THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

A DYNAMIC PERFORMANCE COMPUTER FOR GAS TURBINE ENGINES

V. L. Larrowe

M. M. Spencer

M. Tribus

January, 1957

IP-206

SYMBOLS

h	Absolute enthalpy in BTU/lb*
h_s	Sea level standard enthalpy (123.96 BTU/lb)
T	Total temperature in degrees Rankine*
T_s	Sea level standard temperature (518.4° R.)
J	Mechanical equivalent of heat (778 ft-lb/BTU)
P	Total absolute pressure in psia*
P_s	Standard pressure at sea level (14.7 psia)
N	Rotor Speed in Revolutions per minute
Θ	Referred temperature $\left(\frac{T}{T_s}\right)$ *
φ	Referred enthalpy $\left(\frac{h}{h_s}\right)$ *
δ	Referred total pressure $\left(\frac{P}{P_s}\right)$ *
I	Rotor moment of inertia in slug-ft^2
ω	Angular velocity of rotor shaft in radians per second
W	Gas flow rate in lbs/second*
W_f	Fuel flow rate in lbs/second
P_t	Turbine power in ft-lb/second
P_c	Compressor power in ft-lb/second
P_a	Rotor accelerating power in ft-lb/second ($P_t - P_c$)

* Numerical subscripts refer to stations in the engine, as defined by Figure 1.

ABSTRACT

Standard analog computing equipment is combined with electromechanical "map readers" made from modified X-Y plotters to form a gas-turbine-engine performance computer. The complete engine computer assembly is composed of a number of smaller assemblies, each of which represents a separate element of the engine. All of these smaller computers, working simultaneously, exchange and combine information to compute the performance of the entire engine. The computer can be made to represent any gas turbine engine of any degree of complexity by merely adding the required additional engine element computers. It may be used to explore engine behavior, to obtain both steady-state and transient engine operating data, and to test various control systems.

Introduction

Complete and accurate performance data for gas turbine engines in the preliminary design stage can be obtained from a special performance computer, composed of standard electronic analog computing equipment and using modified X-Y plotters as electro-mechanical map readers.

Such a computer may be regarded as an operating analog of the actual engine, with d-c voltages representing the various engine variables, such as rotor speed, temperatures, air weight flow rates, and pressure. In fact, much test data usually obtained from running the engine can be more easily and inexpensively obtained from the computer. Obviously, a computer of this type has many uses.

In early engine studies, the computer may be used to explore engine behavior. It can predict the performance of various proposed designs, and it is especially useful in determining the operating characteristics of twin-spool engines, turboprop engines, and other engines which are extremely difficult to analyze by conventional methods. In addition to this it becomes an invaluable tool for acquainting engineers with gas turbine engine behavior.

Such a computer can be used for power control studies as soon as the performance characteristics of the engine elements are known. This permits most of the power-control system to be designed before the actual engine has been constructed. The ease and rapidity by which the computer produces engine performance data permits a much more thorough power-control study than could be accomplished by hand computation alone. Any proposed fuel control designs can be electronically simulated, and the control principles can be tested by connecting the control simulator to the engine performance computer.

An actual working model of the engine control system may be tested on the computer if suitable transducing equipment is available to convert pressures and shaft positions to analog voltages, and analog voltages to pressures, temperatures, and shaft positions. Under these conditions, the computer is serving as an engine simulator.

Information Flow in the Engine and in the Computer

Figure 1 illustrates the station numbers assigned to the various points in the engine. Air enters the compressor at Station 2, undergoes compression, and leaves the compressor Station 3, where it enters the burner, or combustor. The heated gas from the combustor enters the turbine at Station 4 and leaves the turbine to enter the exhaust nozzle at Station 5. The gas leaving the exhaust nozzle at Station 8 produces the thrust. The gas flowing through the turbine turns the turbine rotor, which transmits power to the compressor rotor through a shaft.

Figure 2 is a block diagram showing the flow of information within the engine performance computer. The compressor, combustor, turbine, and nozzle are each represented by a separate block. The equations within each block show the functional relationships existing between the outputs and inputs for that block. For example, the compressor block contains three equations: The first specifies corrected air weight flow as a function of pressure ratio and corrected rotor speed, and the second specifiies corrected enthalpy rise as another function of pressure ratio and corrected rotor speed. The third equation states that the inlet air weight flow equals the outlet air weight flow, thus assuming the absence of interstage bleed. The functional relationships of the first two equations cannot easily be expressed analytically but are usually available as families of curves, obtained from tests of the compressor. Use of these maps of compressor characteristics placed on electro-mechanical map readers which are interconnected by conventional analog computing equipment permits the computation of all required output variables from the compressor block, using the input variables as basic information.

Similarly, each of the other blocks can compute its output information from its input information, using the relationships specified within that block.

One of the basic outputs of the compressor block is air-flow rate, W_3. This information passes on to the combustor, where it is combined with fuel flow to give the gas flow leaving the combustor and entering the turbine. In passing through the turbine block, it is usually unmodified, but is used in performing some of the computations in that block. It emerges from the turbine block as W_5 and enters the exhaust nozzle block, where it is used in determining the pressure ratio across the exhaust nozzle. Thus, air flow information moves downstream in the computer.

Similarly, temperature or enthalpy information also flows downstream from the compressor. It originates as the compressor inlet enthalpy ratio, φ_2. In the compressor block, the enthalpy rise across the compressor is added to φ_2 to give φ_3, the corrected enthalpy at the combustor inlet. In the combuster block, the enthalpy rise across the combustor is added to φ_3 to give φ_4, the corrected enthalpy of the gas entering the turbine. In the turbine block, the enthalpy drop across the turbine is subtracted from φ_4 to give φ_5; and in the nozzle block, φ_5 along with W_5 and atmospheric pressure are used in determining the nozzle pressure ratio and the thrust.

Pressure information originates at the nozzle and flows upstream. The nozzle pressure ratio and the ambient pressure are used to determine δ_5, the corrected pressure at the nozzle inlet. The turbine pressure drop and δ_5 then determine δ_4, the turbine inlet corrected pressure. The combustor pressure ratio and δ_4 are used in the combustor block to compute δ_3, the combustor inlet pressure. The compressor outlet pressure and inlet pressure (supplied as an external input) form the compressor pressure ratio, which becomes one of the variables used in computing the compressor output quantities.

The rotor dynamics computer uses the difference between turbine power and compressor power to determine the rotor acceleration, which is integrated with respect to time to give the rotor speed N. The rotor speed is an input to the compressor and turbine blocks.

Computer Symbols

Figure 3 shows typical symbols for analog computer elements, as well as the mathematical operations performed by these components. Figure 3a is the symbol for a summer, an operational amplifier using resistors for inputs and for feedback. As shown by the formula, the output is the negative of the sum of the input voltages, with each input voltage multiplied by the gain coefficient of that particular input. Figure 3b is the symbol for an electronic integrator, an operational amplifier using resistors for inputs and a capacitor for feedback. The output of this device is the negative of the integral with respect to time of the sum of the inputs, with each input multiplied by the gain coefficient for that input. The output of the integrator also includes the initial condition (abbreviated IC) corresponding to the constant of integration, the value of the integral at $t = 0$. Figure 3c is the symbol for a coefficient potentiometer, a device which multiplies the input voltage "A" by the potentiometer setting "c" to give cA. Such a potentiometer may also be used as shown in Figure 3d to obtain a fixed voltage if its input is connected to a fixed voltage.

The symbol used in this paper to represent a single-variable function generator is shown in Figure 3e. The output voltage, Y, may be made any desired single-valued function of the input voltage, X, by proper preparation of the function generator itself. The actual function generator may be any of the conventional available types, such as electronic (photoformer), diode, or servo.

