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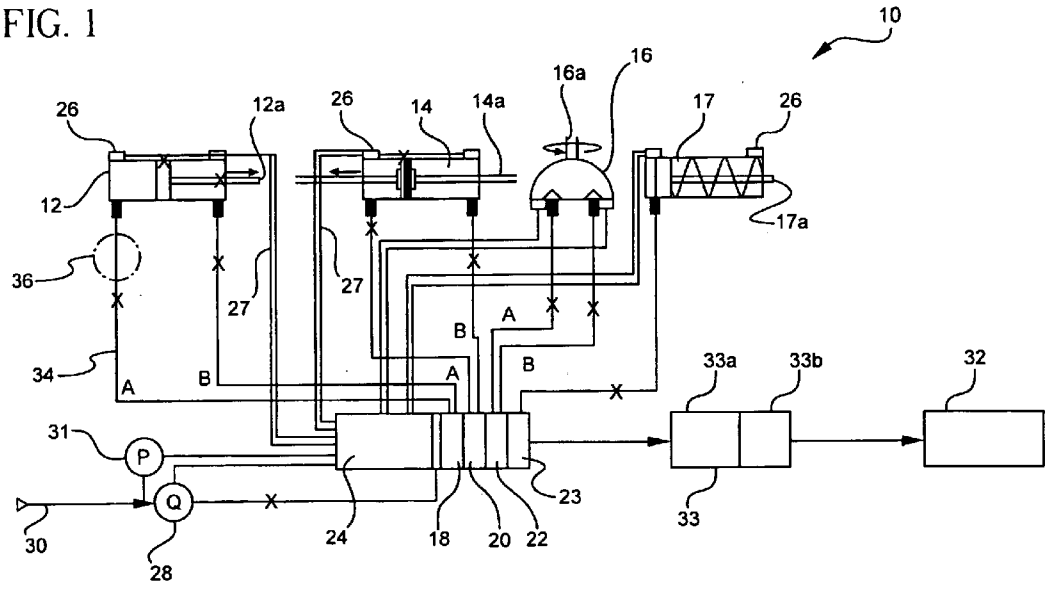
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(54) **Title:** METHOD AND APPARATUS FOR DIAGNOSING A FLUID POWER SYSTEM

FIG. 1



(57) **Abstract:** The present invention includes a method and apparatus for diagnosing a fluid power system and detecting and localizing a fault in the system. The method includes a reference mode for creating a reference dataset and a monitoring mode for monitoring actual system conditions. The actual system conditions are compared to the reference dataset. Variations between the actual and reference data is used to determine a fault condition. System branches which do not show an increase in fluid consumption over the reference data are designated as not having a fault. System branches showing an increase in fluid consumption over the reference data are identified as possibly having a fault. A user is alerted as to the possible faulty branches.

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Method And Apparatus For Diagnosing A Fluid Power System

Field Of The Invention:

[0001] The present invention relates to a method and apparatus for diagnosing a fluid power system and more particularly for detecting and localizing a fault in a cyclic fluid power system.

Background Of The Invention:

[0002] Fluid power systems, such as pneumatic or hydraulic systems, used in industrial automation typically include a number of elements including an arrangement of valves and actuators operatively connected thereto. Additional system elements may include tubing and fittings. The valves may be controlled by a number of devices such as microprocessors or programmable logic controllers, PLC's, or through analog control circuits.

[0003] In a fluid power system, one common fault is leakage. One typical area of leakage is between the actuators and the valves. Such leakage can occur by failure of the tubing, for example, by exposure to corrosive substances, abrasion as the tubing moves along with an actuator, or the tubing may inadvertently being pinched during the manufacturing process. In addition, fittings which attach the tubing to the valves and actuators can become loose and permit leakage from the valve ports and/or cylinder ports. Actuators such as cylinders, may have piston seals and rod seals which can also develop leaks over time.

[0004] It is desirable to reduce or eliminate leakage in a fluid power system since leakage can negatively affect the system. In pneumatic systems, due to the cost of creating pressurized air, even small leaks in a system left in disrepair can lead to significant increase in system operating costs. In clean room environments, leakages in a pneumatic system can result in contamination which could result in larger problem In the case of hydraulic systems, leaks will spill hydraulic oil out of the lines leading to contamination of the surrounding area. While these

leaks may be easier to identify than in a pneumatic system, if left untreated, they can create significant maintenance issues. Leaks in a fluid power system can affect actuator performance, such as by slowing the movement of a piston rod, and reducing the overall performance of the equipment. Accordingly, it is desirable to eliminate and detect the presence of leaks as soon as possible.

[0005] Faults such as leakage in a complex system can be a signal that a certain component is failing, however, if the component is still functioning, the fault may be difficult to detect. Once the component fails the system is compromised and the component typically must be replaced. Such unscheduled maintenance is costly and highly disruptive.

[0006] Systems for monitoring the functionality of fluid power systems are known in the art. Monitoring capabilities offer the possibility of understanding the parameters of the system. Monitoring may rely on numerous sensors (both analog and digital) embedded in the system. These sensors make the system data available in real-time signal form. For example, each fluid power line could include pressure and flow sensors in order to provide information as to the condition of the line. However, the use of numerous sensors increases the cost and complexity of the system and creates a large amount of data that must be processed and interpreted. In addition, since sensors periodically fail, the addition of more sensors increases the number of possible faults.

[0007] The current state of diagnostics available is mainly targeted towards sub-components of the system as a whole. Therefore, each component, such as a valve, would require its own sensor. These lead to numerous sensors creating a significant amount of data. Since this data is specific to a particular component it is difficult for the user to comprehend the diagnostic result of the system as a whole.

[0008] There are also fault localization methodologies, which target the system as a whole. However, these methodologies are applicable only when the movements of actuators in the system are undemanding. The functionality would not sustain if there are multiple

movements at the same instance or even, in some cases, more than one movement at one instance.

[0009] Accordingly, it would be desirable to provide a method and apparatus for diagnosing a fluid power system and for determining which components in a fluid power system may be creating a fault.

Summary Of The Invention:

[0010] The present invention provides a method and apparatus for diagnosing a fluid power system and determining which elements in a fluid power system may be creating a fault.

[0011] The present invention further provides for dividing the system into intervals based on control signals and determining which elements are pressurized during each interval.

[0012] The present invention provides a method of determining increased fluid consumption in a cyclic fluid power system including a plurality of branches which are selectively pressurized. The method includes the steps of:

sensing a fluid flow for the system;

determining a reference fluid consumption value based on the sensed fluid flow;

dividing a system cycle into a plurality of cycle intervals, the cycle intervals being defined by system control signals, and wherein at least one of the cycle intervals includes a plurality of branches that are consuming fluid;

determining an interval fluid consumption reference value of each cycle interval dependant on fluid consumption for each interval;

monitoring a fluid consumption for each system cycle to determine an actual fluid consumption value;

comparing the actual fluid consumption value to the reference fluid consumption value;

in response to the comparison, performing a fault localization process including the steps of;

determining an actual interval fluid consumption value for each of the cycle intervals; and

comparing each actual interval fluid consumption value to a corresponding interval reference value, and in response to the comparison indicating a branch or set of branches which may include a fault.

[0013] The present invention also provides a method of determining leakage in a cyclic fluid power system including a plurality of branches which are selectively pressurized including the steps of:

determining a cycle fluid consumption reference value;

dividing the system cycle into a plurality of cycle intervals corresponding to system control signals;

determining a interval reference value of each cycle interval dependant on fluid consumption for each interval;

monitoring a cycle fluid consumption for each system cycle;

comparing the monitored cycle consumption to the cycle fluid consumption reference value;

determining which system branches are pressurized during each cycle interval;

in response to the comparison, performing a fault localization process including the steps of;

identifying each cycle interval that shows a decrease in fluid consumption over the reference value and storing the components that are pressurized during the identified cycle interval to form a first group of branches;

identifying each cycle interval that shows the same or an increase in fluid consumption over the reference value, and storing the branches that are pressurized during the identified cycle intervals to form a second group of branches;

removing from the second group of branches any branches that are also in the first group of branches; and

indicating the branches remaining in the second group as possibly having a fault.

