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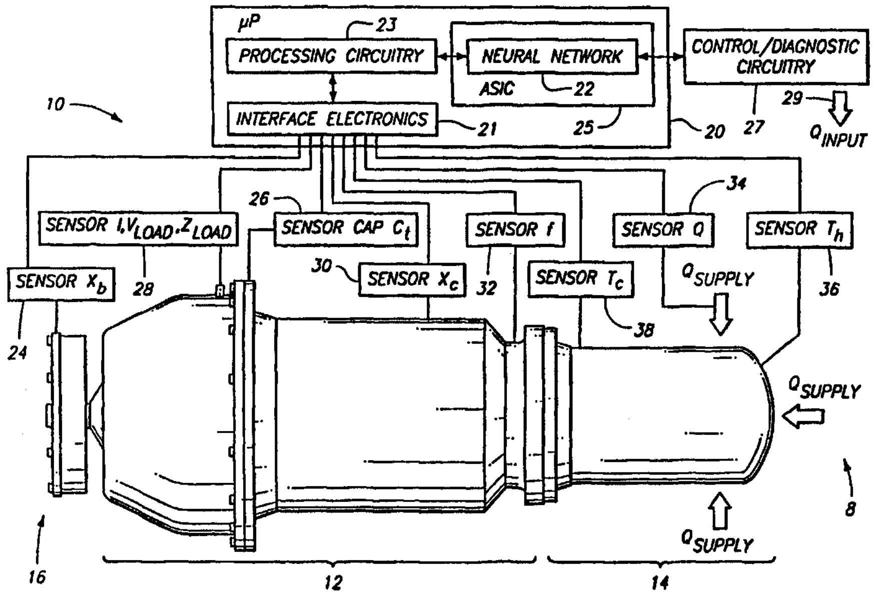

(57) Abstract

A system is provided for diagnosing health of a closed cycle thermal regenerative machine (10). The machine includes a closed cycle thermal regenerative machine (8), a sensor (38), an artificial neural network (22), and diagnostic circuitry (27). The sensor (38) is provided in association with the thermal regenerative machine (8) and is operative to detect an external parameter of the thermal regenerative machine. The artificial neural network (22) is configured to associate at least one internal parameter with the external parameter detected by the sensor. The diagnostic circuitry (27) is configured to receive the associated internal parameter from the artificial neural network (22) and is operative to diagnose at least one operating condition of the thermal regenerative machine. A method is also provided.

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DESCRIPTION

A NEURAL NETWORK CONTROL SYSTEM FOR A THERMAL REGENERATIVE MACHINE

Cross-Reference to Related Application

This application claims the benefits of the U.S. Patent Application Serial No. 09/299,215 filed April 23, 1999.

Technical Field

This invention relates to modeling techniques for estimating internal operating characteristics of closed cycle thermal regenerative machines, and more particularly to a neural network model for controlling and/or evaluating operation of closed cycle free piston machines such as Stirling cycle machines.

Background Art

Closed cycle thermodynamic machines operate under a hermetically sealed environment. In essence, the machine forms a pressure vessel inside of which moving components transfer working gas between several regions. Because the entire operation occurs within a sealed vessel, the ability to monitor internal operating characteristics is greatly complicated. For example, when developing a new machine design, the ability to design optimal operating characteristics, evaluate operating characteristics, evaluate hardware conditions, and/or provide operating information to control operation of the machine becomes very complicated. Presently, sensors are incorporated within the interior of the machine being developed. This can greatly increase cost and complexity during the design and development of a machine.

Furthermore, it is also desirable to monitor internal operating characteristics of a previously designed and presently operating machine in order to optimize the operating characteristics and/or control operation of the machine. It is desirable to obtain information about particular operating characteristics. External characteristics, or parameters, such as outside temperature can be easily measured. However, internal characteristics, or parameters, often desirable in order to control/predict operation of the machine, are not easily measured/detected.

For the case of a free piston, linear drive, Stirling cycle machine, many of the operating components of the device are likely to be totally contained within a hermetic pressure vessel with only the electrical leads to the linear drive motor/alternator crossing the pressure boundary. In a laboratory environment, a number of internally mounted instruments can be employed to evaluate the device's operating characteristics, provide input to various external controllers, and in general help define the basic health of the internal machine hardware. However, all of the sensors and their associated electronics can considerably increase unit cost, complicate hardware assembly, place unnecessary constraints on mechanical design or hardware configurations, and potentially decrease the unit's overall reliability.

Linear motion machines can be configured as engines or as cryogenic coolers, depending on the method of operation. Stirling engines convert heat into reciprocating piston motion within a thermodynamic gas environment, the piston working on the thermodynamic gas to create mechanical power. Stirling cryogenic coolers convert electrical energy into reciprocating piston motion that operates on a thermodynamic gas via a reciprocating displacer to produce a cool region.

One exemplary linear motion machine is a free piston Stirling cycle machine, such as a free piston Stirling cycle engine or generator. A typical free piston Stirling engine contains a single displacer and a single power piston that cooperate in fluid communication via a thermodynamic working gas. Such an engine construction can be resolved into a machine vibration problem that principally has an axial vibration component. To mitigate vibration problems, a passive balance system can be mounted to the outside of the engine. However, vibration is not completely eliminated. This vibration provides a measurable external parameter that is related to the internal operation of components within the engine. Presently, attempts to correlate external parameters with internal parameters have been difficult, and many times the results are inadequate.

Therefore, there is a need to provide a machine development tool for use with closed cycle thermal regenerative machines which provides a predicted response for internal operating parameters. Furthermore, there is a need to provide such a predictor of internal operating parameters usable to control operation and/or diagnose health of such a machine.

The present invention arose from an effort to develop a machine development tool and control system that is relatively low in cost, is relatively light in weight, and has operating characteristics that can be relatively easily tuned to a particular machine by training a model of the machine behavior.

Disclosure of the Invention

A diagnostic and/or control system is provided for relating the component motions, system dynamics and Stirling cycle thermodynamics that occur in a free piston Stirling cycle thermal regenerative machine. A relatively accurate analytical model is provided that relates measurable external parameters to internal parameters for a closed cycle thermal regenerative machine, such as a Stirling cycle generator or cooler.

According to one aspect of the invention, a system is provided for diagnosing health of a closed cycle thermal regenerative machine. The machine includes a closed cycle thermal regenerative machine, a sensor, an artificial neural network (ANN), and diagnostic circuitry. The sensor is provided in association with the thermal regenerative machine and is operative to detect an external parameter of the thermal regenerative machine. The artificial neural network (ANN) is configured to associate at least one internal parameter with the external parameter detected by the sensor. The diagnostic circuitry is configured to receive the associated internal parameter from the artificial neural network (ANN), and is operative to diagnose at least one operating condition of the thermal regenerative machine.

According to another aspect of the invention, a control unit is provided for a closed cycle thermodynamic machine. The control unit includes a sensor, a comparator, and a controller. The sensor is operative to detect an external parameter of the machine associated with an operating condition of the machine. The comparator is operative to compare the detected operating parameter with predetermined experiential values. The controller is operative to produce a correction factor to adjust operation of the thermodynamic machine based upon a neural network such that the detected operating parameter is adjusted so as to bring the operating parameter within a desired value.

According to yet another aspect of the invention, a system is provided for controlling operation of a closed cycle thermal regenerative machine. The system includes a sensor, an artificial neural network (ANN), and control circuitry. The sensor is provided in association with the thermal regenerative machine, and is operative to detect an external parameter of the thermal regenerative machine. The artificial neural network is configured to associate at least one internal parameter with the external parameter detected by the sensor. The control circuitry is configured to receive the associated internal parameter from the artificial network, and is operative to control operation of the thermal regenerative machine based upon the internal parameter.

According to even another aspect of the invention, a method is provided for monitoring operating characteristics of a closed cycle thermal regenerative machine, including the steps of: providing a closed cycle thermal regenerative machine having at least one moving member contained within a containment vessel, and a detector provided externally of the vessel and configured to detect an external operating parameter of the machine; detecting an external operating parameter of the machine with the detector; generating an electrical signal as a function of the detected external operating parameter, the electrical signal containing data; sampling the data to obtain an input signal; and providing a neural network configured to receive the input and operative, when trained, to generate an output signal indicative of the internal operating characteristics of the machine.