Figure 3f is the symbol used to represent a function generator giving a function, Z, of two variables X and Y. This type of function generator may be considered an electronic map reader, since it consists of a servo-driven plotting table which has an electronic map of the function to be generated placed on its plotting surface and an insulated read-out probe substituted for the pen. Figure 4 is a photograph of such a map reader. The map itself consists of a sheet of glass coated with partially-conducting graphite paint, and on this surface are plotted lines of constant Z. The constant Z lines are composed of conducting silver paint, and each line is held at an analog voltage corresponding to the value the lines are produced by the electrical interpolating action of the graphite paint film. The X and Y inputs to the plotting table move the probe to the corresponding X and Y coordinates on the plate, and the voltage received from the plate by the probe corresponds to the value of the function Z for the given X and Y inputs.

Use of Logarithmic Representation

The d-c voltages in the computer are scaled to represent logarithms of the variables rather than the variables themselves. Use of logarithmic representation converts the operations of multiplying, dividing, squaring and taking square roots to those of adding, subtracting, doubling, and halving, respectively. This eliminates the need for large numbers of analog computer multipliers, which are more expensive and less accurate than summing amplifiers.

An additional advantage resulting from the use of logarithmic representation of variables is an increase in the accuracy of computation. Two factors are responsible for this improved accuracy. First, for a given analog voltage error, the percent error for the variable is a constant, regardless of whether the voltage itself is near 100 volts or near zero. Second, through proper scaling, the operating range of the variable may be made to fit exactly the operating range of the computer, thus making use of the computer's full voltage range, from -100 to + 100 volts.

Description of the Compressor

Time does not permit a detailed description of the entire gas-turbine-engine performance computer. Since the compressor represents a typical block for the entire engine, a description of information flow through this block will serve to illustrate the analog computer principles involved.

A simplified computer diagram of the compressor is shown in Figure 5. The inputs to this part of the circuit are shown at the left, and the outputs are shown at the right. The inputs consist of analog voltages representing the logarithms of inlet pressure, inlet temperature, rotor speed, and combustor inlet pressure. The pressures are shown as ratios of the pressure involved to standard atmospheric pressure at sea level (14.7 psia).

Thus, the pressures are actually represented as logarithms of δ_2 and δ_3 instead of the logarithms of P_2 and P_3. The ratio δ_2 is a function of engine speed and altitude and is set in as a fixed input from potentiometer P_1, while the ratio of P_3 to P_s, or δ_3 is a variable, and is obtained from the combustor block. The inlet temperature is shown as φ_2, the ratio of the enthalpy of the inlet air to the enthalpy of air at sea level under standard conditions, and is also obtained as a fixed input from a potentiometer.

The logarithm of the inlet pressure ratio and the negative of the logarithm of the combustor pressure ratio are added in summing amplifier A, and their sum is inverted in sign to give $\left[\frac{\delta_3}{\delta_2}\right]$, which is used as an X-input to the two map readers labeled Table A and Table B. The required Y-input to these two tables, or map readers, is obtained by summing the logarithm of N and the logarithm of $\frac{1}{\sqrt{\varphi_2}}$ to give $\left[\frac{N}{\sqrt{\varphi_2}}\right]$, at the output of amplifier B. The quantity $-[N]$ is obtained from the rotor dynamics computer, while $-\frac{1}{\sqrt{\varphi_2}}$ is obtained by using potentiometer P_3 to multiply $-\left[\frac{1}{\varphi_2}\right]$ by 0.5.

The electrical map on Table A gives corrected air weight flow, $\frac{w\sqrt{\varphi_2}}{\delta_2}$, as a function of compressor pressure ratio, $\frac{\delta_3}{\delta_2}$, and corrected rotor speed, $\frac{N}{\sqrt{\varphi_2}}$, all in logarithmic form. The electrical map on Table B gives corrected enthalpy rise across the compressor, using the same input variables as Table A. The logarithm of absolute air weight flow is obtained by amplifier D, in which $-\left[\frac{w_2\sqrt{\varphi_2}}{\delta_2}\right]$ is added to $-\left[\frac{1}{\sqrt{\varphi_2}}\right]$ and $-\left[\delta_2\right]$ to leave $-\left[W_2\right]$, which becomes inverted in sign to W_2 at the output of amplifier D and is passed on to the combustor. The output of Table B, representing the corrected enthalpy rise, $\left[\frac{h_3-h_2}{\varphi_2}\right]$ or $\left[h_s\frac{h_3-h_2}{h_2}\right]$, in logarithmic form becomes an input to Table C. Table C is a single-variable function generator, giving $[X]$ or $\left[\frac{h_3}{h_2}\right]$ as an output when $[X - 1]$, or $\left[\frac{h_3}{h_2} - 1\right]$, is its input. The constant, h_s, shown also as the input, may be absorbed by properly biasing the function. The output of Table C, which is $\left[\frac{h_3}{h_2}\right]$, is added to $[\varphi_2]$, or $\left[\frac{h_2}{h_s}\right]$, to give $-[\varphi_3]$, or $-\left[\frac{h_3}{h_s}\right]$, as an output of amplifier G. This information is then passed on to the combustor.

As shown in the diagram, amplifiers E, F, and H properly combine variables to give the quantity $\left[\frac{W_3(h_3-h_2)J}{\left(\frac{2\pi}{60}N\right)^2}\right]$, which is needed in the rotor dynamics computer.

Thus, by use of summing amplifiers and function generators, the compressor block accepts all available input information and converts it to the output information required by other parts of the computer.

Computation of Rotor Speed

The rotor accelerating power is equal to the difference between the turbine power and the compressor power. If the accelerating power is denoted by P_a, the turbine power by P_t, and the compressor power by P_c, this becomes in equation form $P_a = P_t - P_c$.

If these powers are expressed in pound-feet per second, then P_a = (torque) x (ω), and torque = $I\dot{\omega}$. Thus: $\frac{P_t-P_c}{\omega^2} = I\frac{\omega\omega}{\omega^2} = I\frac{\dot{\omega}}{\omega}$.

Since

$$\omega = \frac{2\pi}{60}N \tag{1}$$

and

$$\dot{\omega} = \frac{2\pi}{60}\dot{N}, \tag{2}$$

then

$$I\frac{\dot{\omega}}{\omega} = I\frac{\frac{2\pi}{60}\dot{N}}{\frac{2\pi}{60}N} = I\frac{\dot{N}}{N}, \tag{3}$$

and also

$$[e]\int \frac{\dot{N}}{N}\,dt = [e]\ \ln N = [N]. \tag{4}$$

The block of the computer labeled "Rotor Dynamics," in Figure 6, accepts power information from the compressor and turbine and computes rotor speed, using the relations derived above. The input from the compressor is $\left[\frac{W_3(h_3-h_2)J}{\left(\frac{2\pi}{60}N\right)^2}\right]$, or $\left[\frac{P_c}{\omega^2}\right]$. This quantity is converted to direct, or antilogarithm, form by the function generator labled Table D. A corresponding quantity representing the quotient resulting from dividing turbine power by ω^2 is obtained from the turbine block and converted to antilogarithm form by Table E. Amplifier A inverts the expression $\frac{P_t}{\omega^2}$ to permit amplifier B to form the difference between it and $\frac{P_c}{\omega^2}$ as shown in Figure 6. This difference is multiplied by the constant $\frac{[e]}{I}$ by potentiometer P_1 and integrated by integrator C to give - $[N]$ directly. The moment of inertia of the rotor may be changed at will to any desired value by properly adjusting the potentiometer P_1. The integrator C is the only integrator used in the entire computer, so its rate of integration determines the "time scale" of the computer circuit. For example, the computer operates in "real" time if potentiometer P_1 is set to the actual value of $\frac{[e]}{I}$, but if it is set to one-tenth of this value, the computer operates only one tenth as fast as the actual engine would operate. Any desired change of time scale may be easily made.