[0014] The present invention further provides a cyclic fluid power system having fault detection including a plurality of valves, and a plurality of actuators each in fluid communication

with at least one of the valves. A controller is operably connected to the valves and generates system control signals. A flow sensor is disposed in a fluid supply line to the system. A diagnostic component is operatively connected to the flow sensor and the controller. The diagnostic component determines a reference cycle fluid consumption value, and divides the system cycle into a plurality of cycle intervals corresponding to the system control signals. The diagnostic component determines an interval reference value of each cycle interval dependant on a fluid consumption for each interval. The diagnostic unit monitors a cycle fluid consumption for each cycle, and compares the monitored cycle consumption to the cycle fluid consumption reference value. In response to the comparison, the diagnostic unit performs a fault localization process including determining monitored interval fluid consumption values for each of the cycle intervals; and comparing each monitored interval fluid consumption value to the interval reference value for the cycle interval, and in response to the comparison indicating a diagnostic status of the system.

[0015] The present invention also provides a fault localization device for a fluid power cyclic system including a diagnostic unit including a processor and memory. The diagnostic unit is adapted to be in functional communication with system control signals and the output of a system flow sensor. The diagnostic unit determines a reference dataset based on the output of the system flow sensor. The reference dataset is stored in memory. The reference dataset includes fluid consumption information for a plurality of intervals of the system cycle. The diagnostic unit stores in memory a list of system branches which are pressurized during each interval. The diagnostic unit compares the actual air consumption for each of the intervals to the air consumption of the intervals in the reference dataset. As a result of the comparison the diagnostic unit determines which intervals show a decrease in air consumption over the reference dataset and stores the pressurized branches associated with those intervals in a first group. The diagnostic unit determines which intervals show an increase in air consumption over the reference dataset and stores and stores the pressurized branches associated with those intervals in a second group. The diagnostic unit removes from the second group those branches which are also identified in the first group, the diagnostic unit sends a signal to a display which displays the branches remaining in the second group.

[0016] The present invention still further provides a method of triggering a fault localization methodology in a cyclic fluid power system including the steps of :

determining a reference fluid consumption value;

determining a reference pressure value;

calculating a predicted change in fluid consumption value using the reference system fluid consumption value and the reference pressure value;

monitoring the system cycles and determining an actual fluid consumption value for each cycle;

comparing the actual fluid consumption value to the reference system air consumption value to calculate an actual change in fluid consumption for each system cycle;

comparing the actual change in fluid consumption to the predicted change in fluid consumption for each cycle; and

determining when the actual air consumption value exceeds the predicted change in air consumption for a predetermined number of cycles.

Brief Description Of The Drawings:

[0017] Figure 1 is a representation of a fluid power system.

[0018] Figure 2 is a graphical depiction of an air consumption curve divided into a plurality of control signal intervals.

[0019] Figure 3 is a graphical representation of a single interval of the system cycle.

[0020] Figures 4A to 4C are flow diagrams of the diagnostic method of the present invention.

[0021] Figure 5 is a graphical representation of the difference in gradients for each signal interval.

[0022] Figure 6 is a graphical representation of the difference in gradients for each signal interval including the pressurized branches.

[0023] Figure 7 is a graphical representation of the difference in gradients for each signal interval including the pressurized branches grouped to show branches having no faults.

[0024] Figure 8 is a graphical representation of the difference in gradients for each signal interval including the pressurized branches grouped to show branches having faults.

[0025] Figure 9 is a flow chart of a fault localization having a subsystem flow sensor.

Detailed Description Of The Preferred Embodiments:

[0026] The present invention provides for diagnosing a fluid power system and more particularly for determining if there is a fault and locating the source of the fault. Such fault localization includes the ability to predict, based on mathematical manipulation of actual system data, the localized area of the fluid power system which could be affected by a fault such as an increase in fluid consumption, through leakage or other mechanisms.

[0027] The present invention is preferably used to diagnose a cyclic fluid power system. A cyclic system is one in which a series of actions are carried out over and over again. Outside variables acting on the system are preferably the same between cycles. Therefore, the system should perform the same during each cycle. In a cyclic system the parameters, such as fluid consumption, typically remain substantially the same for each cycle. Therefore, changes in parameters between cycles provides information regarding the status of the system. In a preferred embodiment of the present invention, the change in fluid consumption between cycles is used to determine if there is a fault. A change in fluid consumption may, for example, be due to a leakage in a system element or it may be due to a change in flow restrictor. Flow restrictors are typically used to control the speed of an actuator. If the setting of a flow restrictor is improperly changed such that the flow is increased, more air will be consumed and this can be detected.

[0028] With reference to Figure 1, a cyclic fluid power system 10 may include a plurality of actuators 12, 14, 16, 17 controlled by valves 18, 20, 22, 23 and a controller 24. The controller 24 may be a programmable logic controller, PLC, which provides control signals to the valves 18, 20, 22, 23 in accordance with a sequence of preprogrammed instruction in a manner well known in the art. The valves 18, 20, 22, 23 may be solenoid actuated-type valves which are operably connected to the controller via a first conductive paths (not shown). The controller and vales may be mounted together on a sub-base as shown in Figure 1, or alternatively, the valves may be located apart from the controller. Signals generated by the controller 24 cause the valves to shift state and the actuator associated therewith to operate. The actuators may be linear or rotary actuators or other valves. As shown in Figure 1, the actuators 12, 14, 16 and 17 may include linear actuators having piston rods 12a, 14a, 16a, 17a that move, e.g. extend or retract or rotate, based on the shifting of the valves. The actuators may include position proximity sensors 26 to send a signal to the controller 24 via second conductive paths 27 corresponding to the position, e.g. extended or retracted, of the piston rod or other output device.

[0029] In the preferred embodiment, the present invention may include a flow sensor 28 positioned in the fluid supply line 30 of the fluid power system 10 to monitor the fluid supplied to the system. A pressure sensor 31 may also be included to sense the supply pressure. Each of the sensors are operably connected to the controller 24. A display device 32 may be operably connected to the controller and provide an operator with the diagnostic information. The present invention allows for determining the location of a fault even if more than one actuator is being pressurized at the same time.

[0030] The system may further include a diagnostic unit 33 operably connected to the controller 24. The diagnostic unit may be separate from or part of the controller 24. The diagnostic unit 33 may include a microprocessor 33a and memory 33b for storing data to be able to record and evaluate data. The diagnostic unit may be in the form of a personal computer or other type of computer, or processor. The controller and diagnostic unit may carry out their operation based on software, firmware and/or hardware. The diagnostic unit may be operably connected to the controller 24 in order to receive information as to the status of the system such as which valves are being actuated and the position of the actuator output devices.

The diagnostic unit may further be operably connected to the display device 32.

[0031] The fluid power cyclic system 10 may consist of discrete fluid power branches. A branch may include components that are in fluid communication with each other and are pressurized simultaneously. For example referring to Figure 1, when a valve 18 shifts to pressurize an output A, all components which are pressurized by output A constitute a branch. Such components would include the valve 18 the fluid line 34 and the actuator 12 and any fittings between the valve and the actuator. A branch may be pressurized one or more times during a cycle. The fluid expended when the branch is pressurized should be the same every time. However, if there is a leak in the branch, such as in a valve fitting, tubing, or cylinder, the amount of fluid expended when the branch is pressurized will increase. Some examples of where leaks may occur are shown by locations marked X in Figure 1. A fluid power system may include a plurality of branches which are pressurized and exhausted during a system cycle, and a particular branch may be energized multiple times during a cycle. The present invention assists in localizing a fault condition by detecting in which branch, or set of branches, a leak may be occurring such that the appropriate maintenance may be performed in an efficient manner.

[0032] In a preferred embodiment of the present invention, deviations from a normal operating condition are used to determine if a fault exists. When there is no obvious fault evident in the system, a reference status of the system is created in a reference mode. The information obtained in the reference mode is used to create a reference dataset. The determination of the reference status may be performed by the diagnostic unit 33 when the system 10 is new or has been repaired and has no known leaks and is operating properly. The reference mode may be initiated at the selection of a user or it may be automatically initiated upon certain conditions such as system start up.

[0033] With reference to Figures 4A to 4C, reference information is created using data from the flow sensor 28 over a plurality of system cycles, the number of which may be defined by the user. During this reference data creation, the signal from the supply flow sensor 28 is used by the diagnostic unit 33 which calculates the fluid consumption for each cycle, 40. Data from the flow sensor 28 may be obtained over a designated number of system cycles. This data

may be numerically integrated to compute the reference fluid consumption curve for the fluid power system. The end point of the curve for a particular system cycle provides the total fluid consumption for that system cycle.

