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(54) Electrical analog of a piping network having a centrifugal compressor therein.

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FR-A-1 300 125
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US-A-3 506 819
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US-A-3 636 335

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Description

The present invention relates to an electrical analog of a piping network having a compressor therein and has particular reference to an electrical analog for simulating the low frequency pulsations and surge characteristics of centrifugal compressors and pumps and their interaction with their piping systems.

Centrifugal compressors have been widely used in pumping gaseous fluids through piping systems, especially in the transportation of natural gas through pipelines.

Experimental work both in the laboratory and with field centrifugal compressors have evidenced heretofore unexplained transient phenomena in at least two areas, namely:

1. the response of a compressor to pulsations from an external source which might be introduced into either the compressor suction or discharge piping, and
2. the effects of compressor piping on machine surge.

Some of the more specific observed phenomena are:

a) A centrifugal compressor can either amplify or attenuate external pulsations.

b) Even with no positive source of pulsations in the piping system, low frequency pulsations can be experienced at levels sufficiently high to fatigue compressor internals or severely shake the piping.

c) These pulsation problems can often be mitigated by changing the pulsation response of the compressor piping (lengths, diameters, etc.). High level pulsations have been observed at frequencies ranging from less than one Hz and approaching zero, to several hundred hertz. Frequencies are not harmonically related to and do not vary with centrifugal compressor speed.

d) The severe pulsation frequencies normally relate to one of the major piqe resonances of the piping systems, and measurements along the piping show a strong standing wave pattern, often existing across or through the compressor.

e) The onset, frequency, and severity of machine surge can also vary as the piping system is changed.

f) Pulsation levels are most severe when the compressor is situated at or near a velocity maximum (pressure minimum) in the pulsation standing wave field.

g) External pulsations can induce surge in a centrifugal compressor.

It is the principal object of this invention to provide an analog of a centrifugal compressor and its associated piping system in order that the above phenomena, as well as others, can be studied and various variables optimized to minimize the effect of pulsations and machine surge.

An electrical analog model of a piping network having a cylinder compressor is already known from the US—A—3 581 077.

The known analog model has a capacitor pump for simulating the pumping action of a compressor and has circuits connected to its output and input simulating the piping upstream and downstream of the compressor. In use voltages are applied to the input and output of the capacitor pump which are proportional to the suction and discharge pressures of the compressor. The analog model includes electrical means for generating a driving voltage for driving the capacitor pump at a driving input to cause it to simulate the action of the cylinder compressor in that piping network. The electrical means comprises a voltage generator having a sinusoidal output voltage and means for scaling a constant voltage by a factor to produce a reference voltage related to the desired voltage at the outlet of the capacitor pump. In this known arrangement the difference between the reference voltage and the desired voltage is measured and used to modify the amplitude of the sinusoidal output voltage which in turn modifies the output of the capacitor pump so that the output voltage equals the reference voltage. Various electrical circuits are connected in series with the capacitor pump output to simulate pipework, regulator stations, etc. downstream of the compressor station.

Varying compressor output pressures can be simulated by varying the constant voltage source. Although the effects of certain changes downstream of the compressor can be investigated in the known model no provision is made for producing a simulation of low frequency pulsation and surge characteristics of a pump and pipelines functioning together, in particular no provision is made for investigating the effects of pulsations at the inlet to the compressor.

In order to satisfy the principal object mentioned above there is provided, in accordance with the present invention and starting from the known prior art arrangement of US—A—3 581 077, an electrical analog of a piping network having a compressor or pump therein comprising:

a) a capacitor pump for simulating the pumping action of a compressor and having circuits connected to its input and output simulating the piping upstream and downstream of said compressor, the capacitor pump comprising two series connected diodes and a capacitor connected to form a T-section, the driving input being the electrode of the capacitor opposed to the diodes and the input and output of the capacitor pump being the anode and cathode respectively of the series connected diodes;

b) means for applying voltages to the input and output of said capacitor pump which are proportional to the suction and discharge pressures of said compressor; and

c) electrical means for generating a driving voltage for driving said capacitor pump at a driving input, to cause it to simulate the action of the compressor in said piping network, said electrical means comprising:

I) a voltage generator having a sinusoidal output voltage, and

II) means for scaling a constant voltage by a factor A,

said electrical analog being characterised in a centrifugal compressor by said electrical means further comprising:

III) first means for sensing the suction voltage,

IV) means for scaling the output of said first means by a factor (B−1),

V) means for measuring the current I through the first said diode of said capacitor pump and means for scaling it by a factor

$$(C+\frac{1}{fC_o})$$

where C is a numerical coefficient, C_o is the value of said capacitor and f the frequency of said sinusoidal voltage in (I),

VI) means for squaring and scaling said current flow respectively by a factor D,

VII) means for multiplying the suction voltage by the current and means for scaling the result by a factor E;

VIII) means for adding the outputs of items II, III, IV, V, VI and VII to provide a sum voltage; and

IX) means for making the amplitude of said sinusoidal output voltage proportional to said sum voltage.

In effect the invention provides a nonlinear analog which effectively superimposes the dynamic flow impedance characteristics of a piping system upon the compressor curves so that the combined characteristics can be used to predict pulsation gain or loss and system stability and the effect of various variables upon them.

The present invention will now be explained in more detail by way of example only and with reference to the accompanying drawings wherein:

Figs. 1 to 6 are provided to facilitate an explanation of the theoretical background, and

Fig. 7 shows an embodiment of the invention.

