invention utilizes these characteristics to provide the desired phase shift without introducing amplitude variations.

FIG. 11 shows a practical realization of the circuit described in FIG. 10. In this circuit, there is shown a voltage source  $+V$  providing current to an input transistor 133 having base, collector, and emitter leads. The reference voltage passed to the phase shift circuit 104 of FIG. 8 is applied between the base lead and ground at 134 and is indicated as  $E_{in}$  in FIG. 11. The collector and emitter leads include equal valued resistances  $R_1$  and  $R_2$  and connect between the voltage source and ground 134 as shown. A resistance and capacitor circuit comprising the variable photosensitive resistance  $R$  and the capacitor  $C$  connect across the collector and emitter terminals. The circuit is completed by an output field effect transistor 135 having gate, source, and drain leads. The gate lead connects to the junction between the resistance  $R$  and capacitor  $C$ , the source terminal including a load resistance  $R_3$  connects to the voltage source  $+V$  and the drain lead connects to ground. The phase shifted output signal is designated  $E_{out}$  and is taken from across the source and drain terminals.

In the operation of the circuit of FIG. 11, the collector and emitter currents  $i_c$  and  $i_e$  for the transistor 133 are essentially equal. Therefore, from Equation 1 in FIG. 11 Equation 2 follows with the condition that  $R_1$  equals  $R_2$ . This Equation 2 shows that the phase shifting circuit and its current  $i$  have no effect on the currents through  $R_1$  and  $R_2$ . Therefore variations in the values of  $R$  or  $C$  will not change the voltages appearing at the emitter or collector of the transistor.

Since  $R_1$  equals  $R_2$ , the magnitude of the A-C voltages at the emitter and collector of the transistor 133 will be equal. This condition satisfies the input requirements described in FIG. 10 for the generators 130 and 131.

The assumption of a zero current at the output terminals in the simplified circuit of FIG. 10 in turn is satisfied by the use of the field effect transistor 135. The input impedance of this device over the desired frequency range

is so high that its input current can be considered equal to zero.

With the equivalency of the circuit of FIG. 11 to that of FIG. 10 in mind, the transfer function or relationship between the  $E_{out}$  signal and the  $E_{in}$  signal will be the same as set forth in Equation 6 of FIG. 10. In the actual circuit of this invention, a second circuit identical to the circuit of FIG. 11 is connected in cascade so that the overall phase shift is defined by Equation 4 of FIG. 11.

From Equation 4, it will be evident that the limits of the phase shifter are zero degrees with WRC equal to zero and  $360^\circ$  with WRC equal to infinity.

#### OVERALL OPERATION

The overall operation of the waveform generator of this invention as used to simulate the output of a multi-cylinder compressor will be evident from the foregoing detailed description. With reference once again to FIG. 2, the output electrical signals  $I_1$  and  $I_2$  for the head end and crank end of a first cylinder in the compressor are caused to simulate the flow patterns at the head end and crank end valve openings as follows:

First, the input sine wave frequency from the power supply 15 is adjusted to correlate with the contemplated r.p.m. of the compressor. Next, the position ramp generator 70 of FIG. 6 is adjusted in a manner such that the position ramp voltage has a slope defining a position intersection point with the threshold voltage corresponding to the time position that the valve at the head end of the cylinder opens relative to the cycle of operation. At the same time, an independent adjustment may be made of this slope for simulating the position in time that the crank end valve of the cylinder opens.

Next, the actual slope of the output voltage from the slope ramp generator 72 in the wave shaping section is adjusted to define the rate of opening of the respective valves at the head and crank ends. Finally, the head end and crank end current amplifiers in the wave shaping section have their gains individually adjusted to simulate the volume of fluid flow from the head end and crank end portions of the cylinder respectively.

After the foregoing adjustments have been completed, the electrical output signal currents  $I_1$  and  $I_2$  will properly simulate the flow patterns at the head and crank ends of the one cylinder of the compressor under consideration.

Next, the phase shift circuits in the respective slave modules may be set to shift the phase of the input reference signal thereto relative to the signals appearing from the reference module to properly simulate the sequential flow patterns of the remaining three cylinders. As mentioned, these phase shifts may be individually adjusted. After the phase shift adjustments have been made, the respective wave shaping circuits for each of the slave modules may be individually adjusted to simulate the respective time positions that the valves open and the rate of opening of these valves. Finally, the amplitude of the output signals from these slave modules may be adjusted to correspond to the volume flow of fluid from the respective remaining cylinders.