[0034] During the reference mode two values are calculated using the data from the fluid consumption curves, namely, an average fluid consumption reference value and a total fluid consumption reference value. To obtain the average fluid consumption reference value, the fluid consumption value for each of the designated number of reference cycles, $FC_{Refn,}$ is calculated. The obtained values are then averaged to obtain the average fluid consumption reference value.

$$FC_{Tot\ Ref\ Ave} = (FC_{Ref1} + FC_{Ref2} + FC_{Ref3} + FC_{Refn}) / n$$

[0035] The total fluid consumption reference value, $FC_{Tot\ Ref}$, is the sum of the air consumed for all of the reference cycles. Therefore, this value is created by adding together the fluid consumption values for each of the designated number of system cycles.

$$FC_{Ref} = (FC_{Ref1} + FC_{Ref2} + FC_{Ref3} + FC_{Refn})$$

[0036] In the preferred embodiment, the fluid consumption curves and values are calculated by dividing the flow, Q, by the pressure, P, to determine a C value, C= Q/P. The C value is then integrated to obtain an integrated C curve which corresponds to the fluid consumption. By dividing the flow by the pressure, variations caused by fluctuations in the pressure can be taken into account. It is also within the contemplation of the present invention that fluid consumption values may be created by integrating the flow over the system cycle to obtain a fluid consumption curve without the use of data from a pressure sensor.

[0037] With additional reference to Figures 4A and 2, during each system cycle the controller 24, such as a PLC, will send out a series of control signals to the valves in accordance with a preprogrammed sequence in a manner known in the art. These control signals cause the switching of the valves in order to affect the operation of the actuators. During the reference mode, the sequence 42 and number 44 of the control signals in the system cycles is determined

by the diagnostic unit 33 in order to define control signal intervals. Preferably, every time a control signal changes, this sets the beginning of a new control signal interval. For example, if during the cycle signals A, B and C are high and then signal B goes low, the time from when A, B, and C went high to when signal B went low define a control signal interval. The system cycle, and the fluid consumption curve for the cycle may be divided into a series of intervals, e.g., E1, E2, E3, EN , which correspond to control signal intervals as shown in Figure 2. The change in the control signals results in a change in which branches are pressurized.

[0038] With reference to Figures 3 and 4A, the gradient, also referred to as the slope, is calculated for each control signal interval on the fluid consumption curve by the diagnostic unit, 46. The gradient may be calculated by slope-point method using a predetermined number of samples taken along the beginning and end of the fluid consumption curve. Such a method is set forth in U.S. Patent No. 7,031,850, which is incorporated by reference herein in its entirety. The samples are used to determine base points for forming a line from which a gradient can be calculated over an interval. It is within the contemplation of the present invention that any other method for calculating the gradient may be employed. For example, a best fit straight line method may be used. The gradient indicates an estimate of the fluid consumed by the actuator branches active (moving) during that control signal interval in the fluid power system. The gradient values may be stored in memory as reference gradient values for the recorded succession of control signal intervals. Additionally, the list of pressurized actuator branches during each control signal interval is also stored in memory 48. Accordingly, it can be determined which branches are pressurized at any given control signal interval.

[0039] During the reference mode, the sequence of control signals, and the total number of control signal switches for the total number of reference cycles are also stored in the memory of the diagnostic unit as part of the reference data. Additionally, the gradient of the fluid consumption curve for each control signal interval and the list of pressurized branches for each control signal interval are saved parameters as part of the reference data. These various parameters form a reference dataset that is used for comparison during the monitoring mode.

[0040] With the reference dataset established, the system is then monitored by the diagnostic unit in a monitoring mode to determine if a fault is present in the system. During the monitoring mode actual fluid consumption values are compared to the reference values 50. When the presence of a fault, such as leakage or increase air consumption, in the system is detected, a fault localization methodology is triggered to determine the location of the fault.

[0041] In one embodiment, determining if a fault is present may be achieved by comparing the total fluid consumption for each monitored cycle to the reference average fluid consumption value. If the reference value is exceeded 52, this indicates the presence of a leak. In the preferred embodiment, fault localization methodology may be only triggered if there is a substantial increase in the total fluid consumed by the system. A user may set a predefined threshold above the reference fluid consumption. This threshold may be a tolerance set by an operator. During the monitoring phase, the fluid consumption for each machine cycle is compared with this set threshold. If fluid consumption for the current machine cycles ever exceeds the set threshold, this point acts as the trigger for starting the fault localization methodology 54.

[0042] In a preferred embodiment, the fault localization methodology may begin with a confirmatory step 56 to ensure that an increase in air consumption exists before the methodology is actually triggered. When the average fluid consumption reference value is exceeded by the predetermined threshold, the fluid consumption for a series of predetermined number of subsequent system cycles is monitored by the diagnostic unit. The predetermined number of cycles is preferably the same number of system cycles used to create the reference data. If, for any of these subsequent system cycles, the fluid consumption value goes below the set threshold for fluid consumption, the fault localization methodology may be aborted. For example, if three cycles were used to determine the reference data, after the fluid consumption is detected as being above the set threshold, the next two cycles will be monitored, therefore, three cycles in total are used. If during any of these three cycles the cycle fluid consumption drops below the set threshold, the fault localization methodology will not be implemented. The subsequent cycles will then continue to be monitored, 50. Accordingly, false or errant signals or other aberrations can be accommodated.

[0043] However, if the fluid consumption remains above the threshold for each of the number of cycles used to create reference, then the fault localization methodology is continued. The cycle data recorded from when an increase in fluid consumption is first detected may be used for the computation of the fault localization methodology. It is within the contemplation of the present invention that the number of predetermined cycles may be varied and that the fault localization methodology could be continued even if a predetermined number of cycles are below the fluid consumption threshold.

[0044] In an alternative preferred embodiment, the triggering of the fault localization methodology may take into consideration the effects of system pressure changes. In a pneumatic system, due to the compressibility of air, the amount of air consumed will be directly related to the system pressure of the air. Therefore, if during the monitoring of system cycles, the system pressure increases over the pressure used to calculate the reference dataset, more air will be consumed during the monitoring. This is the case even if there is no leakage or other fault in the system. Conversely, if the system pressure drops during the monitoring, less air will be consumed than during the establishment of the reference dataset. In this case a leak could develop, but as long as the total air consumption was below the reference value, the leak would go undetected.

[0045] Accordingly, the present invention may include a triggering mechanism which accommodates for changes in system pressure. This is achieved by calculating a value which predicts the change in air consumption based on a given change in supply pressure. The actual changes in air consumption are then compared to the predicted change. If the actual change is greater than the predicted change, then this is evidence of a leak in the system and the fault localization methodology may be initiated. If, however, the actual change in air consumption is less than the predicted change, no fault exists and the monitoring continues.

[0046] In order to create the trigger, during the creation of the reference dataset, the average fluid consumption reference value $FC_{Ref\,Ave}$ is calculated. In addition, during the creation of the reference dataset, the average supply pressure for each cycle, P_{Refn}, is captured and the pressure for each cycle is averaged to obtain a reference average pressure value.

$$P_{RefAve} = (P_{Ref1} + P_{Ref2} + P_{Ref3} + P_{Refn}) / n$$

[0047] The fluid consumption value is then divided by the average pressure value to obtain a factor value, FV.

$$FV = FC_{Ref\,Ave} / P_{RefAve}$$

[0048] During the monitoring of the system, the average supply pressure for each cycle, P_n, is computed and a difference is taken with the reference average supply pressure, P_{RefAve}. This obtains the change in pressure, dP.

$$dP = P_{RefAve} - P_n$$

[0049] For each monitored cycle, the total fluid consumption, FC_n, is computed and a difference is taken with the average fluid consumption reference value $FC_{Ref\,Ave}$. This difference is the change in fluid consumption, dFC, over the reference value.

$$dFC = FC_n - FC_{Ref\,Ave}$$

[0050] Next a value, called the Factored value of dAC, FVdAC ,is calculated. The FVdAC value is the change in air consumption that should be exhibited for a known change in supply pressure. This is due to the linear tendencies exhibited between change in supply pressure and the corresponding change in system air consumption. Accordingly, FdAC is a calculated predicted value. The value is calculated as follows:

$$FVdAC = dP * FV$$

[0051] For each monitored system cycle, the value dAC is compared to FVdAC. Therefore, the actual change in system fluid consumption is compared to the calculated, or predicted, change in system air consumption. In the present invention, with a system operating properly it is expected that the actual change in system air consumption, dAC, will be below the

calculated change in system air consumption, FVdAC. Accordingly, an increase in dAC, well above FVdAC, is an abnormal condition and could be affected due to leakage in the system. Accordingly, if the dAC exceeds the FVdAC for a predetermined number of cycles a signal may be generated to trigger the fault localization methodology.