Referring firstly to Fig. 1 the curve 10 illustrates the basic nonlinear (square law) nature of pipe flow resistance. Thus as its supply pressure is lowered, pipe flow will decrease, stop or perhaps even backflow. If a centrifugal compressor is the supply source, its performance curves can then be superimposed on the same plot by plotting compressor discharge pressure versus discharge flow velocity as shown by the curve 11 in Fig. 1, curve 11 being plotted for particular suction pressure P_{S1}. The operating point is the intersection of the two curves at point 0. Also shown in Fig. 1 is a second performance curve of the compressor (a dashed line) which can result from lowering suction pressure to P_{S2} or compressor speed. In all cases, the operating point must fall on the pipe impedance curve so long as steady flow conditions are assumed and the pipe steady flow impedance is not changed. If, however, flow is modulated at higher frequencies where inertial effects and line pack effects are significant, then the steady state impedance curve sets the operating point but no longer controls the relations between pulsation pressures and flows. This results in a different impedance line drawn to the operating point and the slope of this dynamic impedance line is quite frequency sensitive for typical piping systems. The dynamic impedance frequency line is shown in Fig. 2 as line 12. In Fig. 2, the operating curves 13, 14 and 15 are shown for a centrifugal compressor operating at an average suction pressure P_{S0} but pressure modulations cause this to vary from P_{S1} to P_{S2}. Under these conditions, both the compressor curves and the pulsation impedance of the discharge line will influence flow and discharge pressure modulations. The slope of the dynamic impedance line 12 in Fig. 2 can be any positive value, theoretically, from near zero to a very high value, depending on pulsation frequency and transient response characteristics of the discharge piping.

Referring again to Fig. 2, it can be seen that when the discharge pressure modulation (P_2-P_1) is larger than the suction pressure modulation $(P_{S2}-P_{S1})$ the compressor appears to amplify suction pressure pulsations, at least under those particular operating conditions, with that particular piping system and at that particular frequency. If the dynamic impedance line is sufficiently flat, then P_2-P_1 can approach zero and the compressor will effectively attenuate suction pressure pulsations.

Fig. 3 illustrates a plot of impedance versus length for the resonance mode of a fundamental half wave in a pipe or vessel closed at both ends. Thus the slope of the dynamic impedance line will vary from a relatively high value at the ends of the vessel to essentially zero at the center of the vessel. Thus if a compressor feeds such a vessel at its center point, a very low impedance would be evidenced at the frequency depicted. On the other hand, a very high impedance would be seen at feed points near the closed ends. Therefore, the mangitude of the dynamic impedance would vary markedly depending upon where the compressor feeds into the vessel and upon the perturbation frequency.

Compressor surge has at times been a problem. To illustrate this, consider a set of compressor curves as shown in Fig. 4 with the operating point B and a dynamic load line as shown at Z_1. If the suction pressure is modulated from P_1 to P_2, the system is stable since in all cases the compressor head is sufficient to supply the discharge pressure required by the dynamic load line. However, if suction pressure drops below P_3, then the compressor cannot supply the piping pressure required to supply the necessary flow and flow therefore diminishes. As flow diminishes, the compressor head inadequacy becomes more pronounced and the entire flow regime collapses and surge results. The piping may begin to backflow locally into the compressor discharge to make up for the compressor inadequacy. As the suction pressure rises, then the compressor rebuilds up the load line into a temporary stable condition, but with a rather violent flow surge. The cycle then repeats.

As will be seen from Fig. 4, the steeper the slope of the dynamic load line, the more stable the system insofar as surge is concerned and a very high impedance system (Z_3) would never go into surge at all but would probable experience rotating stall instead.

The complexity of the pulsation pattern increases as the piping complexity increases for example, the illustration in Fig. 4 implies that discharge pressure and flow are in phase, a condition which can be achieved only in idealized piping systems. For a real system with branches and/or area discontinuities, phase shifts occur, and in fact approach 90 degrees near acoustic resonance. Such a condition is illustrated in Fig. 5 where the orbit of flow versus pressure into a reactive piping system is shown. The orbit of Fig. 5 for a reactive system is comparable to the line Z_3 in Fig. 4 for a non-reactive system, i.e. a state of stability. Fig. 6 illustrates a surge orbit pattern for the reactive system of Fig. 5. The complexity of Figs. 5 and 6 illustrate the need for simulating the various interactions of parameters of the compressor and piping system.

In accordance with this invention, an analog is provided to simulate the operation of a centrifugal compressor utilizing an actual (non-linear) head curve in order to, among other things, simulate surge instability frequencies and amplitudes. Thus, it has been found that a conventional capacitor pump when driven by a sinusoidal voltage proportional to the sum of at least 3, and preferably 5 values, will simulate the dynamic characteristics of a centrifugal compressor. When the input and output of the analog are connected to suitable delay lines and the like to simulate various piping configurations, the interaction of the compressor with the piping system can be simulated.

Referring to Fig. 7, there is shown a conventional capacitor pump comprising the diodes D_1 and D_2 and the capacitor C_0, one form of which is described in the US—A—2,951,638 along with the attendant delay lines for simulating a piping system. Thus there is provided a capacitor pump for simulating the pumping action of a centrifugal compressor and having circuits (not shown) connected to the input and output analogizing the piping upstream and downstream of the compressor.