One advantage of this invention is to provide a control system that correlates measurable external parameters to internal parameters for a closed cycle thermal regenerative machine, such as a Stirling cycle engine, generator or cooler. Another advantage of this invention is to provide a diagnostic system for determining the health of a closed cycle thermal regenerative machine by correlating measurable external parameters with desired internal parameters for a closed cycle thermal regenerative machine. Yet another advantage of this invention is to provide a relatively simple and accurate control system for regulating operating performance of a closed cycle thermal regenerative machine.

Brief Description of the Drawings

Preferred embodiments of the invention are described below with reference to the following accompanying drawings.

Fig. 1 is a side view and simplified schematic diagram of a Stirling generator with an artificial neural network control system embodying this invention;

Fig. 2 is a layout illustrating the assembly of Figs. 3 and 4;

Fig. 3 is a first portion of Fig. 2 illustrating a centerline cross-sectional view of an exemplary linear motion machine having an artificial neural network control/development system embodying this invention;

Fig. 4 is a second portion of Fig. 2 illustrating a centerline cross-sectional view of an exemplary linear motion machine having an artificial neural network control/development system embodying this invention;

Fig. 5 is a simplified schematic diagram illustrating the dynamic system mechanical elements making up the free piston, Stirling cycle device of Figs. 1-4; and

Fig. 6 is a simplified block diagram of an artificial neural network (ANN) model suitable for controlling and/or predicting internal operating parameters for a closed cycle thermal regenerative machine such as the Stirling power generator of Figs. 1-5.

Best Modes for Carrying Out the Invention and Disclosure of Invention

A preferred embodiment of a machine optimization and control system for use on a Stirling power generator is generally designated with reference numeral "8" in Figure 1. The Stirling power generator is generally designated with reference numeral "10" in Figure 1 and includes a power module assembly 12 and an engine module assembly 14. According to Figures 3 and 4, power generator 10 is formed by joining together power module 12 and engine module 14 with a plurality of circumferentially spaced apart threaded fasteners 18. The inside of power generator 10 is filled with a charge of pressurized thermodynamic working gas such as helium. Alternatively, hydrogen or any of a number of suitable thermodynamically optimal working fluids can be used to fill and charge the inside of generator 10.

A heat source is used to apply heat, Q_{SUPPLY} to a heater head 44 (see Fig. 4) of engine module 14, causing power module 12 to generate a supply of electric power, as shown in Figures 3 and 4. A displacer 46, comprising a movable displacer piston that is assembled together with several separate components, reciprocates between a hot space 48 and a cold space 50 in response to thermodynamic heating of the hot space from heater head 46 via the heat source Q_{SUPPLY}. In operation, displacer 46 moves working gas between hot space 48 and cold space 50. A power piston 52, suspended to freely reciprocate within power module 12 and in direct fluid communication with cold space 50, moves in response to cyclic pressure variations within the cold space caused by reciprocation of displacer 46. Details of such a Stirling power generator are similar to those disclosed in our U.S. Patent Application Serial No. 08/637,923 filed on May 1, 1996, and entitled "Heater Head and Regenerator Assemblies for Thermal Regenerative Machines", listing inventors as Laurence B. Penswick and Raymond M. Erbeznik. This 08/637,923 application, which is now U.S. Patent No. 5,743,091, is hereby incorporated by reference.

Power generator 10 produces electrical power when heat source Q_{SUPPLY} applies heat to heater head 44 as shown in Figures 3 and 4. Displacer 46 reciprocates when heat is applied to head 44 as working gas adjacent to displacer 46 expands as it is heated and contracts as it cools. A linear alternator 62, provided in fluid communication with displacer 46 via a power piston 52, is driven by fluid pressure variations created by reciprocation of displacer 46. Reciprocating motion of power piston 52 within a receiving bore 54 of a power module housing 40 causes linear alternator 62 to produce electrical power. Power piston 52 is rigidly carried on an end of an alternator shaft 64. A pair of flexure bearing assemblies 66 and 68 support piston 52 and shaft 64 in accurate, axially movable relation relative to bore 54, forming a clearance seal between bore 54 and power piston 52. Shaft 64 also carries inner moving laminations 63 of linear alternator 62. Power piston 52, alternator shaft 64, moving laminations 63, and flexure assemblies 58 and 60 all move as pressure fluctuations occur within working chamber 56, in response to fluid pressure fluctuations created in the working fluid from movement of displacer 46. As a result, an accurate axially reciprocating motion occurs along the common axis of displacer 46 and alternator shaft 64. However, such motion also produces an unbalanced vibration.

To compensate for the unbalanced vibration that results from such reciprocating motion, a passive balance system 16 is mounted to an exterior housing member 42 of generator 10, according to the construction depicted in Figures 1-5. Balance system 16 has a cylindrical counterbalance mass 76 movably carried on a pair of flexure assemblies 66 and 68 via a rigid mounting post 70 of housing member 42. Mass 76 (and associated moving system components) moves with accurate axial reciprocation along an axis that is perpendicular to a circular plan view profile of cylindrical mass 76 and flexure assemblies 68 and 70. Preferably, balance system 16 is mounted to housing member 42 so that the travel axis of moving mass 76 is parallel to a desired axial unbalanced vibration of machine 10. Alternatively, the travel axis of moving mass 76 is aligned in parallel relation with a recognized component of vibration that one desires to counterbalance on a vibrating machine.

As shown in Figure 1, two unique features are provided by implementing Applicant's invention. First, the operation of a thermal regenerative machine, in this case Stirling generator 10, is diagnosed by system 8 in order to determine whether the machine is operating properly, or is in need of any maintenance and/or repair. Secondly, operation of the thermal regenerative machine is controlled by system 8.

More particularly, generator 10 is monitored by one or more sensors 24-38 to determine one or more externally detectable operating parameters or characteristics that relate to operation of generator 10. A computer, in the form of a microprocessor 20, implements a neural network 25 that is trained to associate such detectable external operating parameters with internal operating parameters of generator 10. In this manner, operation of the internal components of a closed cycle thermal regenerative machine can be monitored indirectly by detecting the readily measured external parameters. Hence, there is not a need to provide additional ports through the pressure vessel of the machine which can complicate design, assembly and maintenance, and can increase the risk for leakage of working gas.

For example, to take full advantage of the unique attributes of a free piston, linear drive, Stirling cycle thermal regenerative machine, the machine components are likely to be totally contained within a hermetic pressure vessel with only the electrical leads to the linear drive motor/alternator crossing the pressure boundary. As shown in Figures 3 and 4, a pressure vessel is formed between housing 40, end cap 42 and heater head 44. Sensor 28 is connected to an external portion of a power generator lead 41 that passes from inside power module, or alternator, 12 to a device that uses or stores generated electrical power (not shown), such as a power grid or a battery.

According to the implementation shown in Figure 1, microprocessor 20 includes interface electronics 21, processing circuitry 23 and an application-specific integrated circuit (ASIC) 25. In one embodiment, microprocessor 20 comprises a single-chip implementation on which ASIC 25 and interface electronics 21 are also formed. Alternatively, microprocessor 20 includes processing circuitry 23, and interface electronics 21 and ASIC 25 are formed by separate integrated circuits that are joined together on a motherboard. Control/diagnostic circuitry 27 is shown implemented on a separate integrated circuit. However, circuitry 27 can alternatively be implemented on a single chip with microprocessor 20.

A neural network 22 is formed in ASIC 25, comprising an artificial neural network (ANN). Artificial neural network 22 can be implemented as a subroutine on microprocessor 20. Neural network 22 is configured, as described below with reference to Figures 5 and 6, to receive external inputs, or external parameters, from one or more of sensors 24-38 and generate internal outputs, or internal parameters, that correspond with specific internal operating characteristics or parameters of generator 10. Signals from sensors 24-38 are conditioned by interface electronics 21 to convert analog signals to digital signals that can be handled by processing circuitry 23. The digitally converted input signals are then input into a trained version of neural network 22.