[0052] With reference to Figures 4A and 4B, when the fault localization methodology is initiated 54, the procedure of processing the monitored dataset may be the same as that for the reference dataset, with the exception of the additional procedure of calculating the fault localization result as set forth below. The various steps may be carried out by the diagnostic unit 33.

[0053] During the monitoring mode, data from all sensors is recorded in sets of machine cycles. This data is then appended, so that it may seem contiguous, non-interrupted recorded data. Accordingly, the data from each of the number of monitored cycles is added and the fluid consumption curve is then calculated by integrating the flow signal of the data cumulated from each of the cycles. As in the reference mode, the fluid consumption curve is preferably an integrated C curve such that fluctuations in pressure may be taken into account.

[0054] Next, the sequence of the control signals which switch the valves is determined and stored in a monitored dataset 60. The actual total number of control signals determined during monitoring is also determined 62. The actual total number of control signals is compared to the total number of control signals determined during the reference dataset 64. If the two totals do not match 66, the fault localization methodology is aborted 68. The mismatch may be caused by a faulty sensor and a signal may be generated 70 to alert an operator of the condition. An error message may then be generated, and the process may start over and continue monitoring.

[0055] If the number of control signals in both the reference dataset and the monitored dataset match, then the actual sequence of control signal is compared to the reference sequence 72. If the sequence does not match 74, then the sequence obtained during the monitoring mode is overwritten by the sequence obtained during the reference dataset 76. Such a mismatch may

occur, for example, due to control signals which are switched very close in time resulting in the latter signal to be recorded first. The list of pressurized branches for each control signal interval determined during the monitored dataset is also overwritten by that computed during the reference dataset. This makes the control signal intervals for the monitored mode match that of the reference mode allowing a comparison to be conducted.

[0056] The fluid consumption curve calculated during the monitored dataset is broken up into intervals, based on the control signal intervals in a manner similar to that done during the reference mode. The gradient is calculated from the fluid consumption curve for each control signal interval by the diagnostic unit 78. The gradient for each control signal interval is calculated by the same gradient calculation method used during the creation of the reference dataset.

[0057] With reference to Figure 4C, since the number of control signal intervals, the sequence of control solenoid coil signals, and the list of pressurized branches for each control signal interval are all the same for the reference and the monitored dataset, each control signal interval in the monitored dataset will have a corresponding control signal interval in the reference dataset. This permits the comparison of the actual gradients to the reference gradients 80. The difference of gradients between the monitored and the reference dataset for each control signal interval may be calculated.

[0058] Each system cycle has a number of control signal intervals. In creating the reference dataset, a predetermined number of system cycles are used. The total number of control signal intervals for each cycle are added together to reach a total number of control signal intervals. In the fault localization methodology, the number of control signal intervals that are examined equals the total number of control signal intervals. For example, if the cycle has 5 control signal intervals and 3 cycles were used to create the reference dataset, a total of 15 control signal intervals may be examined.

[0059] With additional reference to Figure 5, for each control signal interval a difference between the actual monitored gradient and the reference gradient is calculated by the diagnostic

unit 33. If the fluid consumed during that control signal interval is greater than that during the reference, the difference in gradient is positive. Conversely, if the fluid consumed during that control signal interval is less than that during the reference, the difference in gradient is negative. In addition, in some cases, if the control signal interval is extremely small, the gradient need not be calculated and it may be allocated a gradient of zero. This comparison is done for the total number of control signal intervals.

[0060] Referring to Figure 6, each control signal interval includes a branch or branches which are pressurized. For example, in the first interval, actuator 1 is extended, as represented by U_ACT1_A, actuator 2 is retracted, as represented by U_ACT2_B, actuator 3 is extended, as represented by U_ACT3_A, etc. The list of pressurized branches is assigned to each interval and this list is stored in memory.

[0061] If the gradient for a control signal interval is greater than 0 during the reference and 0 for that same corresponding control signal interval during the monitoring stage, the difference of gradient allocated for that control signal interval would be 0. If the gradient for a control signal interval during the reference is 0 and greater than 0 for that same corresponding control signal interval during the monitoring, then the difference in gradient would be the gradient of the control signal interval.

[0062] Figures 7 and 8 show a system having both positive and negative difference in gradients. With the difference in gradients calculated, the faulty branches may be predicted. With specific reference to Figure 7, if the difference for an interval is positive, this indicates that more fluid was consumed during the monitored mode than during the reference mode, and therefore there is a leak. Conversely, if the gradient for an interval is negative, less fluid is consumed during the monitoring mode than the reference mode, so there is no leak. A user may set a threshold for the gradient difference in the fault localization methodology, before the start of the monitoring process. There are two types of thresholds: an interval may be determined to have no leakage when the gradient is less than zero or no leakage is determined when the gradient is less than or equal to zero. Experimentally, it has been found that the threshold less than zero gives a more accurate result; however, either threshold may be used.

[0063] In the preferred embodiment, all the control signal intervals which have a difference of gradient of less than zero (i.e. difference of gradients is negative) are sorted out. Next, whichever branches are pressurized during these control signal intervals are categorized as actuator branches which do not have a fault, and make up a first group of branches 82. This information is then stored in memory. A negative gradient means that less fluid was consumed during the monitoring stage than during the reference stage; thereby indicating no leakage in the pressurized branches during the control signal interval.

[0064] With reference to Figure 8, all of the actuator branches which are pressurized during control signal intervals, having either a positive difference in gradient or zero difference in gradient are categorized as actuator branches which possibly have a fault 84. These branches form a second group and are stored in memory.

[0065] It is possible that a particular actuator branch may be pressurized during more than one control signal interval. For example, as shown in Figure 8, branch U_ACT1_A is pressurized during a control signal interval that has a positive difference and during a control signal interval that has a negative difference. In the case where actuator branches are pressurized during control signal intervals with a negative difference of gradients and also during control signal intervals with a difference in gradient of zero or with a positive difference in gradient, these actuator branches are interpreted as having no leakage and are removed from the second group 86. The reasoning is that if a branch were leaking, it would not be found in any control signal interval with a negative gradient.

[0066] The remaining set of actuator branches in the second group each have an equal probability of having a fault. A signal can be sent to a display alerting an operator as to the fault and in which branch or branches the fault is likely to be 88. A list of components associated with each branch may be stored. Therefore, an operator may be provided with a list of components that may have a fault. Since the possible branches that have a fault have been narrowed, it is easier for an operator to repair the system.

[0067] In a preferred embodiment, once the second group of actuator branches is determined, additional steps may be carried out by the diagnostic unit to further increase the accuracy of the diagnostic system. Accordingly, the initial determination of the branches in the second group proves an intermediate diagnostic result.

[0068] The further steps may be used to determine whether there is a leak in the supply line to the system. If each of the control signal intervals has a difference in gradient which is greater than or equal to zero, this is the criteria to predict a fault in the supply line, which provides fluid power to all the actuators in the system. Therefore, in cases where all gradients are $\geq$ zero, the fault is in the supply line in a location after the flow sensor in the supply line towards the direction of the system. A signal may be generated alerting a user of this information 90.

[0069] Additionally, in some systems a particular subsystem branch or branches may be pressurized for relatively long periods of time. For example, a branch may be pressurized toward the beginning of a cycle and remain pressurized until the end of the cycle. If there is a leak in the pressurized branch, it would affect all the control signal intervals subsequent to the branch being pressurized. Therefore, all subsequent intervals would have a positive gradient making it difficult to localize the fault. With reference to Figures 1 and 9, to address this situation the present invention may include an additional flow sensor 36 in the branch or branches which have a long pressurization time. The fluid consumption during the pressurization of this actuator branch is computed during the reference and also during the monitoring phase. Similar to the threshold for system fluid consumption, the user can set a threshold for exceeding fluid consumption for the subsystem.