Summary of the Entire Computer

Each block in Figure 2 is "mechanized" on the computer in a manner similar to that for the compressor and rotor dynamics computers, and computes all of its required output information, using the available input information as shown in Figure 2. Then, when the computer blocks are interconnected as shown in Figure 2, and the computer is placed in operation, the various map readers and function generators will adjust themselves to positions such as to simultaneously satisfy the conditions specified by the laws of thermodynamics and by the relationships placed on the map readers. If the analog voltage corresponding to the logarithm of fuel-flow is then varied, the entire computer will respond and give the proper transient response, corresponding to the engine's transient response to a similar variation in fuel flow. The rotor speed as well as any desired temperature, pressure, or flow rate may be read out by connecting a Brush recorder or some similar mechanical oscillograph to the proper points of the circuit.

A performance computer for more complex engines, such as a turboprop or a twin-spool engine, can be constructed by adding any necessary additional blocks. An afterburner is easily added, and a simulated power control can be mechanized and added to the computer if desired. Descriptions of some of these more complex configurations may be found in References 1 and 2.

Applications of the Computer

1. Steady-State Data

The possibilities of the computer may perhaps be illustrated better by describing some of the ways in which it can be operated to obtain data. For example, steady-state operating information is obtained by first allowing the rotor speed to stabilize for a given setting of fuel flow and inlet conditions, and then measuring the voltages representing the logarithms of the desired output variables by using a d-c potentiometer bridge, or a digital voltmeter. If a number of output variables, such as $\left[N\right]$, $\left[\varphi_4\right]$, $\left[\delta_3\right]$, etc. are to be read for each steady-state operating point, the voltage-measuring device is connected to the arm of a selector switch and the contact for each position of the switch is connected to a point in the computer circuit producing a voltage corresponding to the logarithm of a variable to be measured. Then, when the computer has reached a steady-state condition, the switch may be rotated and the voltages on the arm for each position measured and recorded.

Although the information obtained from the computer is in logarithmic form, it may easily be converted into the corresponding value of the variable by using conversion curves, which show the engine variable plotted against its corresponding voltage in the computer. If the conversion curve for a variable is plotted on semi-logarithmic graph paper, it becomes a straight line and can thus be determined completely from two points.

For steady-state operation, either the fuel flow or the inlet conditions (inlet pressure and temperature) may be varied as desired. Thus, operating characteristics of the engine at any altitude and with any desired airspeed may be investigated as readily as those for sea level static conditions. Figure 7 is a plot of digitally computed steady-state operating curves for an actual engine. Points obtained from steady-state operation of the analog computer are plotted on the same sheet in order to facilitate comparison.

2. Surge Data

Before the acceleration schedule for an engine control can be specified, the conditions of engine operation which cause surging must be known. The performance computer can be used to determine these conditions rapidly. The surge phenomenon in the computer may be explained by referring to the compressor characteristics maps. Figure 8 is a sketch of a compressor map of the type used as the function for Table A in Figure 5. The surge line is the dividing line between normal operation and surging operation of the compressor. Compressor operation is not defined for the surge region, although the lines of constant corrected air weight flow have been extended slightly into this region in order to improve the electrical interpolating action of the semi-conducting plate. The surge line on the function-generating plate is covered by a narrow strip of plastic electrical tape. If, during the operation of the engine computer, the probe on the map reader starts to cross the surge line, it becomes insulated from the function-generating plate by this tape and causes the computer to become unstable, thus simulating surge in the engine.

A pari of curves such as those shown in Figure 9 can be obtained in the following manner. The computer is first allowed to reach steady-state operation for some value of fuel flow, and thus to locate a point on the operating line. Then, the integrator in the rotor dynamics computer is made to "hold" to the value of [N] so determined, and fuel flow is advanced until surging is encountered. The value of N at which the rotor speed is being held and the value of fuel flow which barely causes surging determine a point on the surge line of Figure 9. The integrator may then be allowed to operate and the process repeated to obtain additional points on the surge line and operating line until these two lines are clearly defined.

3. Sensitivities of Feedback Variables to Control Variables

After the acceleration schedule for an engine control has been determined, it is necessary to compute the sensitivities of various engine variables to changes in other variables, in order that time constants and gains for the power control may be specified. Suppose, for example, that the turbine outlet pressure is to be used as a feedback variable to the power control. In this case, the derivative $\left.\frac{\partial \delta_5}{\partial W_f}\right|_{N \text{ constant}}$ should be known for the entire range of N for the engine. This may be found from operating the engine performance computer as shown in Figure 10. The voltage representing the logarithm of δ_5 is connected to the Y axis and the voltage representing the logarithm of W_f is connected to the X axis of a servo-driven X-Y plotter. The computer settles at a steady-state operating point for some fixed value of fuel flow, and the position of the pen on the plotter is marked. Next, the integrator in the rotor dynamics computer is held at the value of [N] for this point, and the fuel flow input is manually varied back and forth from this point by adjusting the fuel flow potentiometer P. The resulting curve traced by the plotter has a slope at the operating point of $\frac{\partial [\delta_5]}{\partial [W_f]}$. A straight line may be drawn tangent to this curve through the operating point, and its slope measured. This slope may then be converted to $\frac{\partial \delta_5}{\partial W_f}$ as follows: Since $[x] = [e] \ln x$,

$$\frac{\partial [\delta_5]}{\partial [W_f]} = \frac{\partial \ln \delta_5}{\partial \ln \delta_5} = \frac{W_f}{\delta_5} \frac{\partial \delta_5}{\partial W_f} \tag{5}$$

or

$$\frac{\partial \delta_5}{\partial W_f} = \frac{\delta_5}{W_f} \frac{\partial [\delta_5]}{\partial [W_f]} \quad . \tag{6}$$

The sensitivity of δ_5 to changes in W_f for other steady-state points may be determined in a similar manner until the desired range of N has been covered.

Further applications of the computer are listed below. In most cases, making the required measurements involves no particular difficulty, and the method of manipulating the engine performance computer for each type of measurement listed should be readily apparent.

a. Measuring transient response of various engine variables, particularly N, to step changes in fuel flow, exhaust nozzle area, or other control variables. Output data are recorded on a multichannel recorder.

b. Testing simulated fuel controls for stability and acceleration performance when combined with the angle.

c. Investigating effects of changes in operating characteristics of engine elements.

d. Determining effects of compressor bleed (either fixed percentage or scheduled by rotor speed).

e. Effects of imposing limits on pressures and temperatures.

f. Testing the performance of the simulated engine with a simulated airplane.

Conclusion

The degree of agreement between computer results and data from actual engine tests depends mainly upon the validity of the maps and curves used in the computer to describe the operating characteristics of the engine elements. Steady-state results from the computer usually agree with hand-computed steady-state data to within one or two percent, if the same data are used for hand computation as are used by the computer.

Although it is not necessary to have variables represented logarithmically, it has been found desirable to use this technique in order to reduce the complexity of the computer and to obtain sufficient accuracy. Conversion of data to antilogarithmic form is not especially difficult or time-consuming if conversion curves are used.

At the present time, there have been developed a number of methods of generating a function of two variables, some of which show considerable promise. It is felt, however, that the electro-mechanical map readers are the simplest and most reliable device so far available for this purpose.

The method of computing gas turbine engine performance as described in this paper has been in use at the Willow Run Laboratories of The

University of Michigan for over three years and has been proven successful for several types of gas turbine engines. Based upon experience with the computer, it is estimated that the average error in results due to the computer is from .1% to 3%, depending upon the variable under investigation.

ACKNOWLEDGEMENTS

The initial feasibility study was sponsored by the Power Plant Laboratory of the Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. Subsequent work has been sponsored by Westinghouse Electric Corporation, Aircraft Gas Turbine Division, Kansas City, Missouri; and by the Allison Division of General Motors Corporation, Indianapolis, Indiana.

BIBLIOGRAPHY

1. Dynamic Performance Computer for Gas Turbine Engines, V. L. Larrowe, M. M. Spencer, and M. L. Tribus. University of Michigan, Willow Run Research Center (Contract AF 33(616) - 2074), Phase I, Final Report, WADC TR 54-577 (December, 1953).