Neural network 22, in response to the input signal(s), generates one or more corresponding output signal that indicates an internal operating parameter corresponding with operation of internal components within generator 10. Each output signal of an internal operating parameter is then input to the control circuitry portion of circuitry 27 and/or the diagnostic circuitry portion of circuitry 27. For the case where the internal operating parameter is input to the control circuitry of circuitry 27, a control signal, Q_{INPUT}, is output from the control circuitry.

Q_{INPUT} comprises a control signal that is delivered to a heat source, such as a radiant heater head burner (not shown), for controlling the amount of heat, Q_{SUPPLY}, that is delivered to generator 10. Hence, a feedback control signal is provided via circuitry 27 to control operation of generator 10.

Interface electronics 21 includes an analog-to-digital (A/D) converter comprising a circuit whose input is information in analog form and whose output is the same information converted into digital form. Additionally, or optionally, interface electronics 21 can include one or more of an amplifier, digital signal processing circuitry, and filtering circuitry. Interface electronics 21 are used to convert a signal that is detected by one of sensors 24-38 into a suitable form for processing by processing circuitry 23. Accordingly, the specifics of interface electronics 21 might vary depending upon the specific sensor utilized to form sensors 24-38. Hence, interface electronics 21 are provided for each of sensors 24-38 in order to provide a condition signal that is suitable for use with processing circuitry 23, *e.g.*, a detected signal is converted from analog form into digital form which is compatible with microprocessor 20.

Although circuitry 27 is shown in Figure 1 being implemented as control circuitry, it is understood that control signal, Q_{NPUT}, can provide a diagnostic signal that is used to determine whether generator 10 is operating properly, or needs maintenance and/or repair. Furthermore, although microprocessor 20 is shown receiving external input signals from each of sensors 24-38, it is understood that only one signal is needed in order to implement certain aspects of Applicant's invention. For example, sensor 28 can be used to determine whether the current (I) and phase for alternator 12, relative to voltage which is delivered from generator 12, is within a desired range. When such detected value is exceeded, generator 10 can be controlled by reducing the amount of heat, Q_{SUPPLY}, that is delivered to generator 10. Optionally, generator 10 can be diagnosed as needing to be shut down if an operating range is detected as being exceeded.

Neural network 22 is trained with actual test information that correlates external input parameters with measured internal output parameters, representing the operation of components internal to generator 10. In contrast, in a laboratory environment a number of internally mounted instruments can be employed to evaluate the operating characteristics of a closed cycle thermal regenerative machine, such as a Stirling generator, provide input to various external controllers, and in general help define the basic health of the machine hardware. All of these sensors and their associated electronics can considerably increase unit cost, complicate hardware assembly, place unnecessary constraints on mechanical design or hardware configurations, and potentially decrease the unit's overall reliability. Hence, the implementation of a trained neural network 22 rectifies many of these problems.

Figure 5 illustrates a schematic representation of the dynamic and mechanical elements making up a free piston, Stirling cycle device, such as generator 10 (of Figs. 1-4). Although a generator or engine is shown in Figure 5, it is understood that the same concept holds for cooling machines such as Stirling cycle cryocoolers. As can be seen in Table 1, below, the following external parameters may be available for easy measurement with the system of Figure 5; *i.e.*, they exist external to the pressure vessel boundary and are relatively easy to access and measure without compromising the integrity of the pressure vessel portion of the generator.

As shown in Table 1, below, ten different measurable external parameters are defined. Such external parameters are detected variously by sensors 24-38.

Table 1 - Measurable External Parameters:

External Parameter	**Description**
Q_{SUPPLY}	Thermal energy entering acceptor or heater head
T_h	External acceptor heat exchanger wall temperature
T_c	External rejector heat exchanger wall temperature
X_c	Casing motion, velocity, or acceleration
X_b	Balance mass (if accessible) amplitude and phase relative to casing
C_t	Tuning capacitors (if accessible)
I	Motor/alternator current and phase relative to voltage
V_{LOAD}	Motor/alternator voltage
Z_{LOAD}	Load (engine only) characteristics
f	Operating frequency

External parameter Q_{SUPPLY} can be measured with sensor 34 (of Fig. 1). According to one construction, sensor 34 (of Fig. 1) comprises a gas flow sensor configured to detect the quantity of gas being delivered to a heater head burner which can be correlated with the amount of thermal energy, Q_{SUPPLY}, delivered to the heater head of engine module 14.

Also according to Table 1, external parameter T_h describes an external acceptor heat exchanger wall temperature. Such wall temperature T_h can be detected with sensor

36 (of Fig. 1). In one embodiment, sensor 36 (of Fig. 1) comprises a thermocouple configured and arranged to detect wall temperature at a location corresponding with that depicted in Figure 1.

Another external parameter, T_c, of Table 1, describes the external rejector heat exchanger wall temperature. Such wall temperature T_c can be detected with sensor 38 (of Fig. 1). One construction for sensor 38 comprises a thermocouple configured and arranged to measure wall temperature at a location corresponding with that depicted in Figure 1.

Measurable external parameter X_c of Table 1 indicates casing motion, velocity, and/or acceleration. External parameter X_c can be detected via sensor 30 (see Fig. 1). One construction for sensor 30 (of Fig. 1) comprises an accelerometer, wherein acceleration is directly detected, and velocity and displacement (or motion) can be derived from the detected acceleration curve. Optionally, other motion, velocity or acceleration detectors can be utilized.

External parameter X_b of Table 1 describes displacement amplitude for an externally mounted balance mass, and can include phase information relating motion of the balance mass relative to the casing or housing of the thermal regenerative machine. Sensor 24 (see Fig. 1) can be utilized to detect external parameter X_b. According to one construction, sensor 24 comprises an accelerometer.

External parameter C_t describes tuning capacitors that are provided at a location externally of a thermal regenerative machine and at an accessible location. As shown in Figure 1, external parameter C_t can be detected with sensor 26. According to one construction, sensor 26 (of Fig. 1) comprises a combination of voltage and current detecting circuitry such as a voltmeter and a toroidal current sensor that electrically determines the capacitance of tuning capacitors.

External parameter I describes motor/alternator current and phase relative to voltage. Such external parameter I can be detected with sensor 28 (of Fig. 1). One construction for sensor 28 (of Fig. 1) comprises current detecting circuitry such as a toroidal current sensor.

External parameter V_{LOAD} describes motor/alternator voltage. External parameter V_{LOAD} can be measured with sensor 28 (see Fig. 1). One construction for sensor 28 (of Fig. 1) comprises voltage detecting circuitry such as a voltmeter.

External parameter Z_{LOAD} describes engine load characteristics when a closed cycle thermal regenerative machine is configured as an engine. External parameter Z_{LOAD} can be detected with sensor 28 (see Fig. 1). One construction for sensor 28 (of Fig. 1) comprises engine load detecting circuitry such as current detecting circuitry in the form of a toroidal current sensor in combination with a voltmeter. Power is determined using the detected voltage, detected current, and detected phase shift between the voltage and current. The phase shift is then used with the voltage and current to calculate Z_{LOAD}.

External parameter f describes operating frequency for a closed cycle thermal regenerative machine. External parameter f can be detected with sensor 32 (see Fig. 1). According to one construction, sensor 32 (of Fig. 1) comprises an accelerometer and associated signal processing circuitry. The accelerometer and circuitry are used to monitor vibrations corresponding to the cyclical motions imparted by movements of internal operating components such as the piston and displacer of a Stirling engine.

As shown in Figure 5, a heater head gas burner delivers thermal energy, Q_{SUPPLY}, to Stirling generator 10, at the heater head. Stirling generator 10 includes a power module 12 and an engine module 14, with a movable piston displacer 46 carried in engine module 14, and a reciprocating piston 52 provided within power module 12. A linear motor or alternator 62 is also provided within power module 12. A balance unit, or passive balance system, 16 is affixed to an external housing portion of generator 10. The balance unit 16 is operative to at least in part counterbalance vibrations induced by movement of displacer 46 and piston 52.

One problem associated with running generator 10 results when too much heat, Q_{SUPPLY}, is delivered from heater head 44 to engine module 14 which can result in displacer 46 and/or piston 52 overstroking within generator 10. Such overstroke condition can cause serious damage to generator 10. Therefore, it is desirable to measure one or more external parameters that indicate when overstroke might occur with displacer 46 and/or piston 52, wherein overstroke of displacer 46 and piston 52 each form internal parameters of generator 10.