After all of the foregoing adjustments have been completed, the output leads from the various modules are fed into the electrical analog of the piping system designated 14 in FIG. 2. The frequency of the input sine wave from the power supply may now be manually varied to simulate changes in the r.p.m. of the compressor and the response exhibited by the electrical analog of the piping system analyzed accordingly. In this respect, it should be noted that changing of the frequency can be carried out smoothly and continuously so that there are no frequencies overlooked during the analysis as was the case in prior art operations wherein only spot frequency checks are made. Moreover, any changes in various settings such as the phase settings that might occur with a change in frequency are automatically compensated for by the cir-

15

cuitry described heretofore all to the end that once the initial adjustments have been made, no readjustments are necessary during a changing of the input frequency.

Moreover, the internal circuitry correcting the time position and rate of change of the position ramp and slope ramp simulating the valve opening for each of the valves with frequency changes, assures that the output wave shapes are maintained over the entire operating frequency range.

During the analysis, the amplitude-frequency control switch may be shifted between the Q and the Q/F positions. As stated heretofore, when in the first or Q position the electrical output signals behave like normal compressor flow wherein the amplitude of the output signals increases with increasing frequency. When in the second or Q/F position, the output signals will represent a different compressor output parameter, specifically the volume of fluid per cycle.

Because of the various adjustments as described, the wave form generator is capable of simulating compressors with from one to four cylinders of any arbitrary phasing. Further, compressors of one to eight cylinders may be simulated by simply employing two of the waveform generators for operation together. It is also possible in the case of a single action compressor as opposed to the double action described to employ only the signals from for example the head end to simulate this compressor type.

The various features described will thus allow the analysis of a wider range of piping problems and will produce more accurate analysis than methods used heretofore.

What is claimed is:

1. A waveform generator for providing at least one electrical output signal of wave shape simulating a given fluid flow pattern, comprising, in combination:

- (a) power supply means for generating a cyclic waveform and including means for varying the frequency of said waveform;
- (b) reference waveform generating means responsive to said cyclic waveform for generating a reference waveform and an A-C signal corresponding in waveform to said cyclic waveform; and,
- (c) wave shaping means connected to said reference waveform generating means to receive said A-C signal, said wave shaping means including means for independently
  - (1) changing the starting position,
  - (2) the leading edge slope, and
  - (3) the amplitude of the waveform of said A-C signal to provide said electrical output signal of said wave shape, said starting position and leading edge slope being automatically adjusted for changes in frequency to automatically maintain the shape of said waveform throughout a given frequency range.

2. A waveform generator according to claim 1, in which said reference waveform generating means includes frequency-amplitude control switch means for increasing the amplitude of said A-C signal with increasing frequency of said cyclic waveform when in a first position, and maintaining the amplitude of said A-C signal constant with increasing frequency when in a second position.

3. A waveform generator according to claim 1, including means responsive to said reference waveform for shifting the phase of said A-C signal relative to said reference waveform.

4. A waveform generator according to claim 3, in which said means for shifting the phase of said A-C signal comprises a phase shift circuit including a voltage source; an input transistor having base, collector, and emitter leads, said reference waveform being received between said base lead and ground, said collector and emitter leads including equal valued resistances and being connected between said voltage source and ground; a resistance and capacitor circuit connected across said emit-

16

ter and collector leads; and an output field effect transistor having gate, source, and drain leads, said gate lead being connected to the junction between said resistance and said capacitor; a load resistance connected between said source lead and voltage source, and said drain lead being connected to ground, the output of said phase shift circuit being taken from between said drain lead and ground, said resistance constituting a variable resistance such that changing of its value will change the degree of phase shifting of said A-C signal.

5. A waveform generator for providing a plurality of electrical output signals of wave shapes simulating given fluid flow patterns, comprising, in combination:

- (a) power supply means for providing an input sine wave and including manual means for changing continuously the frequency of said sine wave as desired;
- (b) a reference module including

- (1) a reference section connected to said power supply means for deriving from said sine wave a reference signal, a first A-C signal, a second A-C signal 180° out of phase with said first A-C signal, and a control signal;

- (2) a wave shaping section connected to said reference section to receive said first A-C signal, said second A-C signal, and said control signal, said wave shaping section including position means, slope means, and amplitude means responsive to said control signal for changing the starting position, the leading edge slope, and the amplitude of each wave form cycle of said first and second A-C signals respectively.

to provide output signals constituting some of said plurality of electrical output signals;

- (c) a plurality of slave modules, each including:

- (1) a phase shift section connected to said reference section to receive said reference signal and including phase shift means for shifting the phase of said reference signal to provide a phase shifted first A-C signal, a phase shifted second A-C signal 180° out of phase with said phase shifted first A-C signal, and a phase shifted control signal; and

- (2) a wave shaping section connected to said phase shift section to receive said phase shifted first A-C signal, said phase shifted second A-C signal and said phase shifted control signal, and including position means, slope means and amplitude means similar to said first-mentioned position means, slope means and amplitude means in said first-mentioned wave shaping section, responsive to said phase shifted control signal for changing the starting position, the leading edge slope, and the amplitude respectively of each waveform cycle of said phase shifted first and second A-C signals respectively,

to provide output signals constituting the remaining ones of said plurality of electrical output signals, said position means and slope means in said wave shaping sections automatically adjusting the starting position and leading edge slope of said phase shifted first and second A-C signals with changing frequency to automatically maintain the relative shape of the waveforms thereof throughout a given frequency range of said input sine wave.