[0070] Various scenarios are possible as shown in Figure 9. For example, if the methodology output, O/P, identifies one or more branches and if the fluid consumption, F. C., for the sensed actuator branch is exceeded then the sensed actuator branch may be added to the group of branches with a possible leak, Case V. If the sensed actuator branch also figures in the intermediate diagnostic results of the fault localization methodology, then this actuator branch alone is the diagnosed branch and the user may be informed that this is the branch with a fault.

If the methodology identifies one or more branches and if the fluid consumption for the sensed actuator branch is not exceeded then the sensed actuator branch may be subtracted from the group of branches with a possible leak, Case VI. If the fault localization methodology does not identify any faulty branches, and if a branch has a flow sensor which shown an increase in fluid consumption, F. C., then that branch may be identified as having a leak, Case III. If no branches are identified and the sensed branch does not exceed the reference fluid consumption, then no branch will be identified as having a leak, Case II. As shown in Cases I and IV no additional information is provided to the intermediate results absent a branch flow sensor.

[0071] During the operation of a system, one of the system elements such as an actuator may develop a fault, other than a leak, that would affect its air consumption. For example, a pneumatic cylinder may not reach its intended position during the system cycle. This may happen for example if a piston rod bends or if a flow control is improperly set. This failure can be detected since the cylinder will fail to activate its position sensor. Therefore, the position proximity sensors 26 disposed on actuators 12, 14, 16, and 17 may be employed to assist in fault detection. If an actuator fails to activate a position sensor, that actuator may be excluded from the diagnostic process, or if it occurs during the fault localization methodology, this methodology could be ended. In any event, a signal could be generated to alert an operator of the problem.

[0072] By limiting the number of sensors and other diagnostic components, the present invention reduces component costs and limits the complexity and computational speed of the diagnostic unit. The present invention provides an effective way of locating a fault and permits for expedited repair of a system with multiple components and multiple actions occurring simultaneously.

[0073] While there have been described what is presently believed to be the preferred embodiments to the invention, those skilled in the art will realize that various changes and modifications may be made to the invention without departing from the scope of the invention, and it is intended to claim all such changes and modifications that fall within the true scope of the invention.

Claims:

1. A method of determining increased fluid consumption in a cyclic fluid power system including a plurality of branches which are selectively pressurized comprising the steps of:

sensing a fluid flow for the system;

determining a reference fluid consumption value based on the sensed fluid flow;

dividing a system cycle into a plurality of cycle intervals, the cycle intervals being defined by system control signals, and wherein at least one of the cycle intervals includes a plurality of branches that are consuming fluid;

determining an interval fluid consumption reference value of each cycle interval dependant on fluid consumption for each interval;

monitoring a fluid consumption for each system cycle to determine an actual fluid consumption value;

comparing the actual fluid consumption value to the reference fluid consumption value;

in response to the comparison, performing a fault localization process including the steps of;

determining an actual interval fluid consumption value for each of the cycle intervals; and

comparing each actual interval fluid consumption value to a corresponding interval reference value, and in response to the comparison indicating a branch or set of branches which may include a fault.

2. The method as defined in claim 1, further comprising the steps of:

determining which branches are pressurized during each cycle interval;

identifying each cycle interval that shows a decrease in fluid consumption over the reference value and identifying the branches that are pressurized during the identified cycle interval to form a first group of branches.

3. The method as defined in claim 2, further comprising the steps of identifying cycle intervals which show the same or an increase in fluid consumption over the reference value, and

storing the branches that are pressurized during the identified cycle intervals to form a second group of branches.

4. The method as defined in claim 3, further comprising the steps of removing from the second group of branches any branches that are also in the first group of branches; and

indicating the branches remaining in the second group as branches possibly having a fault.

5. The method as defined in claim 4, further including the step of identifying which components form each of the branches.

6. The method as defined in claim 1, further comprising the step of integrating the flow of the system to determine a fluid consumption curve, and wherein the fluid consumption curve is used to determined the reference cycle fluid consumption value.

7. The method as defined in claim 1, wherein the reference cycle fluid consumption value is determined using the integral of the fluid flow.

8. The method as defined in claim 6, wherein the reference interval value and the actual interval value are determined by calculating a gradient of the fluid consumption curve for a potion corresponding to the interval.

9. The method as defined in claim 1, wherein the system control signals include signals adapted to switch valves in the system.

10. The method as defined in claim 9, wherein the system control signals are generated by a PLC.

11. The method as defined in claim 1, wherein determining the interval fluid consumption reference value for each cycle interval includes calculating a fluid consumption curve based on

the sensed fluid flow, and determining the gradient of the fluid consumption curve for each cycle interval.

12. The method as defined in claim 11, wherein the gradient for each of the cycle intervals is compared to a corresponding interval reference value.

13. The method as defined in claim 1, further comprising the steps of:

monitoring the cycle fluid consumption for a predetermined number of cycles;

determining if the cycle fluid consumption for any of the predetermined number of cycles is less than the cycle reference fluid consumption value, and if so, terminating the fault localization process.

14. The method as defined in claim 13, wherein the predetermined number of cycles equals a number of cycles used to determine the reference fluid consumption value.

15. The method as defined in claim 1, further comprising the steps of determining a reference number of system control signals, and the fault localization process further included the step of comparing the reference number to an actual number of actuator signals, and if there is a difference then terminating the fault localization process.

16. The method as defined in claim 1, further comprising the step of determining a reference sequence of system control signals, and the fault localization process further including the step of comparing the reference sequence to an actual signal sequence, and if there is a difference then replacing the actual sequence with the reference sequence.

17. The method as defined in claim 1, further comprising the steps of determining a branch fluid consumption value for at least one of the branches, and determining a change in fluid consumption for the at least one branch.

18. The method as defined in claim 1, further comprising the steps of monitoring a system pressure,

calculating a predicted change in fluid consumption value using the fluid consumption reference value and the system pressure,

comparing an actual fluid consumption value to a reference system air consumption value to calculate an actual change in fluid consumption for each system cycle;

comparing the actual change in fluid consumption to the predicted change in fluid consumption for each cycle;

initiating the fault localization methodology when the actual air consumption value exceeds the predicted change in air consumption for a predetermined number of system cycles.

19. A method of determining leakage in a cyclic fluid power system including a plurality of branches which are selectively pressurized comprising the steps of:

determining a fluid consumption reference value;

dividing the system cycle into a plurality of cycle intervals corresponding to system control signals;

determining an interval reference value of each cycle interval dependant on fluid consumption;

monitoring a cycle fluid consumption for each system cycle;

comparing the monitored cycle consumption to the cycle fluid consumption reference value;

determining which system branches are pressurized during each cycle interval;

in response to the comparison, performing a fault localization process including the steps of;

identifying each cycle interval that shows a decrease in fluid consumption over the reference value and storing the components that are pressurized during the identified cycle interval to form a first group of branches;

identifying each cycle interval that shows the same or an increase in fluid consumption over the reference value, and storing the branches that are pressurized during the identified cycle intervals to form a second group of branches;

removing from the second group of branches any branches that are also in the first group of branches; and

indicating the branches remaining in the second group as possibly having a fault.

20. A cyclic fluid power system having fault detection comprising:

a plurality of valves;

a plurality of actuators each in fluid communication with at least one of the valves;

a controller operably connected to the valves and generating valve switching signals;

a flow sensor disposed in a fluid supply line to the system;

a diagnostic unit operatively connected to the flow sensor and the controller, the diagnostic component:

determining a reference cycle fluid consumption value;

dividing the system cycle into a plurality of cycle intervals corresponding to system control signals;

determining an interval reference value of each cycle interval dependant on fluid consumption for each interval;

monitoring a cycle fluid consumption for each cycle;

comparing the monitored cycle consumption to the cycle fluid consumption reference value;

in response to the comparison, determining monitored interval fluid consumption values for each of the cycle intervals; and

comparing each monitored interval fluid consumption value to the interval reference value for the cycle interval, and in response to the comparison indicating a diagnostic status of the system.

21. The system as defined in claim 20, wherein the system further includes a display for indicating the diagnostic status of the system.