Means are also supplied for applying a voltage E_S to the input of the capacitor pump which is proportional to the suction pressure of the compressor, this means being indicated by "Suction E_s". Similarly, means are provided for applying a voltage to the output of the capacitor pump proportional to the discharge pressure and indicated by the term "Discharge E_D".

F_s and F_d are low pass filters which are inserted to filter out any stray alternating currents which may have an adverse effect on the capacitor pump.

Electrical means are provided for driving the capacitor pump to cause it to simulate the action of the centrifugal compressor in the piping network. The driving means has a sinusoidal voltage output which is proportional to the sum

$$E_B = A + (B-1)E_S + \left(C + \frac{1}{f\,C_o}\right)I + DI^2 + EIE_s \quad (1)$$

The driving means includes a first means for sensing the suction voltage here shown as amplifier A2. Means are also provided for scaling the output of the first means (A2) by a first factor $(B-1)$, here illustrated as the potentiometer B, to yield the value $(B-1)\,E_s$ in equation (1). $(B-1)$ is derived by appropriate feed back around amplifier A2 as shown from the resistor network 9R and R.

Means are also provided for sensing and scaling the current flow through the capacitor pump by a second factor:

$$C + \frac{1}{f\,C_o} \quad (2)$$

to yield the value

$$\left(C + \frac{1}{f\,C_o}\right)I. \quad (3)$$

Where C is a numerical coefficient and C_o is the value of capacitance C_o in the circuit. This means is illustrated as including the amplifier A8 and potentiometer alpha. The latter is set in accordance with the calculated value of equation (2) above. In this connection, the components within the dashed block labeled "Meter" is a Hall effect metering circuit. In any event, the current flowing to amplifier A8 is directly proportional to the current flowing through the capacitor pump.

As a part of the driving means, means are also provided for squaring and scaling the current flow through the capacitor pump to obtain the value:

$$DI^2. \quad (4)$$

This means includes a potentiometer D for scaling the current being fed to amplifier A1 and a wide band precision analog multiplier M1 which squares the current value multiplied by the factor D.

Means are also provided for scaling a constant voltage by a fourth factor which includes a constant voltage source V_{cc}, and a scaling potentiometer A to obtain value A.

Means are also provided for multiplying the suction voltage E_s by the current flowing through the capacitor pump and scaling the result by a fifth factor E to obtain the value:

$$EIE_s. \quad (5)$$

Thus wide band precision analog multiplier M2 is employed to multiply the current and voltage as shown and the output is scaled in potentiometer E and then passed to amplifier A6.

Means are also provided for adding the foregoing values in accordance with equation (1) to provide a sum voltage E_B. This means of addition includes resistors R_A, R_B, R_C, R_D and R_E hooked into an adding circuit as shown and amplifier A7. The various factors involved in these means are selected to define the coefficient of the terms of the above equation which equation in turn defines the sum voltage required for the electrical driving means to cause the capacitor pump to simulate the behavior of the centrifugal compressor. As shown in the drawing, this sum voltage is applied to a broad band precision analog multiplier M3 where the sum voltage is multiplied by a sinusoidal voltage EG of constant magnitude and frequency. As a result, the sinusoidal voltage fed to amplifier A5 has an amplitude proportional to the sum voltage.

It is preferred that the amplifiers A1 through A9 all be wide band precision analog amplifiers.

To simulate a given compressor head curve and therefore to arrive at an E_B which will drive the capacitor pump to cause such simulation of such a given head curve, a current modulator CM can be provided as shown in Fig. 7 and an oscilloscope connected as shown to display the output of the capacitor pump. The current modulator causes a periodic variation in current flow and provides an analog voltage output which is proportioned to such current, which voltage is used to drive the X-axis of the oscilloscope. The Y-axis is driven directly by E_D. Then using the given head curve, the various coefficients of equation 1 can be adjusted in the circuit of Fig. 7 to force conformance of the capacitor pump output curve, which is E_D, to the desired head or performance curve.

Claim

An electrical analog of a piping network having a compressor or pump therein comprising:

a) a capacitor pump (D_1, D_2 C_o) for simulating the pumping action of a compressor and having circuits connected to its input and output simulating the piping upstream and downstream of said compressor, the capacitor pump comprising two series connected diodes (D_1, D_2) and a capacitor (C_o) connected to form a T-section, the driving input being the electrode of the capacitor opposed to the diodes and the input and output of the capacitor pump being the anode and cathode respectively of the series connected diodes;

b) means for applying voltages (E_S and E_D respectively) to the input and output of said capacitor pump which are proportional to the suction and discharge pressures of said compressor and

c) electrical means for generating a driving voltage for driving said capacitor pump at a driving input, to cause it to simulate the action of the compressor in said piping network, said electrical means comprising

I) a voltage generator having a sinusoidal output voltage (E_G) of frequency (f), and

II) means (A4, A) for scaling a constant voltage (V_{cc}) by a factor A,

said electrical analog being characterised in a centrifugal compressor by said electrical means further comprising:

III) first means (A2) for sensing the suction voltage (E_S),

IV) means (B, A3) for scaling the output of said first means (A2) by a factor (B−1),

V) means for measuring the current I through the first said diode (D_1) of said capacitor pump (D_1, D_2, C_o) and means (A8, Alpha, A9) for scaling it by a factor

$$(C + \frac{1}{fC_o})$$

where C is a numerical coefficient, C_o is the value of said capacitor and f the frequency of said sinusoidal voltage in (I)

VI) means (D, A1, M1) for squaring and scaling said current flow respectively by a factor D

VII) means (M2) for multiplying the suction voltage by the current and means (E, A6) for scaling the result by a factor E;

VIII) means (R_A, R_B, R_C, R_D and R_E, A7) for adding the outputs of items (II), (III), (IV), (V), (VI) and (VII) to provide a sum voltage E_B; and

IX) means (M3) for making the amplitude of said sinusoidal output voltage (E_G) proportional to said sum voltage.