2. A Dynamic Performance Computer for Gas Turbine Engines, V. L. Larrowe and M. M. Spencer. University of Michigan, Willow Run Research Center (Contract AF 33(616) -2074), Phase II, Final Report, WADC TR 54-577 (August, 1955).

3. A Conventional X-Y Plotter Converted into a Two-Variable Function Generator, V. L. Larrowe, University of Michigan, Engineering Research Institute, Report 2489-1-F (August, 1956).

4. Uniformly Conductive Surfaces, Icing Research Staff, University of Michigan, Engineering Research Institute. (Contract AF 18(600)-51) Project M992-4, September, 1953.

5. "Use of Semi-Conducting Surfaces in Analog Function Generation," V. L. Larrowe and M. M. Spencer, Proceedings of the National Simulation Conference, Dallas, Texas, January 1956, pp. 33.1-33.6.

6. "Logarithmic Representation of Variables in D. C. Analog Computers," V. L. Larrowe and M. M. Spencer. Unpublished paper presented at a general meeting of the Association for Computing Machinery, Ann Arbor, Michigan, June 24, 1954. (Copies are available from the authors.)

7. Theory and Design of Gas Turbines and Jet Engines, E. T. Vincent, McGraw-Hill Book Company, New York, First Edition, 1950.

8. Jet Propulsion and Gas Turbines, M. J. Zucrow, John Wiley & Sons, Inc., New York, 1948.

LIST OF FIGURES

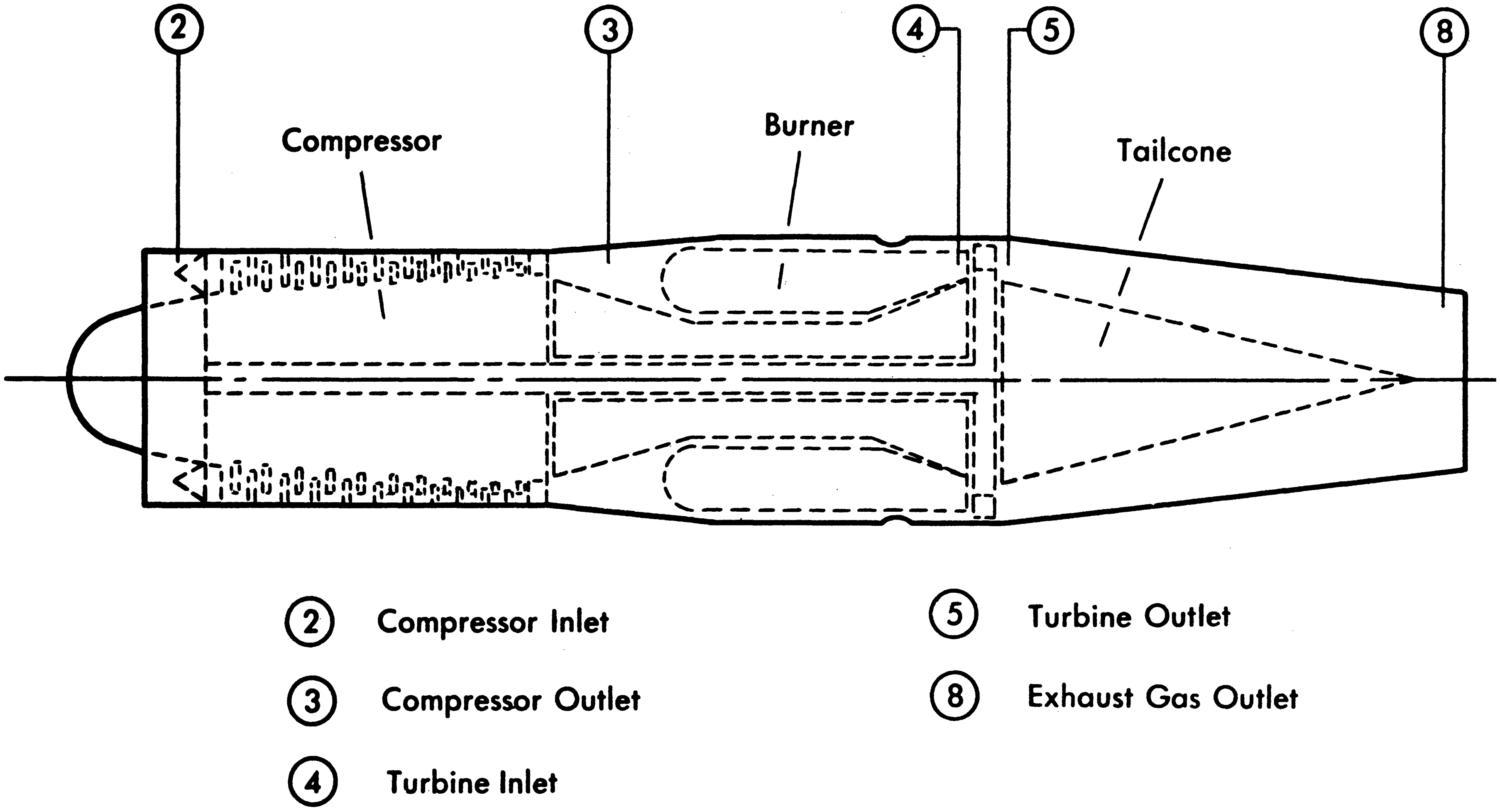


Figure 1. Stations of a Gas Turbine Engine

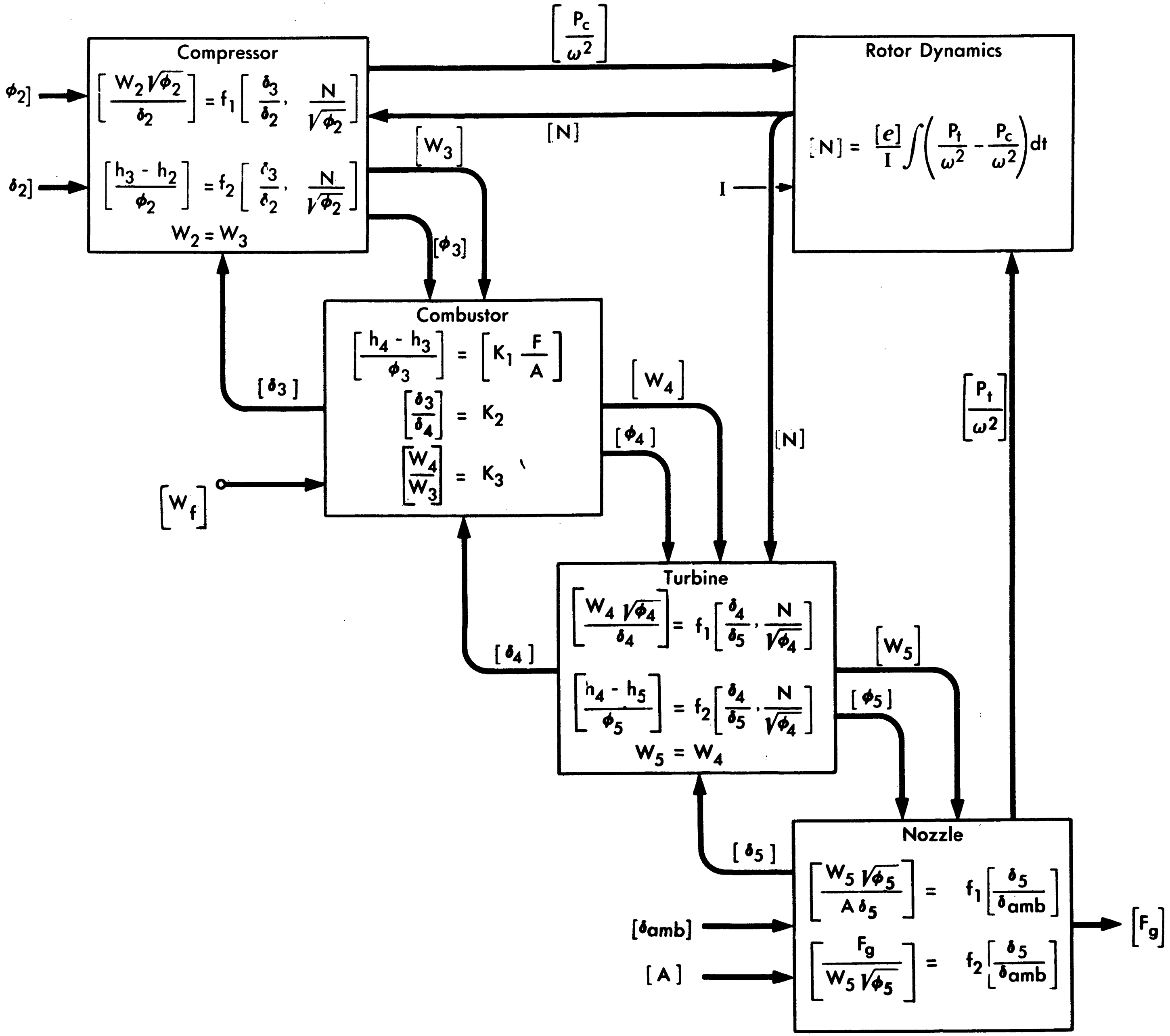
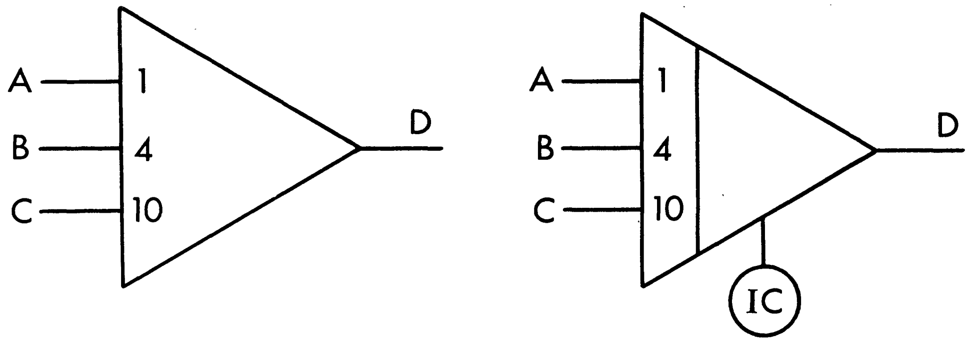