22. A fault localization device for a fluid power cyclic system comprising:

a diagnostic unit including a processor and memory, the diagnostic unit being adapted to be in functional communication with system control signals and the output of a system flow sensor, the diagnostic unit determines a reference dataset based on the output of the system flow sensor, the reference dataset is stored in memory, the reference dataset includes fluid consumption information for a plurality of intervals of the system cycle, the diagnostic unit stores in memory a list of system branches which are pressurized during each interval, the

diagnostic unit compares the actual air consumption for each of the intervals to the air consumption of the intervals in the reference dataset, as a result of the comparison the diagnostic unit determines which intervals show a decrease in air consumption over the reference dataset and stores the pressurized branches associated with those intervals in a first group, the diagnostic unit determines which intervals show an increase in air consumption over the reference dataset and stores and stores the pressurized branches associated with those intervals in a second group, the diagnostic unit removes from the second group those branches which are also identified in the first group, the diagnostic unit sends a signal to a display which displays the branches remaining in the second group.

23. A method of triggering a fault localization methodology in a cyclic fluid power system comprising the steps of:

determining a reference fluid consumption value;

determining a reference pressure value;

calculating a predicted change in fluid consumption value using the reference system fluid consumption value and the reference pressure value;

monitoring the system cycles and determining an actual fluid consumption value for each cycle;

comparing the actual fluid consumption value to the reference system air consumption value to calculate an actual change in fluid consumption for each system cycle;

comparing the actual change in fluid consumption to the predicted change in fluid consumption for each cycle; and

determining when the actual air consumption value exceeds the predicted change in air consumption for a predetermined number of cycles.

24. The method as defined in claim 23, wherein when the actual air consumption value exceeds the predicted change in air consumption for a predetermined number of cycles initiating a methodology for locating a system fault.

25. The method as defined in claim 23, wherein calculating the predicted change in air consumption value includes calculating and average total fluid reference consumption, $FC_{Tot\ Ref\ Ave}$

calculating a reference average pressure value, P_{RefAve}

calculating a factor value FV by the equation $FC_{Tot\ Ref\ Ave} / P_{RefAve}$,

26. The method as defined in claim 25, further including the step of calculating the average pressure for each cycle and comparing that value to P_{RefAve} to obtain a pressure change value, dPn.

27. The method as defined in claim 26, further including the step of determining the total fluid consumption for each system cycle and comparing that value to the $FC_{Tot\ Ref\ Ave}$ value to determine a change in air consumption, dFC, from the reference value.

28. The method as defined in claim 26, wherein calculating the predicted change in fluid consumption value FVdAC includes the step of

FVdAC = dPn * FV

29. The method as defined in claim 26, further including the steps of comparing the dFC value to FVdAC for each cycle, and if the dFC exceeds the FVdAC for a predetermined number of steps, initiating the fault localization methodology.

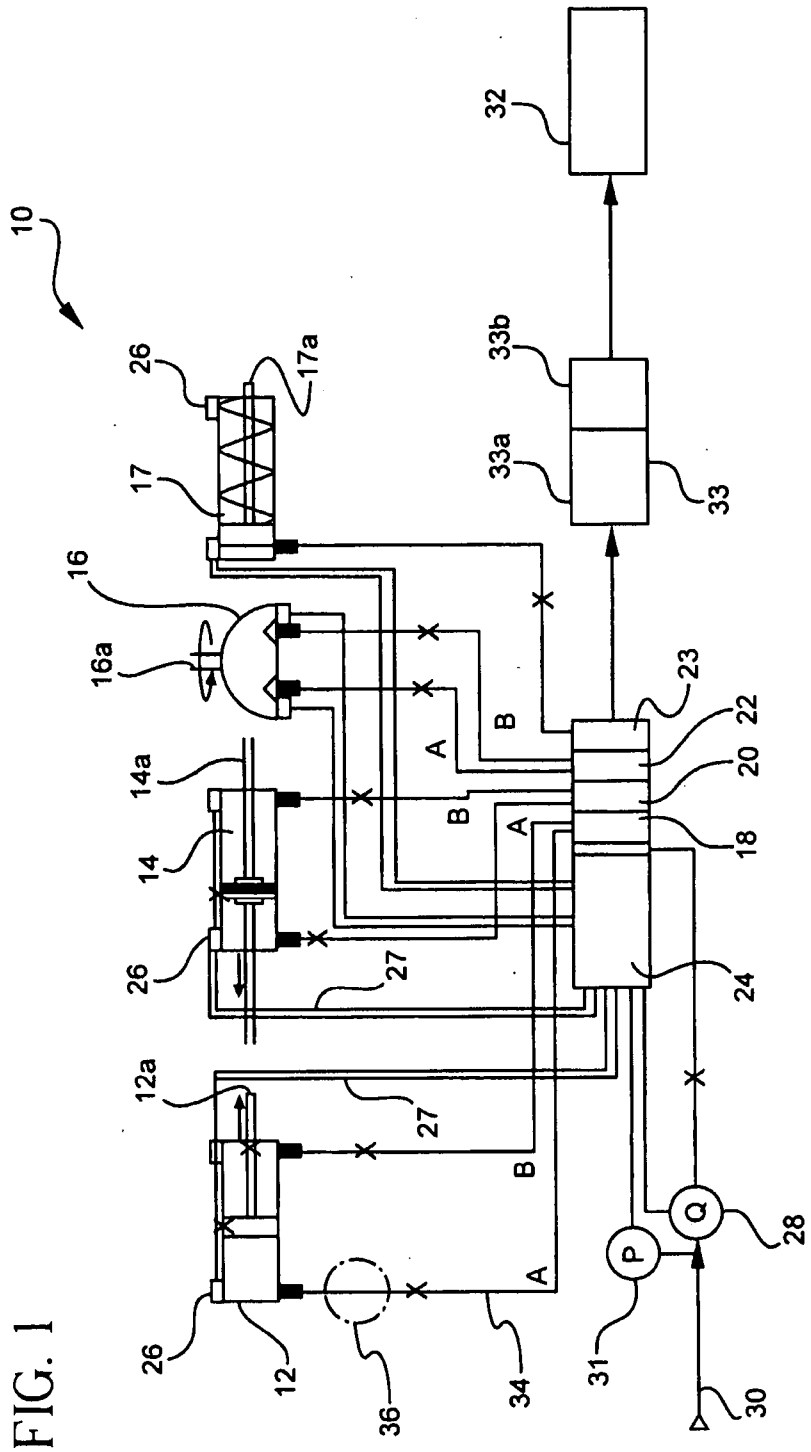

10
32
33b
33a
33
26
17a
17
16
16a
14a
14
26
27
12a
27
26
12
36
34
A
B
B
A
B
A
23
22
20
18
24
P
Q
28
31
30

FIG. 1

FIG. 2

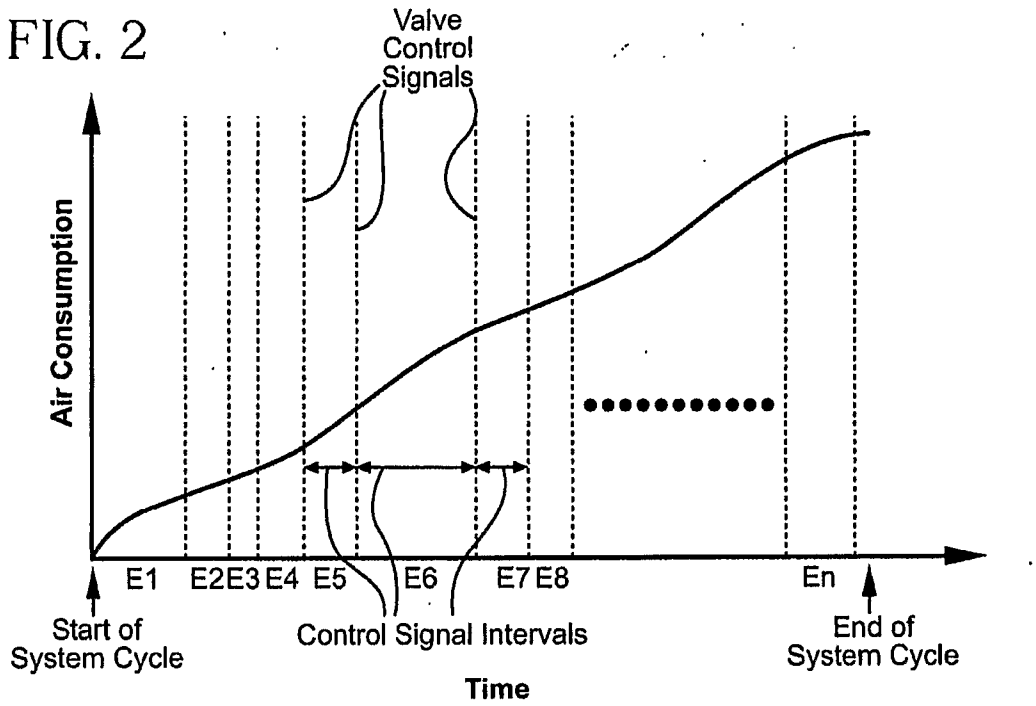

Valve
Control
Signals
Air Consumption
E1
E2
E3
E4
E5
E6
E7
E8
En
Start of
System Cycle
Control Signal Intervals
End of
System Cycle
Time