Patentanspruch

1. Elektrische Simulationseinrichtung eines Röhrennetzwerkes, das einen Kompressor oder eine Pumpe enthält, mit:

a) einer Kondensatorpumpe (D_1, D_2, C_0) zum Simulieren der Pumpwirkung eines Kompressors mit an ihrem Eingang und ihrem Ausgang angeschlossenen Kreisen, die die zustrom- un abstromseitige Verrohrung des Kompressors simulieren, wobei die Kondensatorpumpe zwei in Reihe verbundene Dioden (D_1, D_2) und einen Kondensator (C_0) umfaßt, die zur Bildung eines T-Gliedes miteinander verbunden sind, wobei der Antriebseingang die den Dioden gegenüberliegende Elektrode des Kondensators und der Eingang und der Ausgang der Kondensatorpumpe die Anode bzw. die Katode der in Reihe geschalteten Dioden sind;

b) Mitteln zum Anlegen von Spannungen (E_S bzw. E_D), die den Ansaug- und Ausstoß-Druckwerten des Kompressors proportional sind, an den Eingang bzw. Ausgang der Kondensatorpumpe, und

c) elektrischen Einrichtungen zur Erzeugung einer Antriebsspannung zum Antreiben der Kondensatorpumpe an einem Antriebseingang, um sie die Wirkung des Kompressors in dem Röhrennetzwerk simulieren zu lassen, wobei die elektrischen Einrichtungen enthalten

I) einen Spannungsgenerator mit einer sinusförmigen Ausgangsspannung (E_G) der Frequenz (f) und
II) Einrichtungen (A4, A) zum maßstäblichen Verändern einer konstanten Spannung (V_{cc}) um einen Faktor A,

wobei die elektrische Simulationseinrichtung bei einem Zentrifugalkompressor dadurch gekennzeichnet ist, daß die elektrische Einrichtung weiter enthält:

III) erste Einrichtungen (A2) zum Erfassen der Saugspannung (E_S),
IV) Einrichtungen (B, A3) zum maßstäblichen Verändern des Ausgangssignales der ersten Einrichtung (A2) mit einem Faktor (B−1),
V) Einrichtungen zum Messen des Stromes I durch die erste Diode (D_1) der Kondensatorpumpe (D_1, D_2, C_0) und Einrichtungen (A8, ALPHA, A9) zum maßstäblichen Verändern desselben mit einem Faktor

$$\left(C+\frac{1}{fC_0}\right),$$

wobei C ein numerischer Koeffizient,
C_0 der Wert des Kondensators und f die Frequenz der Sinusspannung in (I) ist,

VI) Einrichtungen (D, A1, M1) zum Quadratieren und maßstäblichen Verändern des Stromflusses mit einem Faktor D,
VII) Einrichtungen (M2) zum Multiplizieren der Saugspannung mit dem Strom und Einrichtungen (E, A6) zum maßstäblichen Verändern des Resultates mit einem Faktor E;
VIII) Einrichtungen (R_A, R_B, R_D, R_C und R_E, A7) zum Addieren der Ausgangssignale der Gegenstände (II), (III), (IV), (V), (VI) und (VII) zur Schaffung einer Summenspannung (E_B); und
IX) Einrichtungen (M3), um die Amplitude der sinusförmigen Ausgangsspannung (E_G) proportional der Summenspannung zu machen.

Revendication

Simulateur électrique d'un réseau de canalisations comportant un compresseur ou une pompe, comprenant:

a) une pompe à condensateur (D_1, D_2, C_0) destinée à simuler l'action de pompage d'un compresseur et possédant des circuits connectés à ses entrées et sorties, simulant la canalisation an amont et en aval dudit compresseur, la pompe à condensateur comprenant deux diodes (D_1, D_2) montées en série et un condensateur (C_0) monté de façon à former une section en T, l'entrée d'attaque étant l'électrode du condensateur opposée aux diodes et l'entrée et la sortie de la pompe à condensateur étant l'anode et la cathode, respectivément, des diodes montées en série;

b) des moyens destinés à appliquer des tensions (E_S et E_D, respectivement) à l'entrée et à la sortie de ladite pompe à condensateur, qui sont proportionnelles aux pressions d'aspiration et de refoulement dudit compresseur, et

c) des moyens électriques destinés à générer une tension de commande pour la commande de ladite pompe à condensateur à une entrée de commande, afine de l'amener à simuler l'action du compresseur dans ledit réseau de canalisations, lesdits moyens électriques comprenant

(I) un générateur de tension ayant une tension de sortie sinusoîdale (E_G) de fréquence (f), et
II) des moyens (A4, A) destines à démultiplier une tension constante (V_{cc}) par un facteur (A),

ledit simulateur électrique étant caractérisé, dans un compresseur centrifuge, par lesdites moyens électriques comprenant en outre:

III) des premiers moyens (A2) destinés à détecter la tension d'aspiration (E_S),
IV) des moyens (B, A3) destinés à démultiplier le signal de sortie desdits premiers moyens (A2) par un facteur (B−1),
V) des moyens destinés à mesurer le courant I traversant la première (D_1) desdites diodes de ladite pompe à condensateur (D_1, D_2, C_0) et des moyens (A8, ALPHA, A9) destinés à le démultiplier par un facteur

$$\left(C+\frac{1}{fC_0}\right)$$

où C est un coefficient numérique, C_0 est la valeur dudit condensateur et *f* la fréquence de ladite tension sinusoîdale dans (I)

VI) des moyens (D, A1, M1) destinés à conformer et démultiplier ledit écoulement de courant, respectivement, par un facteur D,
VII) des moyens (M2) destinés à multiplier la tension d'aspiration par le courant et des moyens (E, A6) destinés à démultiplier le résultat par un facteur E;
VIII) des moyens (R_A, R_B, R_C, R_D et R_E, A7) destinés à additionner les sorties des points (II), (III), (IV), (V), (VI) et (VII) pour produire une tension de somme E_B; et
IX) des moyens (M3) destinés à rendre l'amplitude de ladite tension de sortie sinusoîdale (E_G) proportionnelle à ladite tension de somme.