Due to the complex interrelationships between the component motions, system dynamics, and the Stirling cycle thermodynamics in a free piston device, it would be very complicated, and possibly essentially impossible in some cases, to develop an accurate analytical model that relates the above-detailed ten external parameters to desired and/or critical internal parameters. An artificial neural network implementation overcomes this problem. Even further, with an ANN implementation, it is possible to use a fewer number of such external parameters. The internal operating parameters of interest may include: Xp (piston amplitude), Xd (displacer amplitude), mechanical phase angle between the displacer and piston, A1 (motor/alternator constant), or mean charge pressure. Other internal operating parameters are also possible. Several exemplary groups of external parameters are described below with reference to Table 2.

Artificial neural network (ANN) 22 of Figure 1 represents a unique modeling technique that can effectively identify the complex and often subtle interrelationships between the externally measured parameters and the desired internal parameters of a closed cycle thermal regenerative machine, such as a Stirling cycle engine or cooler. A simplified artificial neural network (ANN) is shown in Figure 2 in which a selected group of the external parameters of the Stirling generator, or engine, 10 are employed as inputs to the neural network.

During training of the neural network, which is based on test results from actual hardware, the neural network is exposed to known input and out parameter values. For example, a table of input parameters and associated output parameters can be provided in a look-up table that is generated by bench testing the generator in the laboratory, and by measuring the resulting output parameters, which represent the internal operating parameters of the generator.

More particularly, neural network 22 is trained via any of a number of standard training techniques presently understood in the art. More particularly, training is implemented by providing input data for a relatively large number of regenerative machine operating conditions, extending over a range of conditions that span the expected entire operating range for the machine. The provided input data also includes known or measured output data which is used to train the neural network.

Figure 6 illustrates one implementation of a simplified artificial neural network 22. Such neural network 22 provides a highly parallel, distributed data processing system such as a continuous perceptron-type network or a Hopfield network. As shown in Figure 6, a three-layer continuous perceptron network forms a feed-forward architecture of neurons. Such a three-layer feed-forward network uses neurons at an input layer of input nodes, an intermediate hidden layer of nodes, and an output layer of output nodes.

According to Figure 6, an input layer 88 of nodes contains only two units, or nodes, a hidden layer 90 that contains only four units, or nodes, and an output layer 92 that contains only a single unit, or node. Inputs 84 are delivered to the input layer 88 and a single output 86 is generated based upon the coefficients that are applied to the nodes within the three layers, based upon training of neural network 22.

Also as shown in Figure 6, there is no coupling within individual layers of neural network 22. It is further understood that there is coupling between the neurons in a common layer of the three layers, with coupling weights being applied between the nodes of respective layers.

An error back propagation technique is employed to adjust the weights in each connection between the nodes, or neurons, in order to minimize the error of the artificial neural network (ANN) predicted output 86 and an actual measured value that has been obtained by testing in the laboratory. The resulting artificial neural network (ANN) model can be easily incorporated into a simple EPROM, or ASIC as shown in Figure 1, which will output estimates of the desired internal parameters. These output parameters 86 can then be used in controlling the device or diagnosing/evaluating health of the operating system.

According to one implementation, artificial neural network 22 (see Figs. 1 and 6) is implemented with a commercially available software package. One such software package is sold under the name "Propagator", by ARD Corporation, 9151 Ramsey Road, Columbia, Maryland 20145. Optionally, other commercially available neural network packages can be utilized to implement artificial neural network 22.

One aspect of Applicant's invention has been to develop a low cost technique to evaluate the internal operating characteristics of free piston equipment based on measurement of external parameters. An artificial neural network (ANN) has been used to carry out this process. The use of artificial neural networks (ANNs) has been shown implemented to evaluate operating parameters which cannot be directly measured during early testing and debugging of hardware for closed cycle thermal regenerative machines, such as Stirling cycle coolers and engines.

It is understood that a number of different combinations of measurable external parameters, identified in Table 1 and Figures 3-4, can be utilized with the neural network of Figure 5 to determine internal parameters. Sensors 24-38 can be used individually or in various combinations to achieve each of the eight applications depicted in Table 2. The internal parameters can be used to gauge the overall health of a complete closed cycle thermal regenerative machine system, or to control operation of such a system. As shown below, Table 2 illustrates eight exemplary machine optimization and control system implementations for the apparatus depicted in Figures 1-5. Eight applications are shown for assessing eight features of a machine system, with utilized sensors being indicated by an "X" in the accompanying column.

Table 2 - Machine Optimization Control System Implementations:

	Sensor 24	Sensor 26	Sensor 28	Sensor 30	Sensor 32	Sensor 34	Sensor 36	Sensor 38
Application	Xb	Ct	I,V,Z	Xc	f	Q	Th	Tc
1. Overall health		X	X	X	X	X	X	X
2. Heater head temperature			X	X				X
3. Alternator condition			X	X				X
4. Burner/Heat supply			X	X		X		X
5. Piston/Displacer overstroke	X		X	X				
6. Loss of pressure			X	X	X		X	X
7. Displacer condition			X	X			X	X
8. Mounting system condition	X		X	X	X			

A first application, referred to as Application 1, is provided for assessing overall health of a closed cycle thermal regenerative machine, such as machine 8 of Figures 1-5. Such implementation enables the determination of overall health of a complete engine system which is important for many commercial engine applications. More particularly, sensors 26-38 are utilized as measurable external parameters in determining the overall health of a complete engine system via an artificial neural network.

A second application, referred to as Application 2, enables determination of heater head temperature, T_h, indicating the gas temperature within the hot end of a Stirling engine, by utilizing sensors 28, 30, and 38. In this application, the heater head temperature, T_h, cannot be measured within the hot head of a Stirling engine because the thermal environment is too harsh to use a heater head sensor. Accordingly, the artificial neural network (ANN) tells the system controller to vary Q_{SUPPLY} by controlling gas flow to a heater head burner in order to maintain a constant heater head temperature, T_h. Alternatively, the artificial neural network (ANN) tells the diagnostic system that the heater head temperature, T_h, is too hot, and the diagnostic system shuts down the engine system. Such implementation is particularly important for commercial applications since many temperature sensors do not have a high degree of reliability over extended periods of time. Temperature sensors which do have a high degree of reliability tend to be very expensive which discourages their use and limits their application.

A third application, referred to as Application 3, determines the condition of the alternator by diagnosing the health of the alternator. Sensors 28, 30 and 38 are utilized to determine an "alternator constant" which defines the condition of the alternator magnets, coil, and stationary alternator components. Such implementation is important for many commercial applications.

A fourth application, referred to as Application 4, evaluates burner/heat supply to a Stirling engine in order to determine whether there is any degradation of the heat supply, or whether the condition of the internal heat exchanger on the hot engine of the Stirling engine has degraded. Sensors 28, 30, 34 and 38 are utilized to assess such burner/heat supply condition. Such implementation is very important for many commercial applications.

A fifth application, referred to as Application 5, determines piston/displacer overstroke conditions via sensors 24, 28 and 30. According to one implementation, the system controller is used to produce an input parameter, such as Q_{INPUT}, such as by reducing the energy being delivered by an external heater to the heater head. Alternatively, a diagnostic system associated with the control circuitry is used to shut the engine system down. Such application is important for many commercial systems.

A sixth application, referred to as Application 6, determines a loss of pressure from within the closed cycle thermal regenerative machine. For example, a slow loss of Stirling engine charge pressure due to a small leak of thermodynamic gas can lead to component damage which results in a significant degradation of performance of the engine. According to such implementation, sensors 28, 30, 32, 36 and 38 are utilized. Optionally, a lesser number of such sensors can be utilized.

A seventh application, referred to as Application 7, determines a displacer condition within a closed cycle thermal regenerative machine. Sensors 28, 30, 36 and 38 are utilized to determine degradation of a displacer assembly within a closed cycle thermal regenerative machine; *e.g.*, a Stirling engine. Such displacer assembly degradation could result because of a flexure failure or because of mechanical contact occurring between the displacer and its surrounding cylinder, such as might occur for the case of clearance-seal displacer assemblies. Such implementation can be very important for certain commercial applications.