FIG. 3

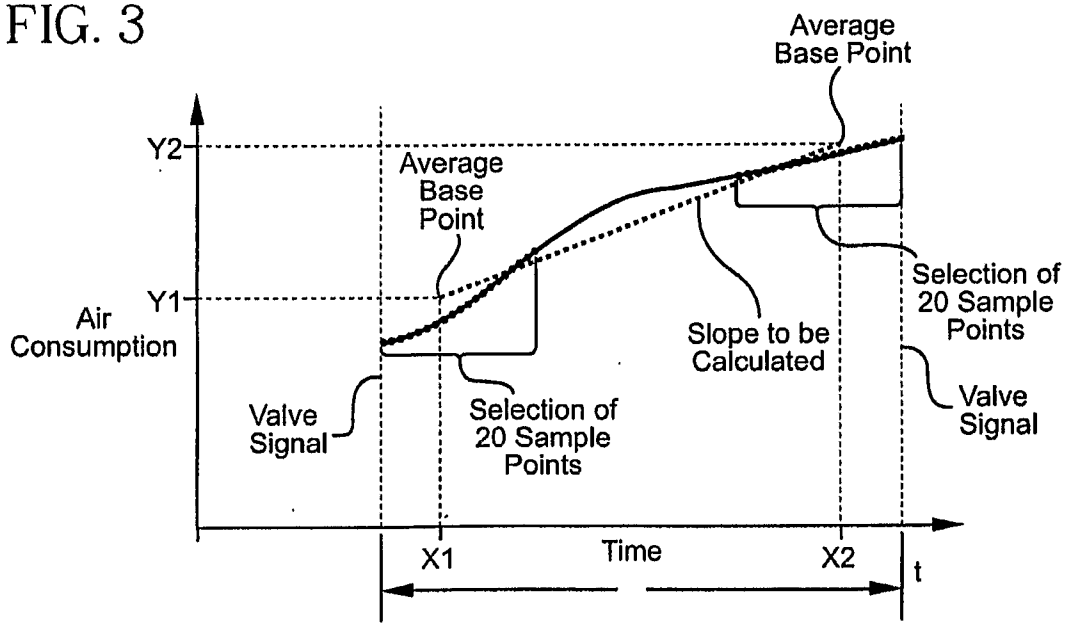

Average
Base Point
Y2
Average
Base
Point
Y1
Air
Consumption
Selection of
20 Sample
Points
Slope to be
Calculated
Valve
Signal
Valve
Signal
Selection of
20 Sample
Points
X1
Time
X2
t

FIG. 4A

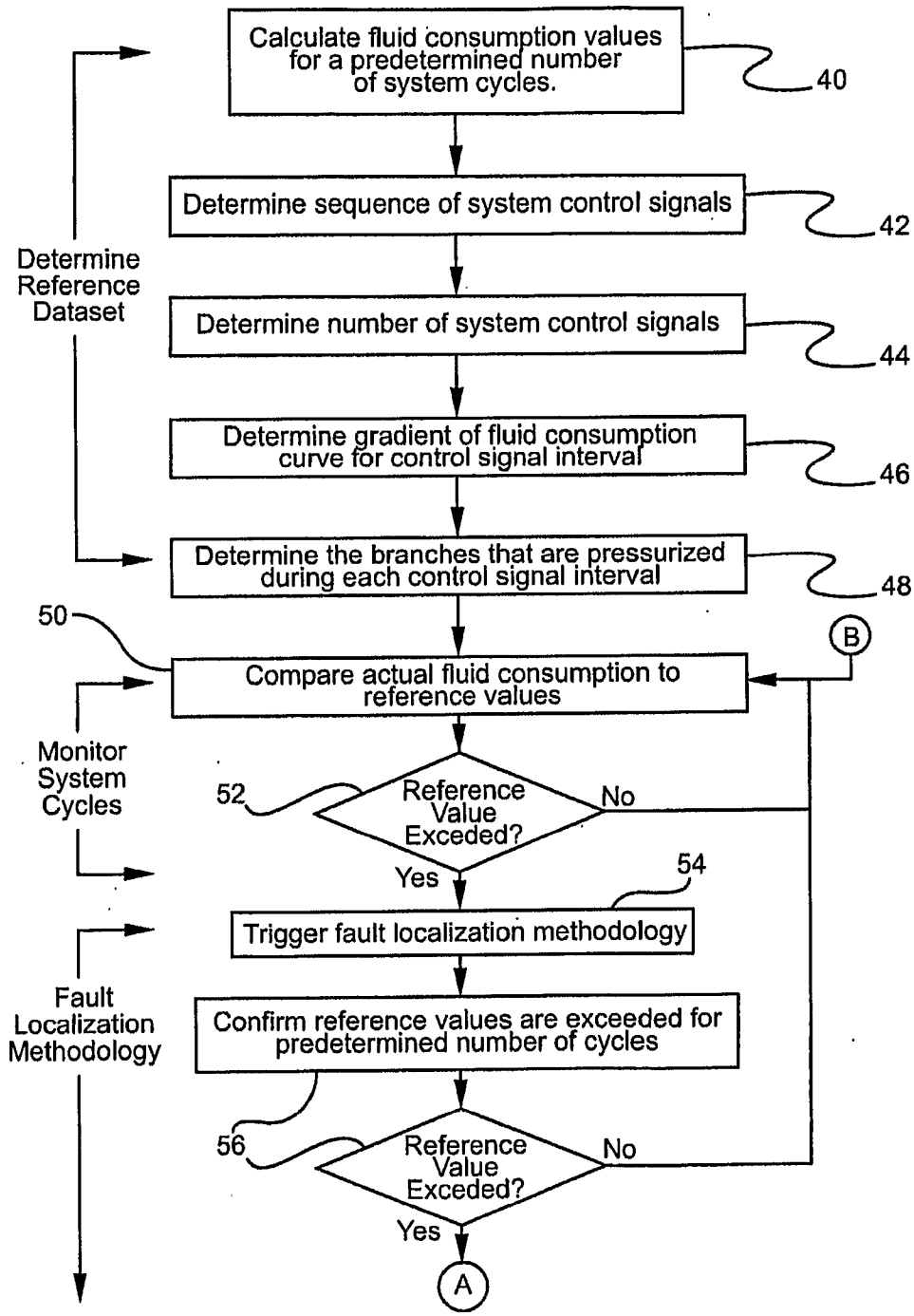

Calculate fluid consumption values for a predetermined number of system cycles.
40
Determine sequence of system control signals
42
Determine number of system control signals
44
Determine gradient of fluid consumption curve for control signal interval
46
Determine the branches that are pressurized during each control signal interval
48
Determine Reference Dataset
50
Compare actual fluid consumption to reference values
B
Monitor System Cycles
52
Reference Value Exceeded?
No
Yes
54
Trigger fault localization methodology
Fault Localization Methodology
Confirm reference values are exceeded for predetermined number of cycles
56
Reference Value Exceeded?
No
Yes
A