6. A waveform generator according to claim 5, in which said reference section includes frequency-amplitude control switch means for generating first and second D-C control signals respectively when said switch means is in first and second positions, and in which each of said wave shaping sections includes frequency-amplitude responsive means selectively responsive to said first and second D-C control signals in accord with the position of said switch means to increase the amplitudes of said electrical output signals with increasing frequency in response to said first D-C control signal, and to maintain

17

constant the amplitudes of said electrical output signals with increasing frequency in response to said D-C control signal.

7. A waveform generator according to claim 5, in which said position means in each of said wave shaping sections includes: a trigger pulse generator connected to receive said control signal and provide a series of trigger pulses corresponding in time to the zero axis cross-over points of said first and second A-C signals; a position ramp generator responsive to said pulses to generate a ramp voltage; means for generating a given threshold voltage level; a detecting circuit receiving said position ramp voltage and said threshold voltage level, said slope means in each of said wave shaping sections being connected to said detecting circuit and including a slope ramp generator responsive to the point in time when said position ramp voltage intersects said threshold voltage to initiate generation of a slope ramp voltage; first and second wave shaping circuits connected to receive said slope ramp voltage and connected to receive respectively said first and second A-C signals to provide output signals whose leading edges start in time positions corresponding to the time position of initiation of said slope ramp voltage and having slopes corresponding to the slopes of said slope ramp voltage; and in which said amplitude means in each of said wave shaping sections constitute first and second current amplifiers connected to receive said output signals and provide at their outputs said electrical output signals, the positions thereof being adjustable by changing the intersection point of said threshold voltage level and said position ramp voltage, the slopes thereof being adjustable by changing the slope of said slope ramp voltage, and the amplitudes thereof being adjustable by changing the gains of said current amplifiers.

8. A waveform generator according to claim 5, in which said phase shift means in each of said phase shift sections includes: a phase shift circuit incorporating a variable resistance the value of which determines the degree of phase shifting of said reference signal; a phase detector circuit connected to receive said control signal from said reference section and said phase shifted control signal and provide an output signal of voltage level proportional to the degree of phase shift; a phase control circuit receiving said voltage level; a manually controllable phase setting means providing a selected voltage signal to said phase control circuit for comparison with said voltage level, said phase control circuit generating an error signal proportional to the difference between said selected voltage signal and said voltage level; and feed-

18

back means connected between said phase control circuit and said phase shift circuit and responsive to said error signal to change the value of said resistance in a direction to minimize said error signal whereby the phase shifting of said electrical output signals from said slave modules is adjustable by manually adjusting the value of said selected voltage signal.

9. A waveform generator according to claim 8, in which said resistance is photo-sensitive, said feedback means including a lamp positioned to irradiate said resistance, the intensity of said lamp constituting a function of said error signal.

10. A waveform generator according to claim 8, in which said phase shift circuit includes: a voltage source; an input transistor having base, collector, and emitter leads, said reference voltage being received between said base lead and ground, said collector and emitter lead including equal valued resistances and being connected between said voltage source and ground; a resistance and capacitor circuit connected across said emitter and collector leads; and an output field effect transistor having gate, source, and drain leads, said gate lead being connected to the junction between said resistance and said capacitor, a load resistance connected between said source lead and voltage source, and said drain lead being connected to ground, the output of said phase shift circuit being taken from between said drain lead and ground, said resistance constituting said variable resistance.

11. A waveform generator according to claim 5, in which said electrical output signals simulate the fluid flow patterns generated at the head end and crank end fluid flow valve outlets of a multi-cylinder compressor.

#### References Cited

##### UNITED STATES PATENTS

|           |         |           |           |
|-----------|---------|-----------|-----------|
| 2,990,531 | 6/1961  | Morris    | 328—31 X  |
| 3,041,541 | 6/1962  | Gerr      | 328—31    |
| 3,262,069 | 7/1966  | Stella    | 235—197 X |
| 3,319,079 | 5/1967  | Matsumoto | 307—295 X |
| 3,356,865 | 12/1967 | Woster    | 307—295 X |
| 3,364,366 | 1/1968  | Woolfson  | 307—229 X |
| 3,392,352 | 7/1968  | White     | 307—246 X |

MALCOLM A. MORRISON, Primary Examiner  
F. D. GRUBER, Assistant Examiner

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