Figure 2. Information Flow in Gas Turbine Engine Performance Computer

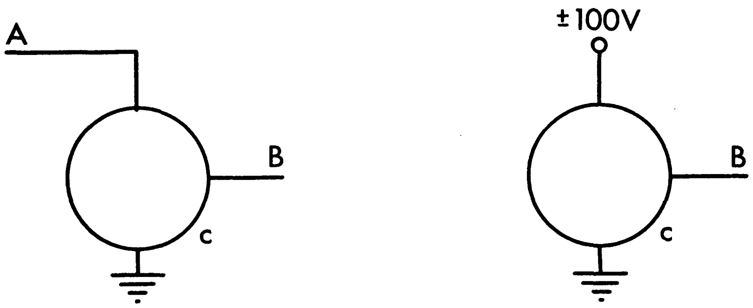
OPERATIONAL AMPLIFIERS



$D = -(A + 4B + 10C)$ $D = -IC - \int (A + 4B + 10C)\,dt$

a. Summer b. Integrator

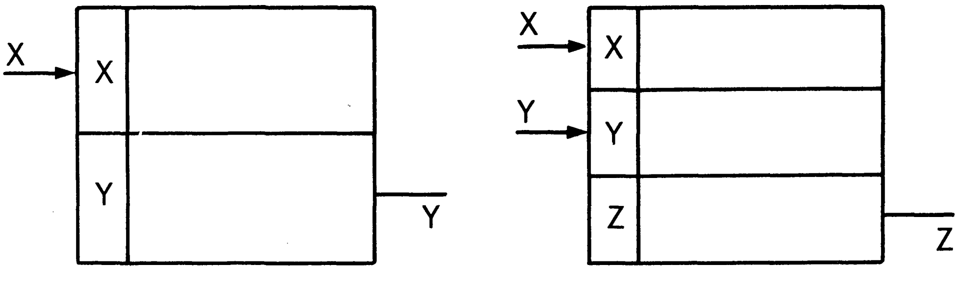
COEFFICIENT POTENTIOMETERS



$B = cA$ $B = \pm 100c$

c. Multiplying a Variable by a Constant d. Used to Obtain a Fixed Voltage

FUNCTION GENERATORS



$Y = f(X)$ $Z = f(X,Y)$

e. Generating a Function of One Variable f. Generating a Function of Two Variables