An eighth application, referred to as Application 8, determines a mounting system condition within a closed cycle thermal regenerative machine. Sensors 24, 28, 30 and

32 are utilized to define the condition of an engine mounting system contained within an overall package of a closed cycle thermal regenerative machine. For example, the engine mounting system within a Stirling cycle engine can be determined by monitoring such sensors to indicate degradation in the mounting system. For example, rubber isolation mounts within such engine system can degrade over time. Such degradation can be externally monitored via sensors 24, 28, 30 and 32 and in an artificial neural network pursuant to the implementations depicted in Figures 1-5. Even furthermore, failure of a mounting system can be detected, which can be used by control circuitry and/or diagnostic circuitry, to shut the engine system down before mechanical damage occurs to the engine.

It is understood that the artificial neural network (ANN) 22 of Figure 6 does not have to be a three-layer arrangement. Optionally, such artificial neural network can have four, five, six or more layers. However, such additional layers tend to be overkill for many applications, increasing cost, complexity and training difficulty for the neural network. It is presently believed that such implementation requires at least three layers.

Industrial Applicability

The invention is useful in the power generation, energy conversion, and cooler industry for diagnosing health and controlling operation of closed cycle thermal regenerative machines.

CLAIMS

1. A system for diagnosing health of a closed cycle thermal regenerative machine, comprising:

a closed cycle thermal regenerative machine;

a sensor provided in association with the thermal regenerative machine and operative to detect an external parameter of the thermal regenerative machine;

an artificial neural network (ANN) configured to associate at least one internal parameter with the external parameter detected by the sensor; and

diagnostic circuitry configured to receive the associated internal parameter from the artificial neural network (ANN) and operative to diagnose at least one operating condition of the thermal regenerative machine.

2. The system of claim 1 wherein the thermal regenerative machine comprises a Stirling cycle generator.

3. The system of claim 1 wherein the sensor comprises an accelerometer configured to detect at least one of motion, velocity, and acceleration for a portion of the thermal regenerative machine to which the accelerometer is secured.

4. The system of claim 3 wherein the thermal regenerative machine includes a housing, and wherein the sensor is rigidly secured to the housing.

5. The system of claim 3 wherein the thermal regenerative machine includes a passive balance system, and wherein the sensor is rigidly secured to the passive balance system.

6. A control unit for a closed cycle thermodynamic machine, comprising:

a sensor operative to detect an external parameter of the machine associated with an operating condition of the machine;

a comparator operative to compare the detected operating parameter with predetermined experiential values; and

a controller operative to produce a correction factor to adjust operation of the thermodynamic machine based upon a neural network such that the detected operating parameter is adjusted so as to bring the operating parameter within a desired value.

7. The system of claim 1 wherein the artificial neural network (ANN) comprises a three-layer feed-forward neural network including an input layer of nodes, a hidden layer of nodes, and an output layer of nodes.

8. The system of claim 1 wherein the thermal regenerative machine includes an alternator and wherein a first sensor is provided for detecting load on the alternator and a second sensor is provided to detect current being generated by the alternator, the first sensor and the second sensor each providing an input comprising an external parameter of the thermal regenerative machine to the artificial neural network, and wherein the artificial neural network generates an output comprising an internal parameter indicative of an overstroke condition for the thermal regenerative machine.

9. A system for controlling operation of a closed cycle thermal regenerative machine, comprising:

a sensor provided in association with the thermal regenerative machine and operative to detect an external parameter of the thermal regenerative machine;

an artificial neural network configured to associate at least one internal parameter with the external parameter detected by the sensor; and

control circuitry configured to receive the associated internal parameter from the artificial neural network, and operative to control operation of the thermal regenerative machine based upon the internal parameter.

10. The system of claim 9 further comprising a microprocessor having interface electronics and processing circuitry, the artificial neural network implemented as a sub-routine on the microprocessor.

11. The system of claim 10 wherein the microprocessor further includes an application-specific integrated circuit (ASIC), the artificial neural network provided on the ASIC.

12. The control system of claim 9 wherein the thermal regenerative machine comprises a Stirling cycle generator, and the control circuitry is configured to generate an output signal that controls delivery of heat to the generator.

13. The system of claim 9 wherein the artificial neural network comprises a feed-forward neural network having an input layer, at least one hidden layer, and an output layer.

14. A control apparatus for a Stirling cycle machine, comprising:

a detector for sensing an external operating parameter of the machine;

a neural network having weighting functions for receiving at least one detected operating parameter of the machine and for processing the detected operating parameter in accordance with the weighting functions, and outputting an associated internal operating parameter; and

circuitry coupled with the neural network and configured to receive the internal operating parameter, the circuitry further operative to generate an output signal indicative of an operating state of the Stirling cycle machine.

15. The control apparatus of claim 14 wherein the detector comprises a motion sensor.

16. The control apparatus of claim 14 wherein the detector comprises a temperature sensor.

17. The control apparatus of claim 14 wherein the circuitry comprises diagnostic circuitry operative to diagnose an operating condition of the Stirling cycle machine.

18. The control apparatus of claim 14 wherein the circuitry comprises diagnostic circuitry operative to diagnose health of the Stirling cycle machine.

19. The control apparatus of claim 14 wherein the neural network comprises a feed-forward neural network having an input layer, at least one hidden layer, and an output layer.

20. The control apparatus of claim 14 wherein the detector comprises an accelerometer affixed externally to a housing of the Stirling cycle machine, and wherein the detected operating parameter comprises at least one of displacement, velocity, and acceleration of the housing.

21. A closed cycle thermal regenerative machine control system, comprising:

a sensor provided externally of a thermal regenerative machine and operative to detect an external parameter of the machine;

processing circuitry configured to receive the external parameter;

a neural network coupled with the processing circuitry and operative to associate an internal parameter with the detected external parameter; and

circuitry associated with the neural network and configured to receive the internal parameter, the circuitry operative to generate an output signal indicative of operating characteristics of the Stirling cycle machine.

22. The machine control system of claim 21 wherein the circuitry comprises diagnostic circuitry configured to generate an output signal indicative of diagnosed health of the thermal regenerative machine.

23. The machine control system of claim 21 wherein the circuitry comprises control circuitry operative to generate an output signal comprising a control signal that regulates operation of the thermal regenerative machine.

24. The machine control system of claim 21 wherein the thermal regenerative machine comprises a Stirling cycle machine, and wherein the sensor comprises an accelerometer affixed externally to a housing of the Stirling cycle machine, the sensor operative to detect motion of the machine.

25. A method of monitoring operating characteristics of a closed cycle thermal regenerative machine, comprising:

providing a closed cycle thermal regenerative machine having at least one moving member contained within a containment vessel, and a detector provided externally of the vessel and configured to detect an external operating parameter of the machine;

detecting an external operating parameter of the machine with the detector;

generating an electrical signal as a function of the detected external operating parameter, the electrical signal containing data;

sampling the data to obtain an input signal; and providing a neural network configured to receive the input signal and operative, when trained, to generate an output signal indicative of the internal operating characteristics of the machine.

26. The method of claim 25 further comprising the step of: training the neural network by providing a plurality of input signals associated with determined output signals.