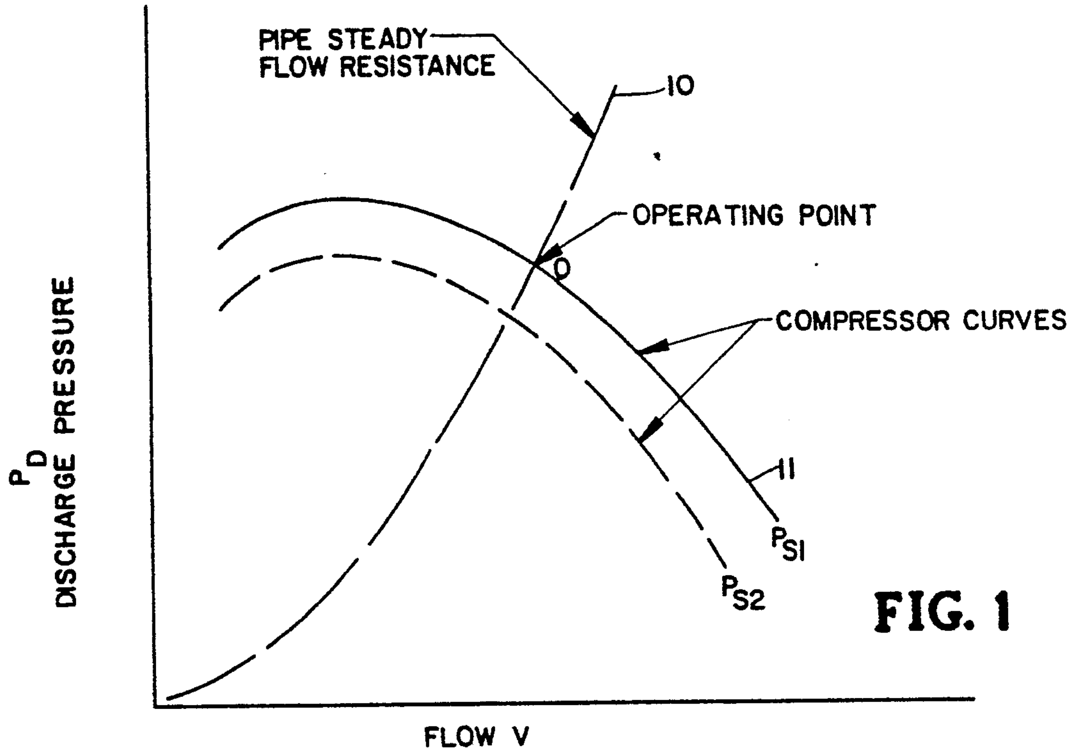

PIPE STEADY
FLOW RESISTANCE
10
OPERATING POINT
O
COMPRESSOR CURVES
11
P_{S1}
P_{S2}
P_D
DISCHARGE PRESSURE
FLOW V

FIG. 1

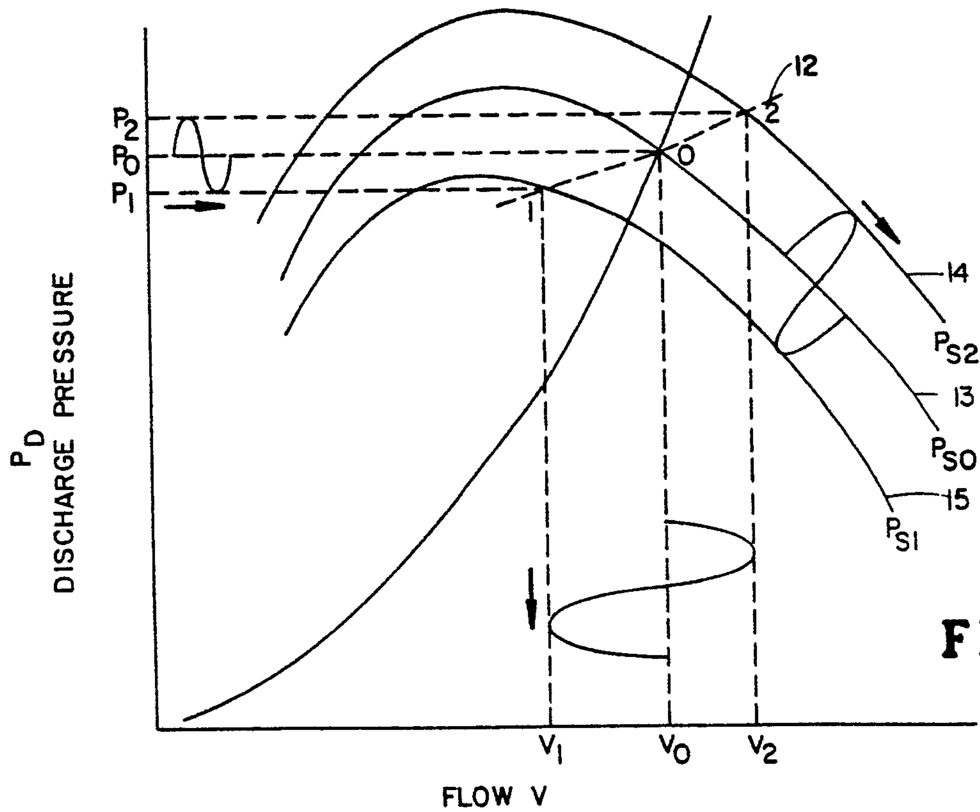

12
P_2
P_0
P_1
2
O
1
14
P_{S2}
13
P_{S0}
15
P_{S1}
P_D
DISCHARGE PRESSURE
V_1
V_0
V_2
FLOW V

FIG. 2

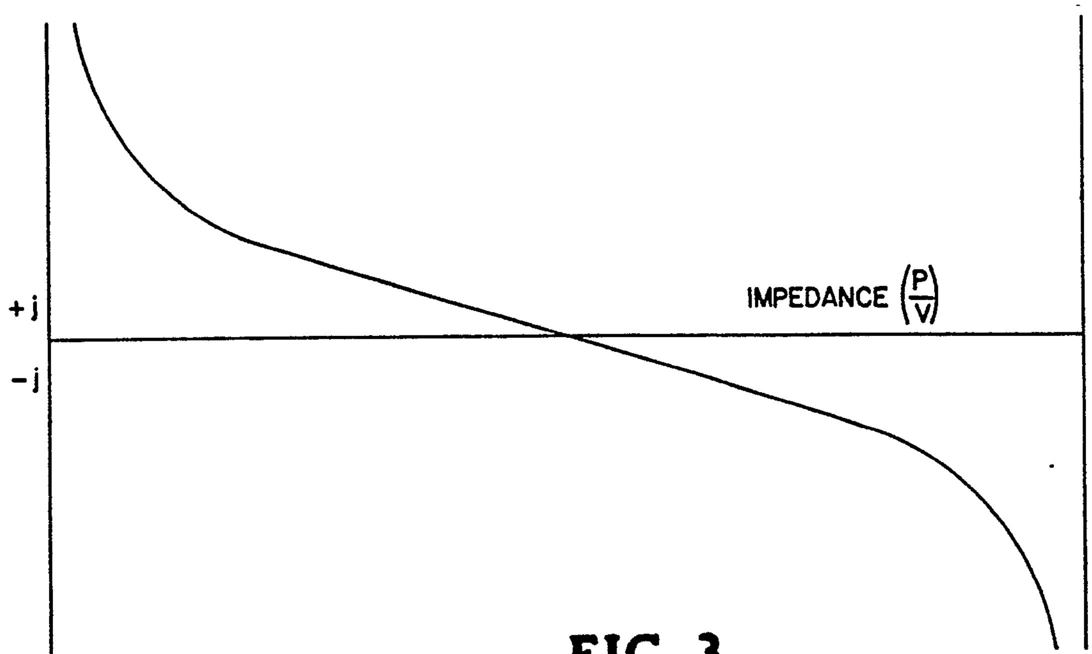

+j
-j
IMPEDANCE (P/V)