Figure 3. Analog Computer Symbols

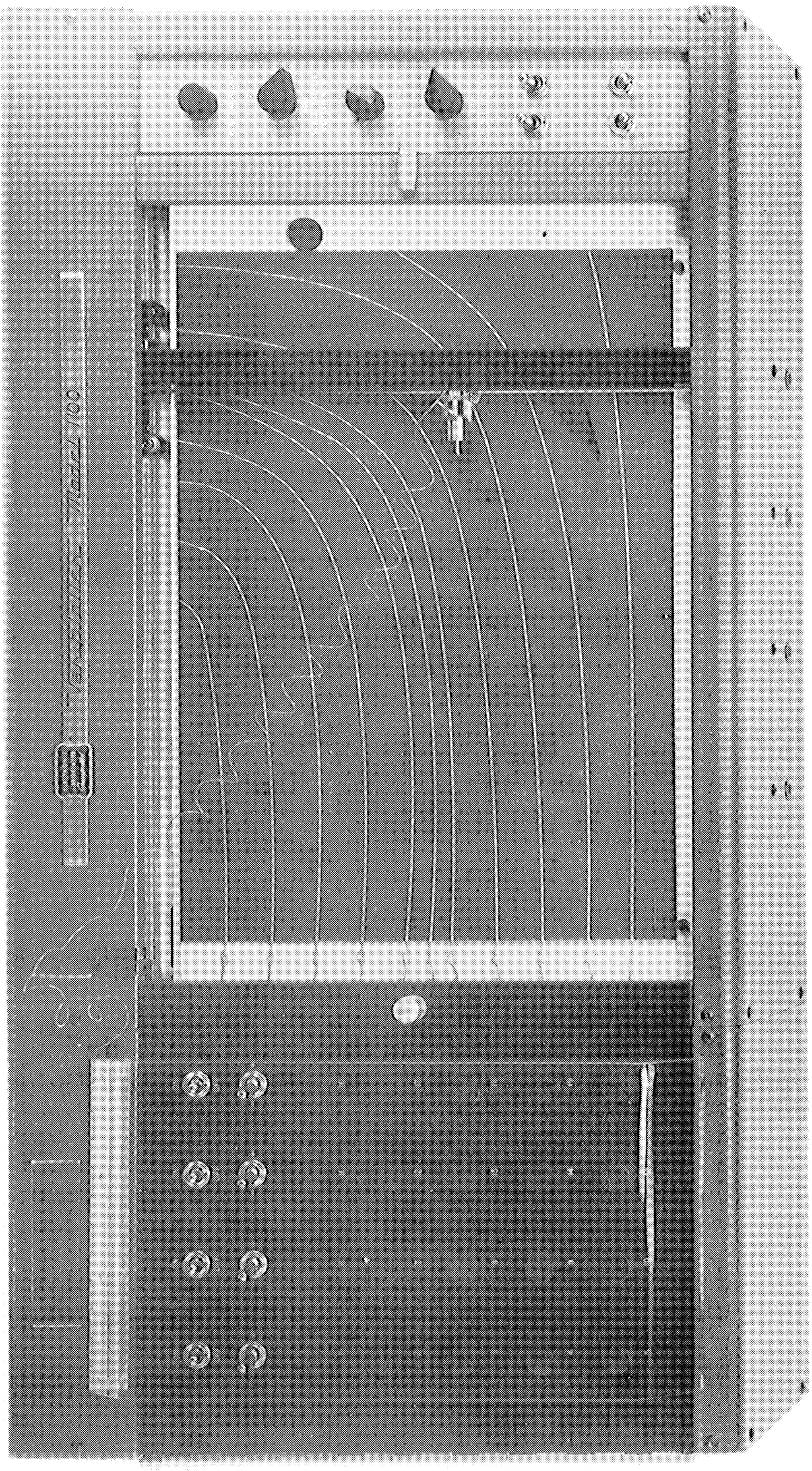


Figure 4. Electro-Mechanical Map Reader

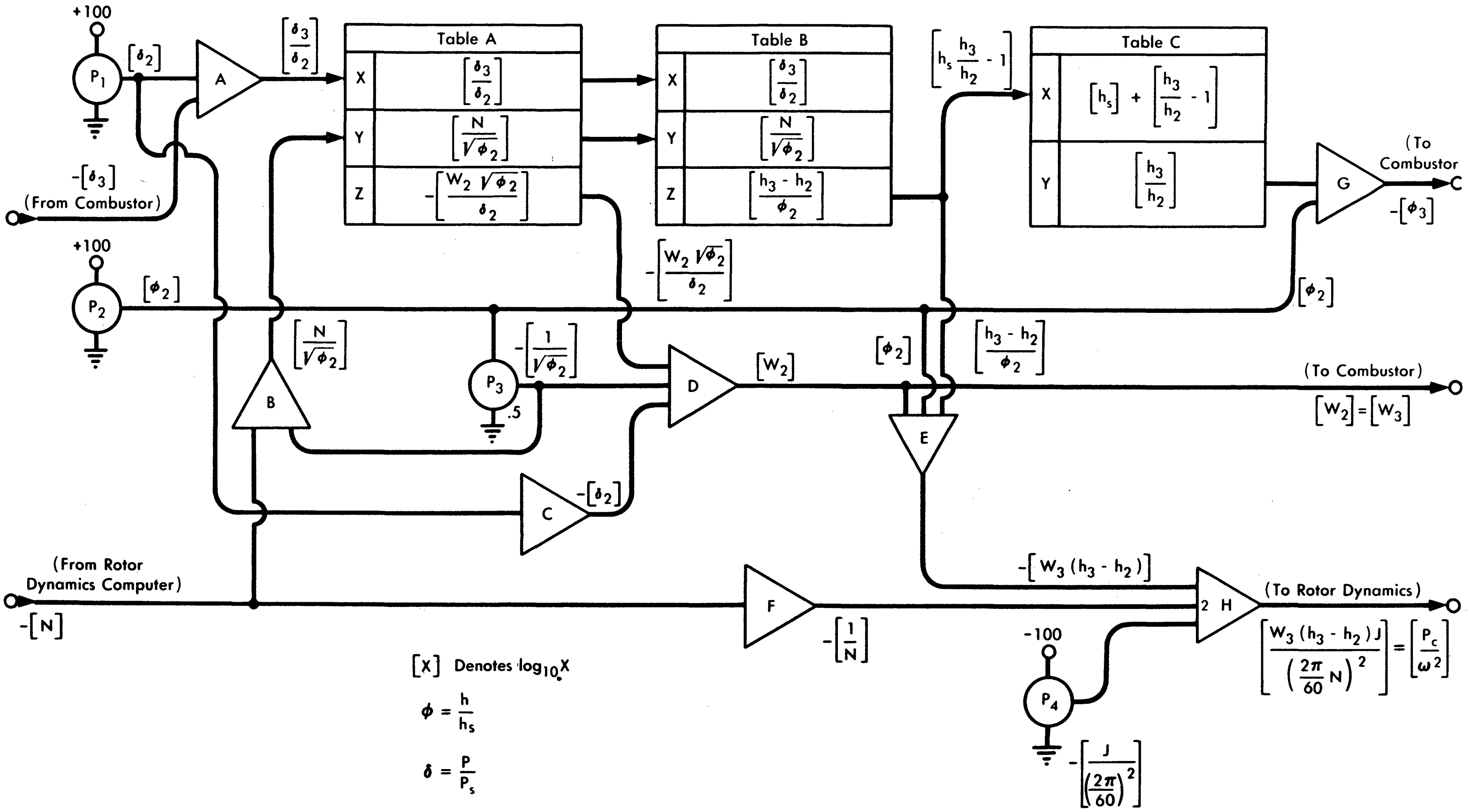


Figure 5. Simplified Computer Diagram of Compressor Computer

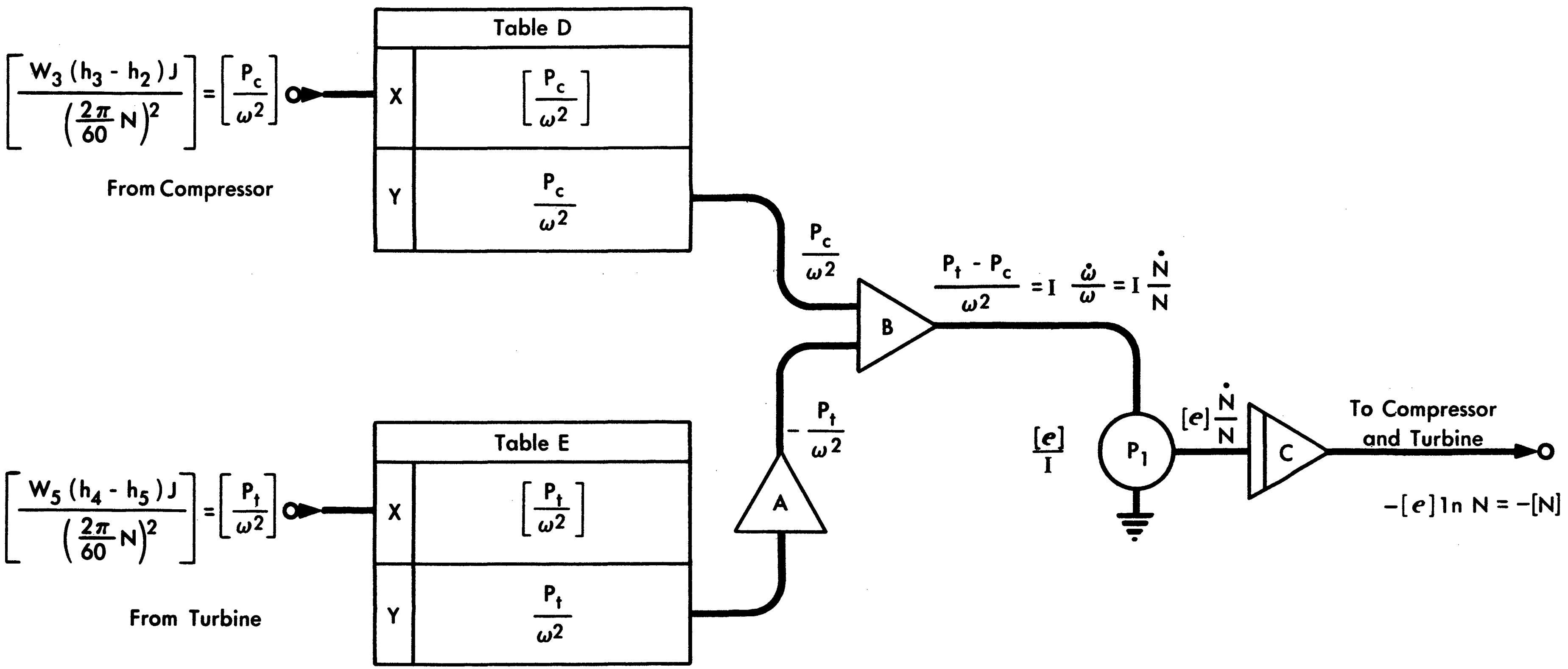