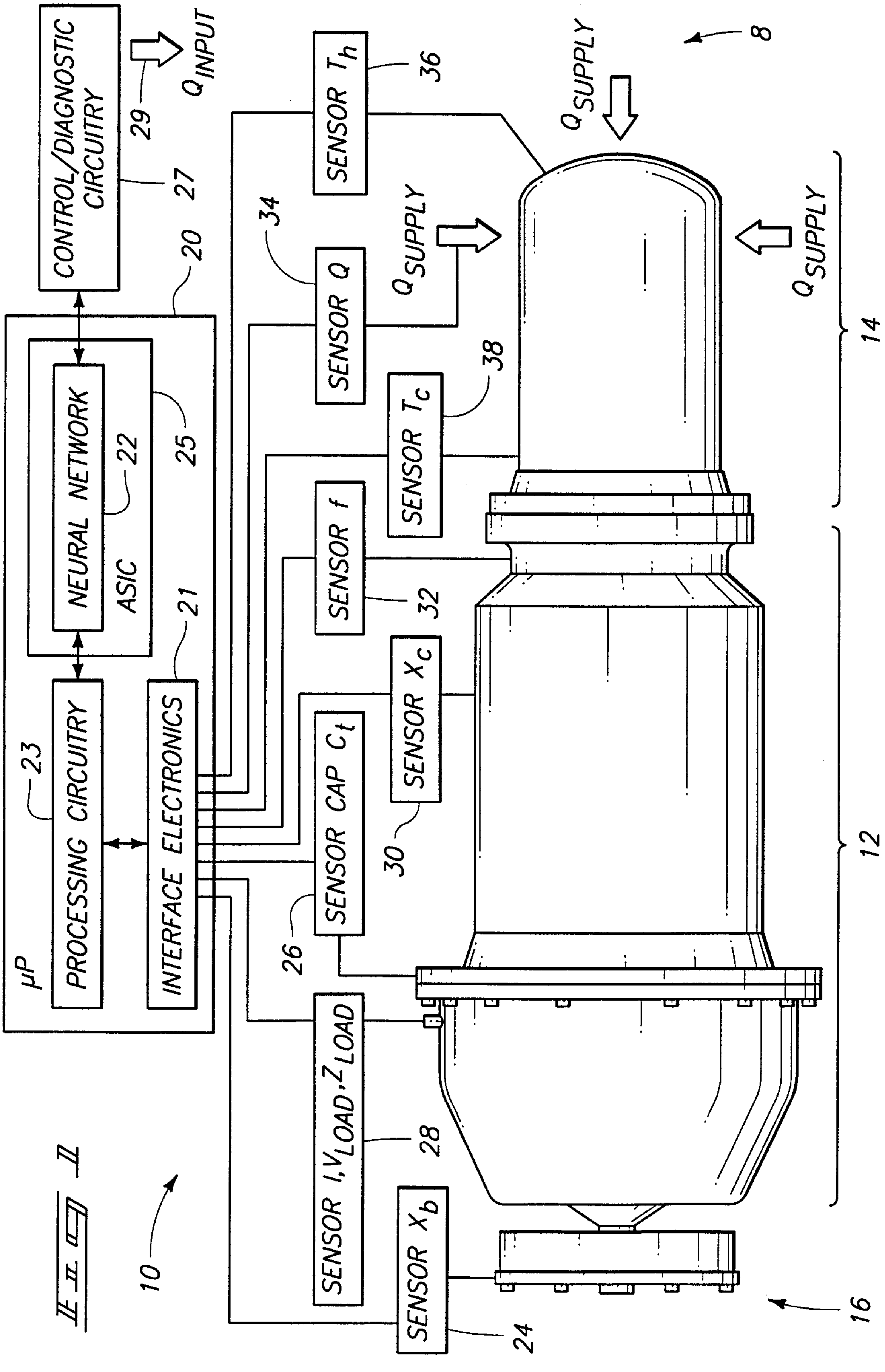
27. The method of claim 25 wherein individual input signals are provided to the machine, and associated output signals generated by the machine are measured so as to determine the output signals.

28. The method of claim 25 wherein closed cycle thermal regenerative machine comprises a Stirling cycle generator, and the at least one moving member comprises a piston and a displacer.

29. The method of claim 28 further comprising the steps of delivering the output signal to a heat source of the Stirling cycle generator, and controllably adjusting heat delivery to the Stirling cycle generator responsive to the input signal.

30. The method of claim 25 wherein the detector comprises a sensor affixed externally to the closed cycle thermal regenerative machine and operative to detect the external operating parameter of the machine.

31. The method claim 25 wherein the neural network comprises a feed-forward neural network having an input layer configured to receive at least one input signal, at least one hidden layer, and an output layer configured to generate the output signal.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PROCESSING CIRCUITRY
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Q_{SUPPLY}
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Q_{SUPPLY}
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SENSOR T_c
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14
SENSOR f
32
SENSOR X_c
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SENSOR X_b
SENSOR
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16

FIG. 1

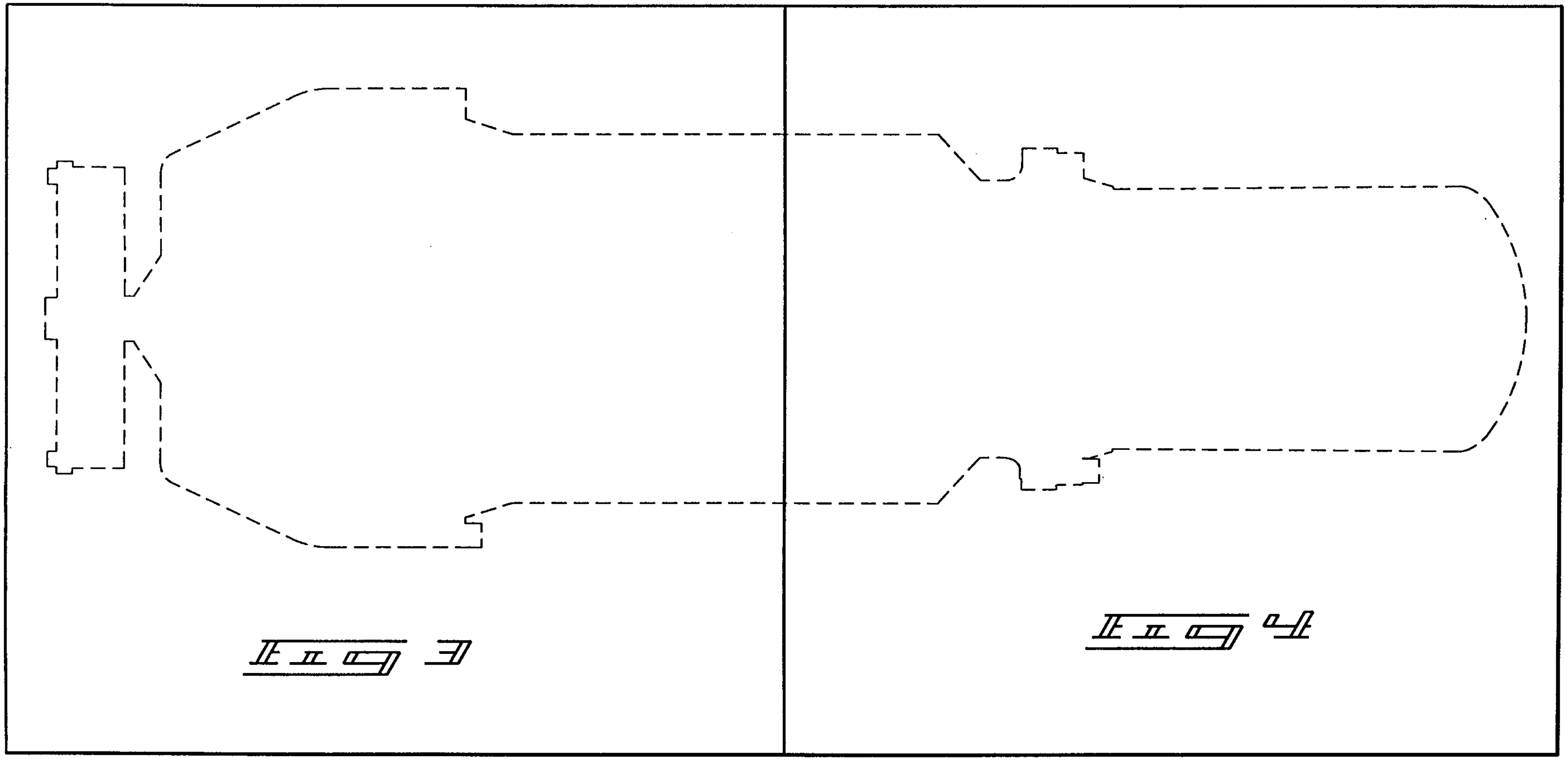
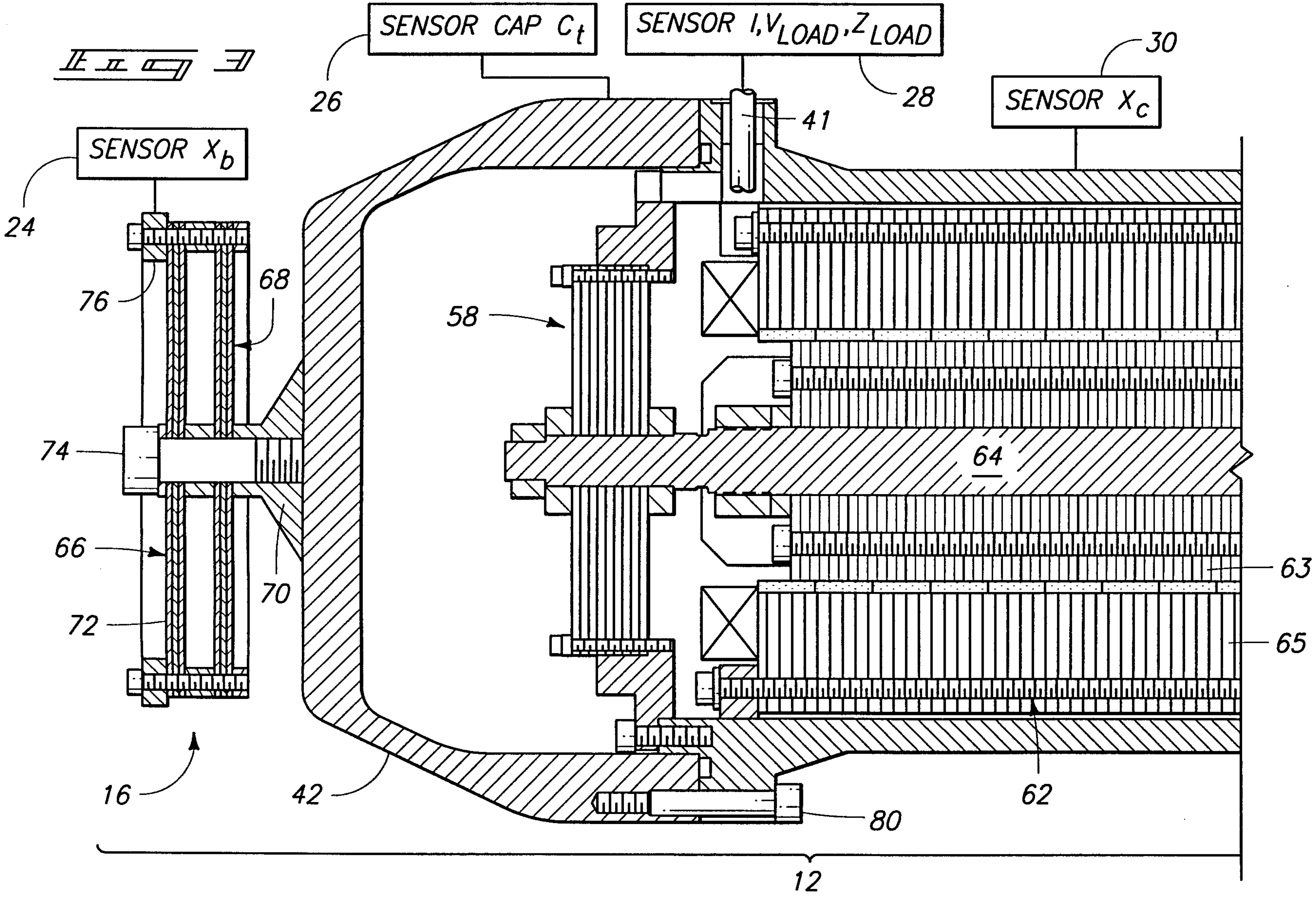