FIG. 3

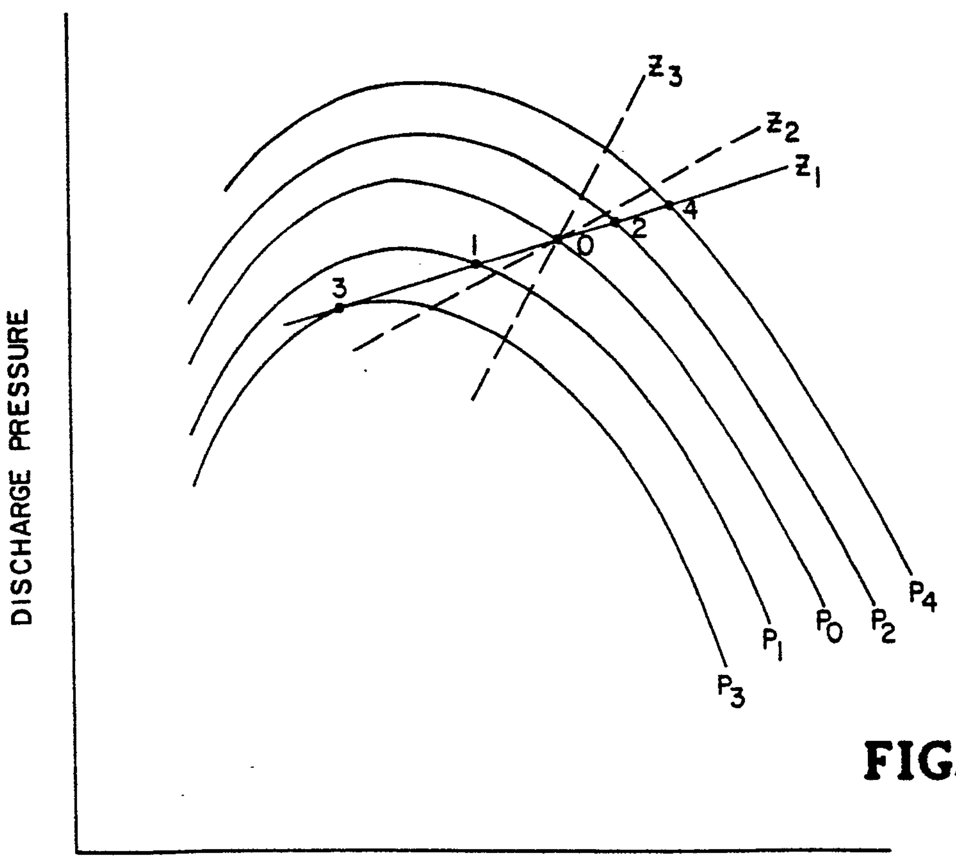

DISCHARGE PRESSURE
FLOW
Z3
Z2
Z1
0
1
2
3
4
P0
P1
P2
P3
P4

FIG. 4

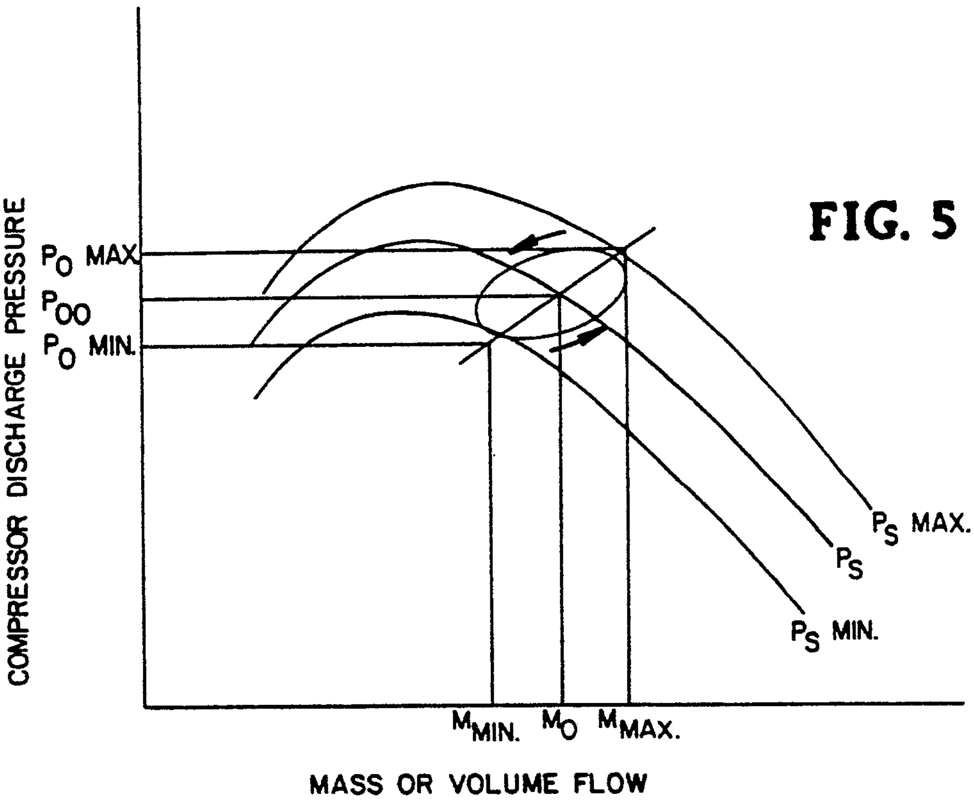

COMPRESSOR DISCHARGE PRESSURE
P0 MAX
P00
P0 MIN.
PS MAX.
PS
PS MIN.
MMIN.
M0
MMAX.
MASS OR VOLUME FLOW

FIG. 5