Figure 6. Diagram of Rotor Dynamics Computer

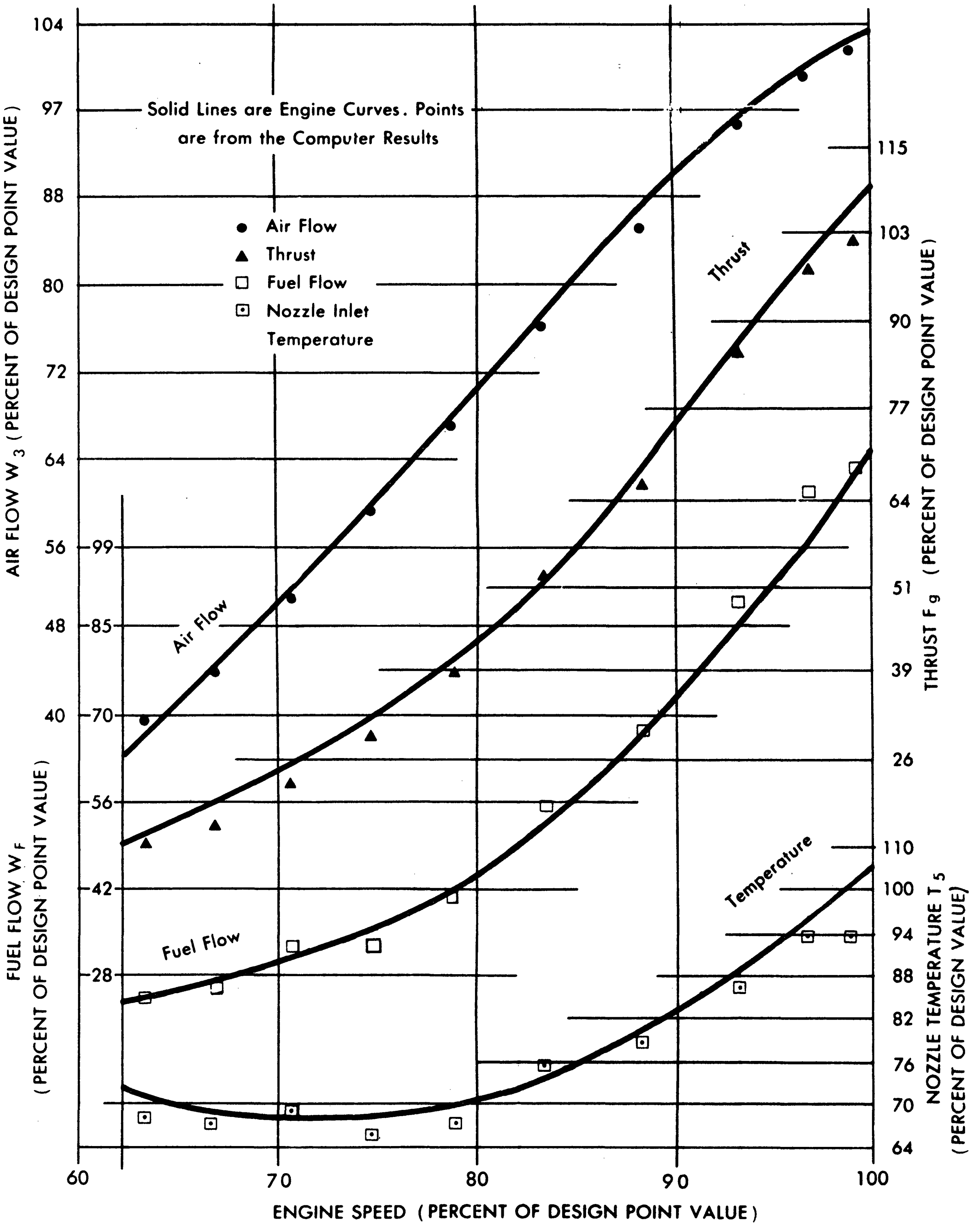


Figure 7. Steady-State Operating Curves for a Gas Turbine Engine

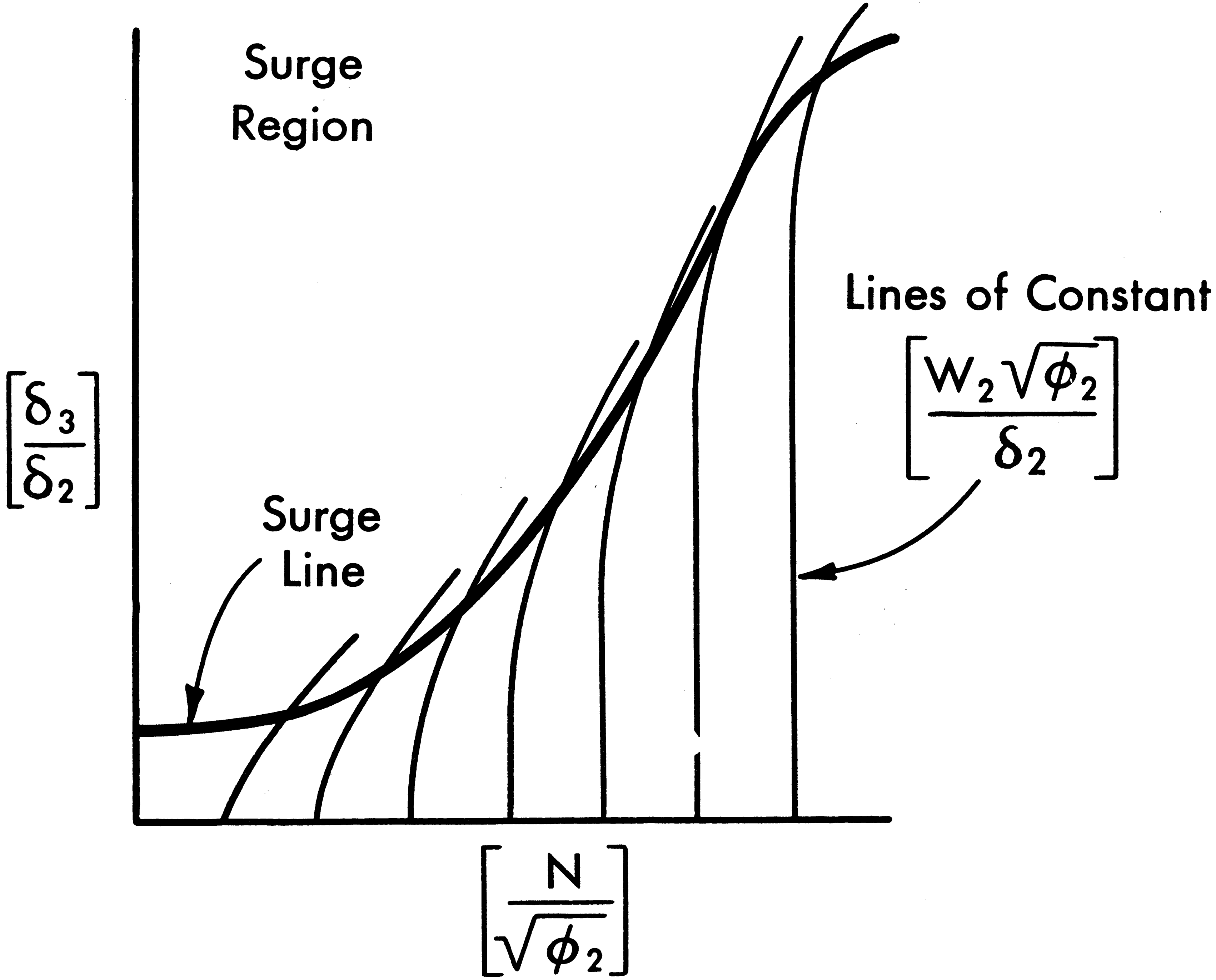


Figure 8. Compressor Air-Flow Characteristics