Fig 3

Fig 4

Fig 2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SENSOR X_b
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FIG 3

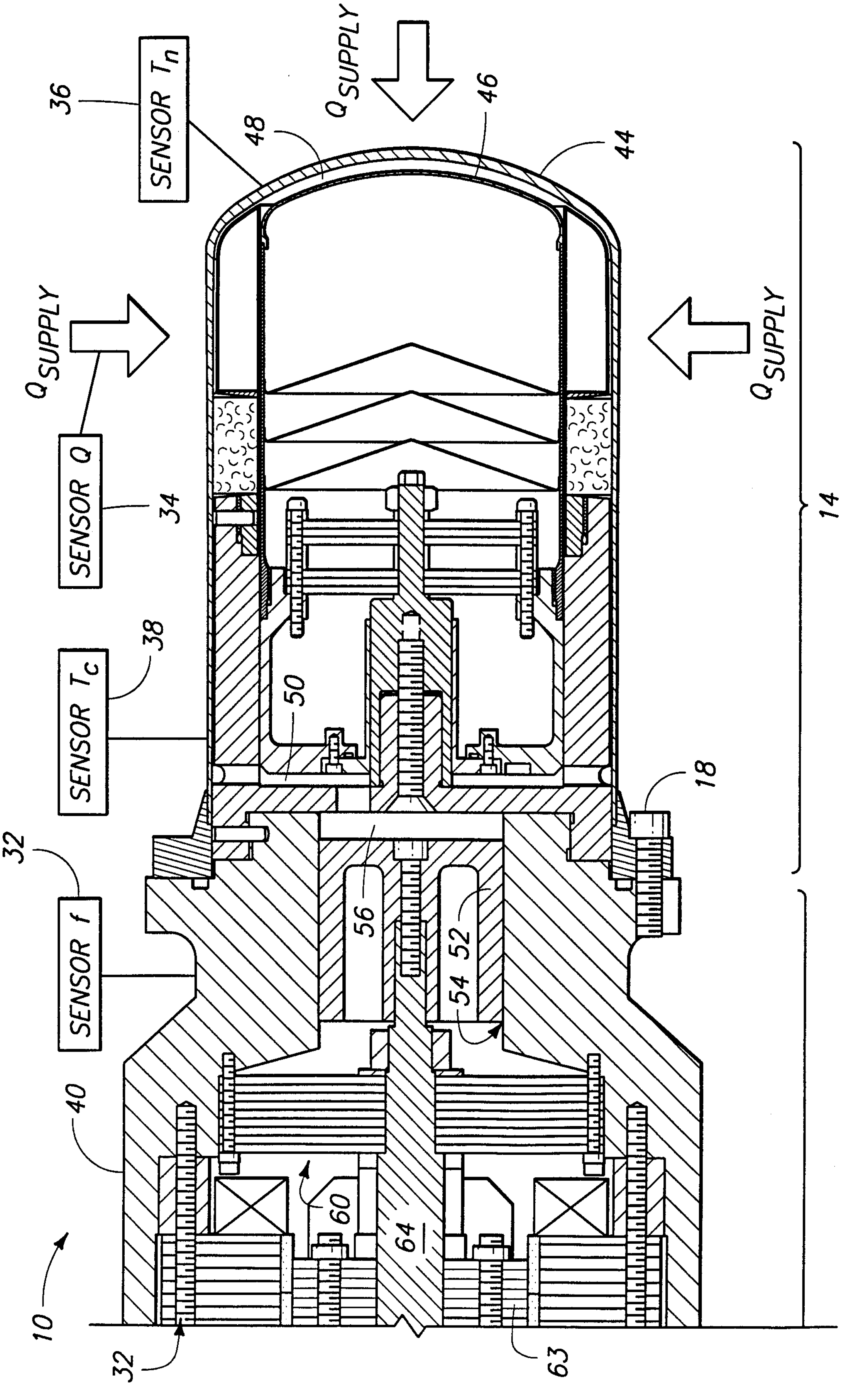
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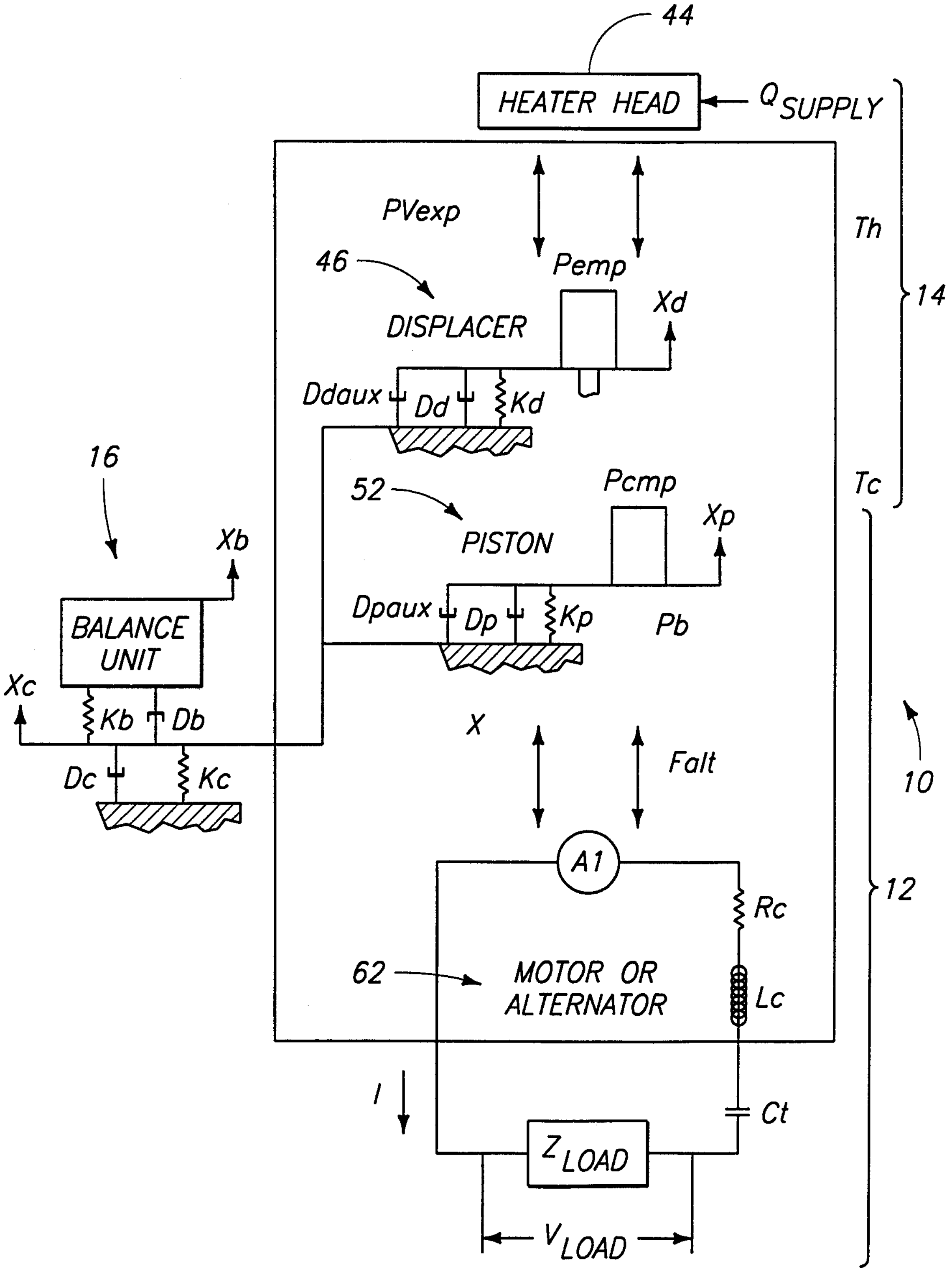
Fig 4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Kp
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Kb
Db
X
Falt
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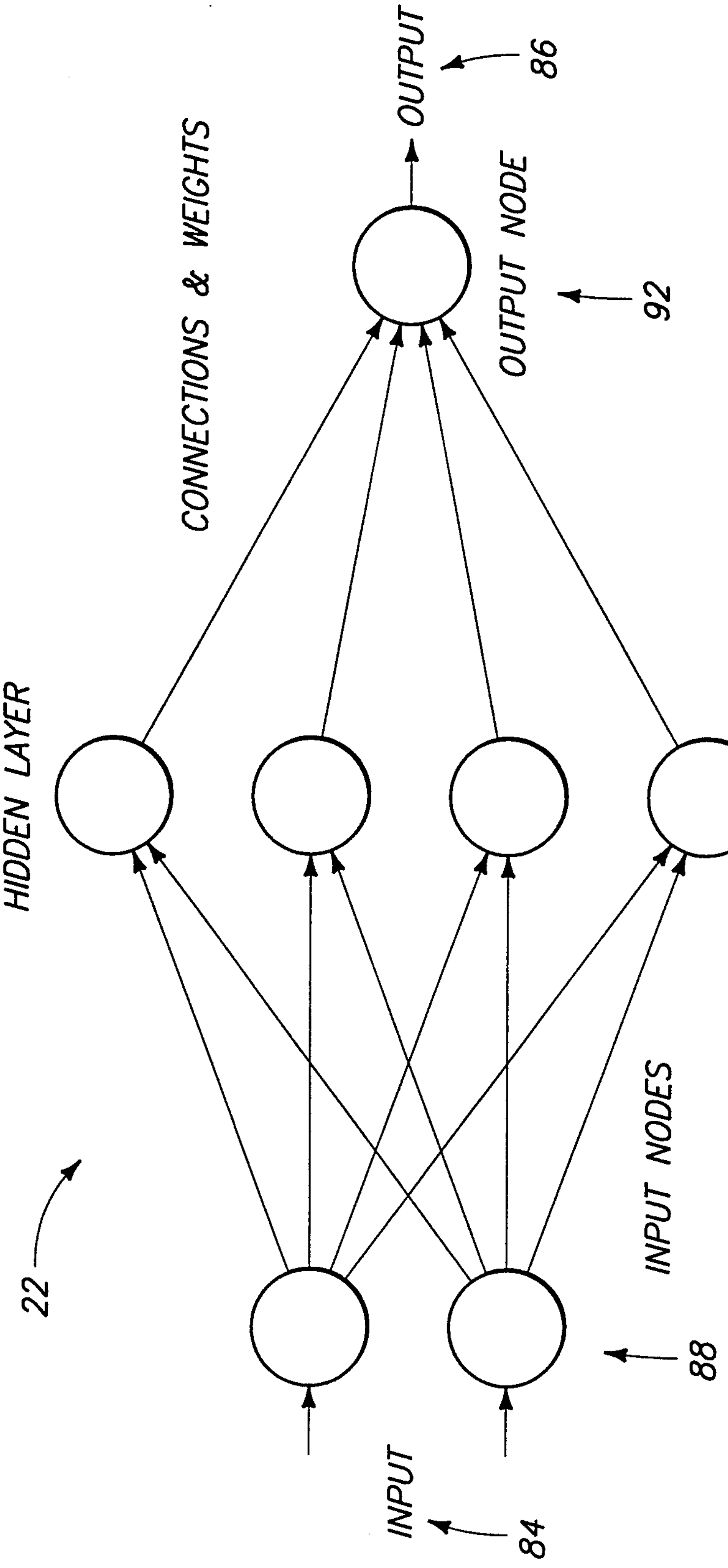
Ct
Z_{LOAD}
V_{LOAD}

Fig 5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HIDDEN LAYER
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INPUT NODES
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INPUT
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FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/10843

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : G05B 13/02
US CL : 700/48;60/250;62/6
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 700/48,47,299,300;702/81,130;60/250;322/3;62/6

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EAST (stirling, neural, intelligent, control, cryogenic)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,552,608 A (GALLAGHER et al.) 03 September 1996 (03.09.1996), Figure 9, column 1 lines 34-37, column 12 lines 21-22, column 13 lines 58-67, column 14 lines 1-8, column 15 lines 24-65, column 21 lines 56-67, column 22 lines 1-23	1-31
Y	US 5,496,153 A (REDLICH) 05 March 1996 (05.03.1996), column 1 lines 48-67, column2 lines 1-12	1-31
Y	US 5,678,409 A (PRICE) 21 October 1997, (21.10.97), column 2 lines 27-31	5
Y	US 5,371,809 A (DESIENO) 06 December 1994 (06.12.1994), column 1 lines 29-33 and lines 50-68, column 2 lines 8-13	7

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance		
"E"	earlier application or patent published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search 30 June 2000 (30.06.2000)	Date of mailing of the international search report 17 AUG 2000
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703)305-3230	Authorized officer William Grant James R. Matthews Telephone No. 703