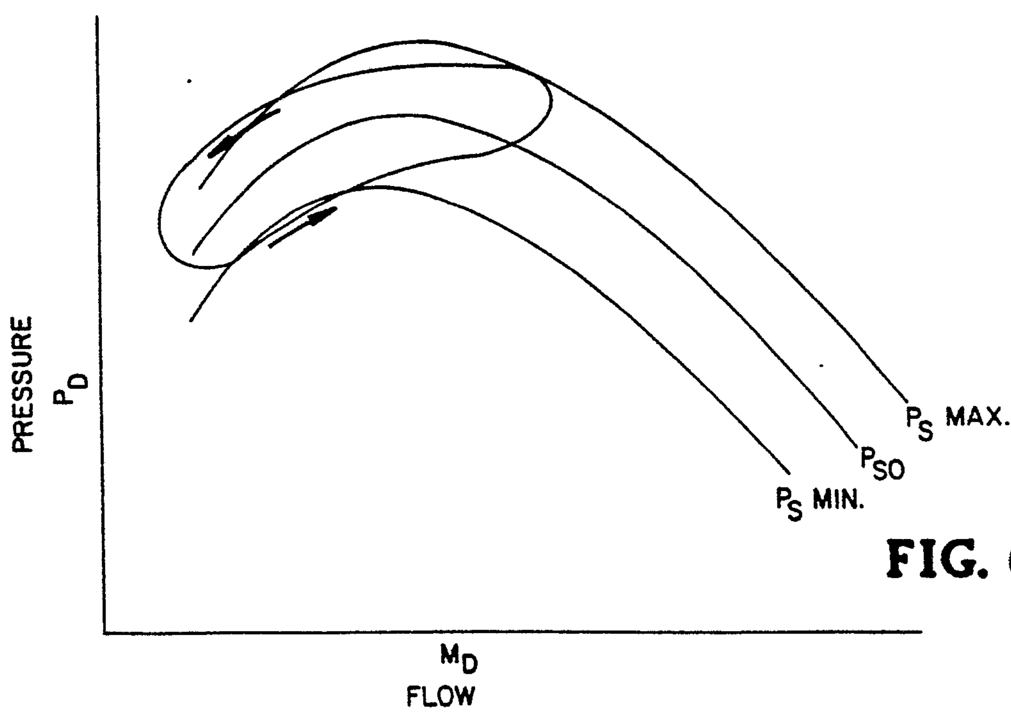
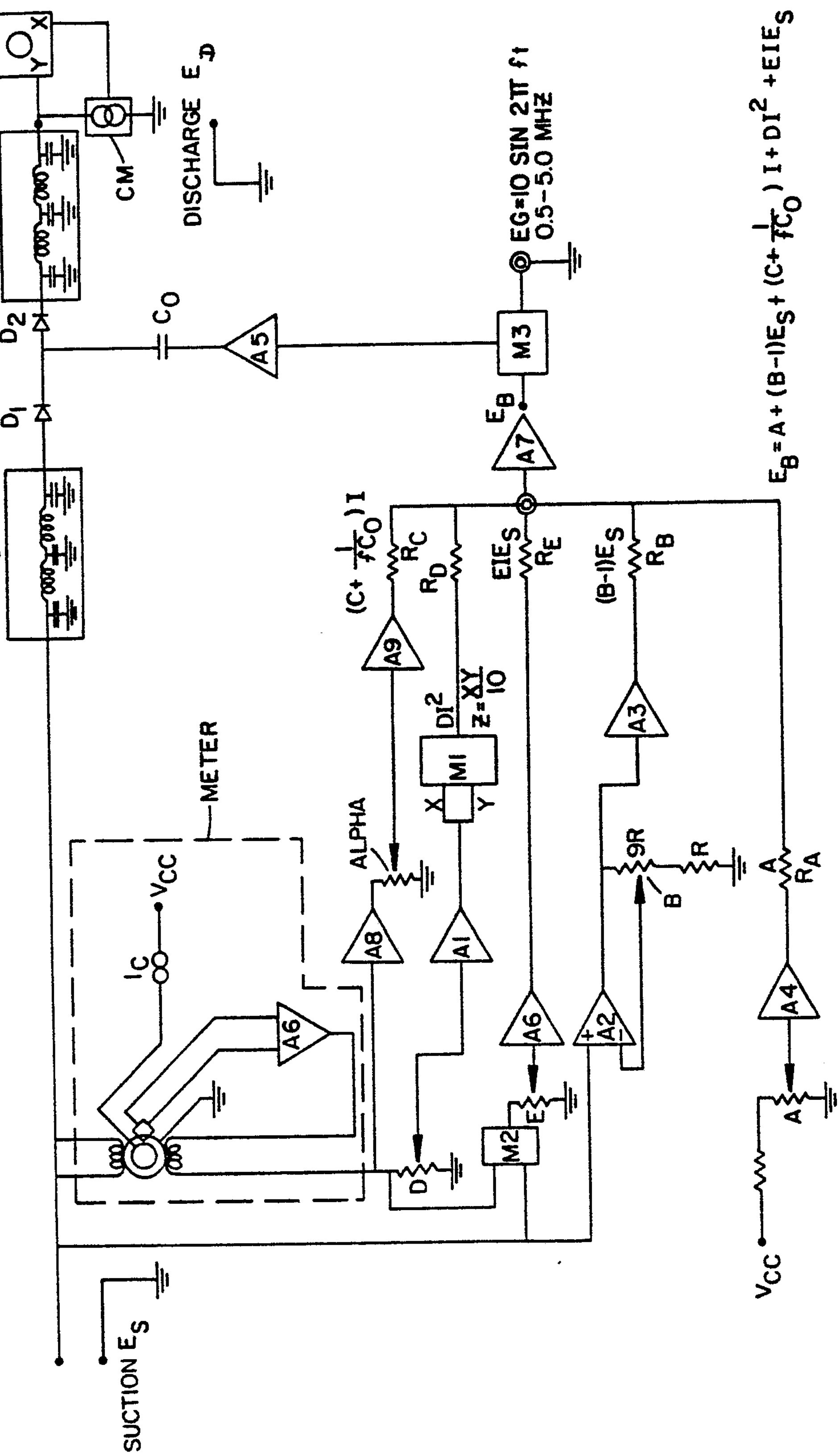

PRESSURE
PD
PS MAX.
PSO
PS MIN.
MD
FLOW

FIG. 6

FIG. 7


SCOPE
CM
DISCHARGE E_D
EG=10 SIN 2π ft 0.5-5.0 MHZ
METER
ALPHA
SUCTION E_S
E_B = A + (B-1)E_S + (C + 1/fC_O) I + DI^2 + EIE_S