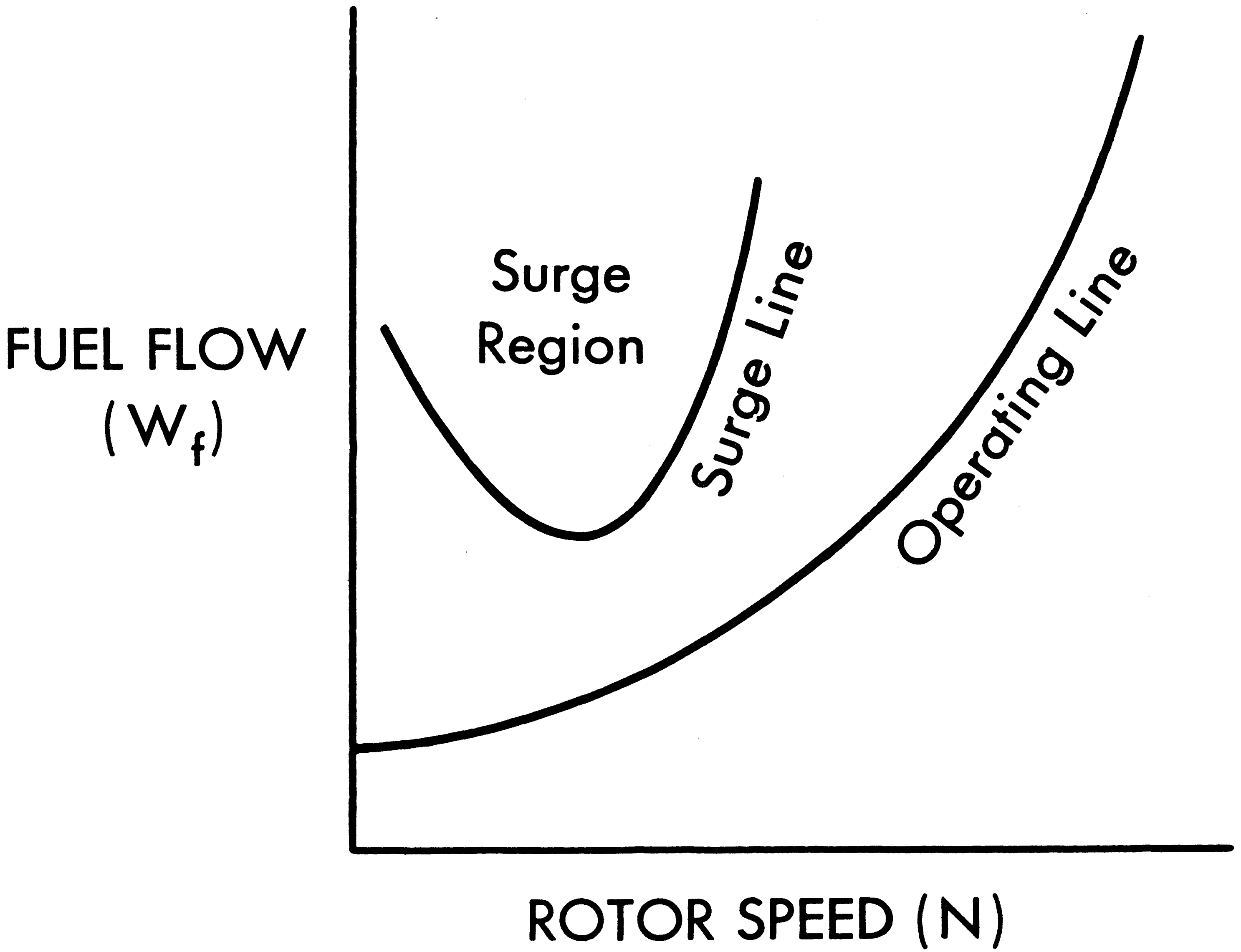


Figure 9. Location of Operating Line and Surge Line

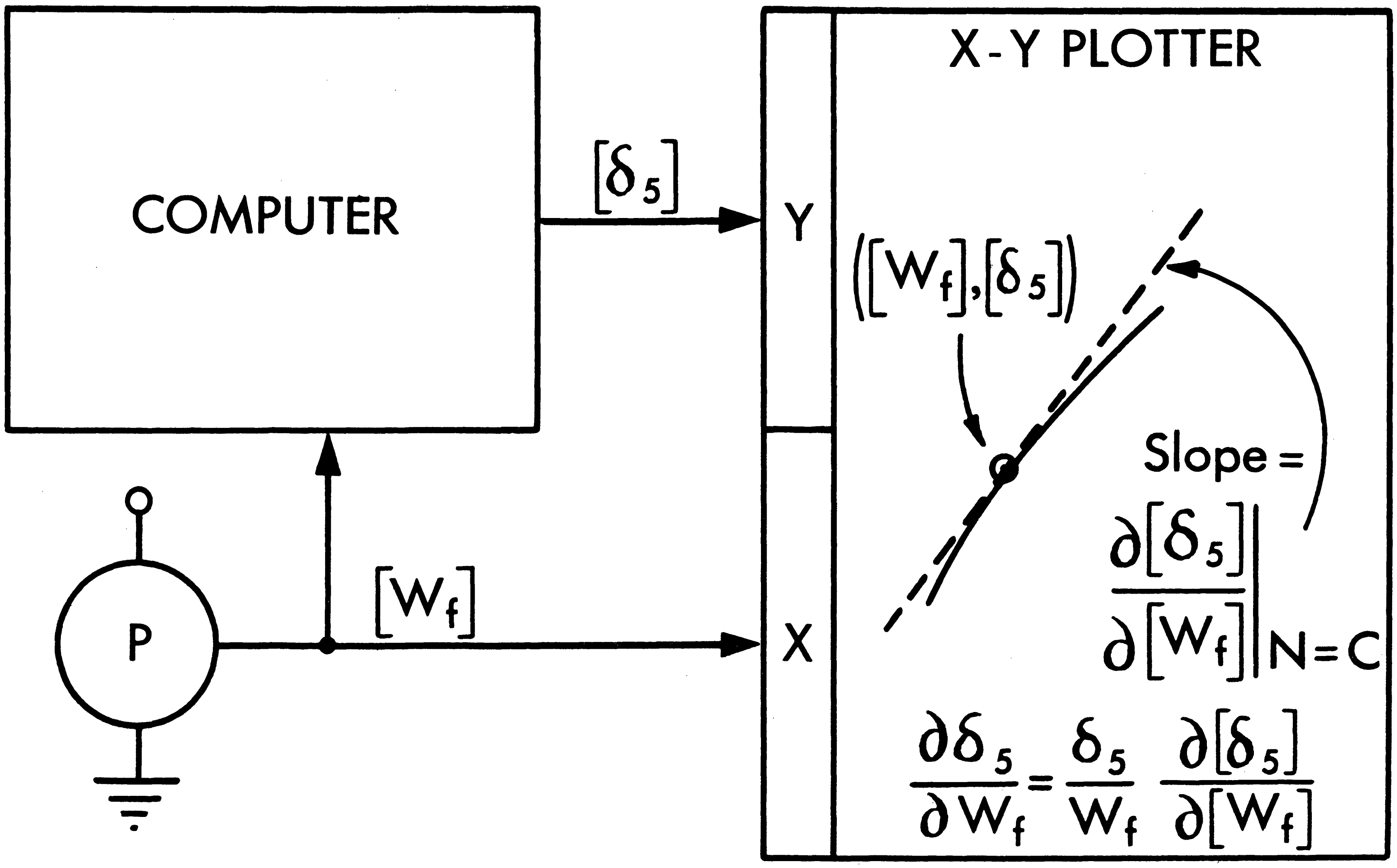


Figure 10. Use of X-Y Plotter with Computer to Obtain $\left.\frac{\partial\delta_5}{\partial W_f}\right|_{\text{N constant}}$