FIG. 4B

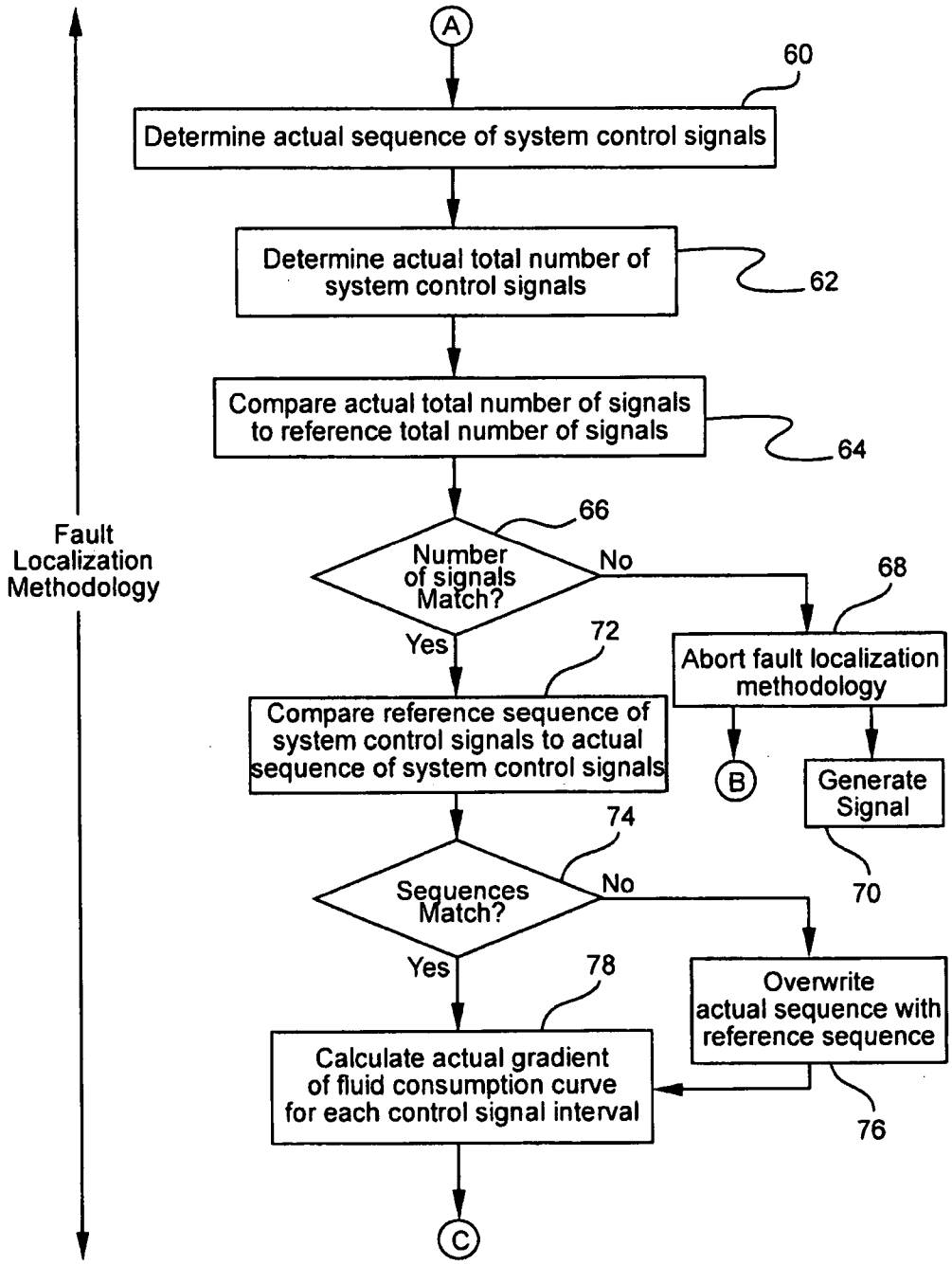

Fault Localization Methodology
A
60
Determine actual sequence of system control signals
Determine actual total number of system control signals
62
Compare actual total number of signals to reference total number of signals
64
66
Number of signals Match?
No
68
Yes
72
Abort fault localization methodology
Compare reference sequence of system control signals to actual sequence of system control signals
B
Generate Signal
70
74
Sequences Match?
No
Yes
78
Overwrite actual sequence with reference sequence
Calculate actual gradient of fluid consumption curve for each control signal interval
76
C

FIG. 4C

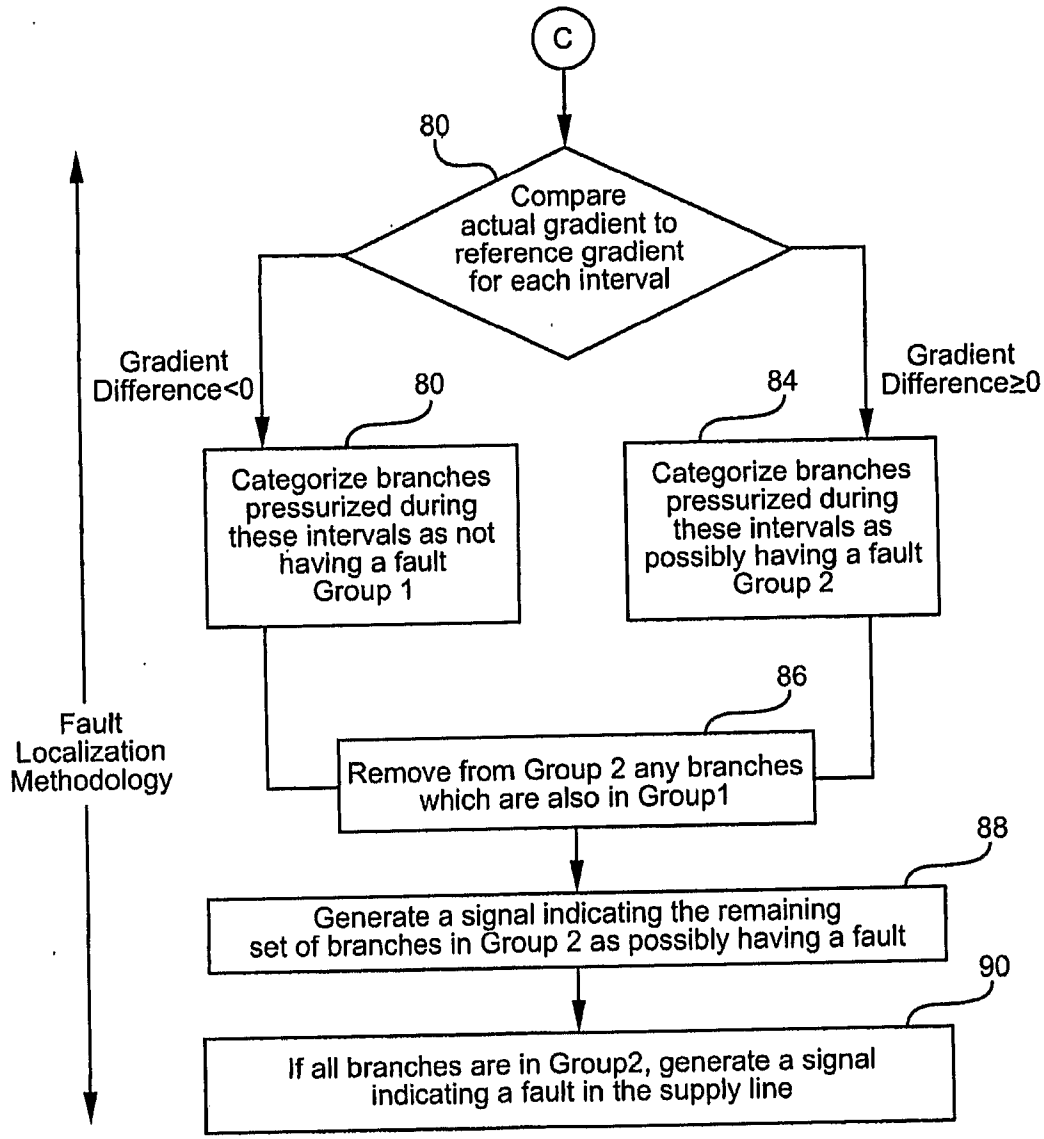

C
80
Compare actual gradient to reference gradient for each interval
Gradient Difference<0
Gradient Difference≥0
80
84
Categorize branches pressurized during these intervals as not having a fault Group 1
Categorize branches pressurized during these intervals as possibly having a fault Group 2
86
Remove from Group 2 any branches which are also in Group1
88
Generate a signal indicating the remaining set of branches in Group 2 as possibly having a fault
90
If all branches are in Group2, generate a signal indicating a fault in the supply line
Fault Localization Methodology

FIG. 5

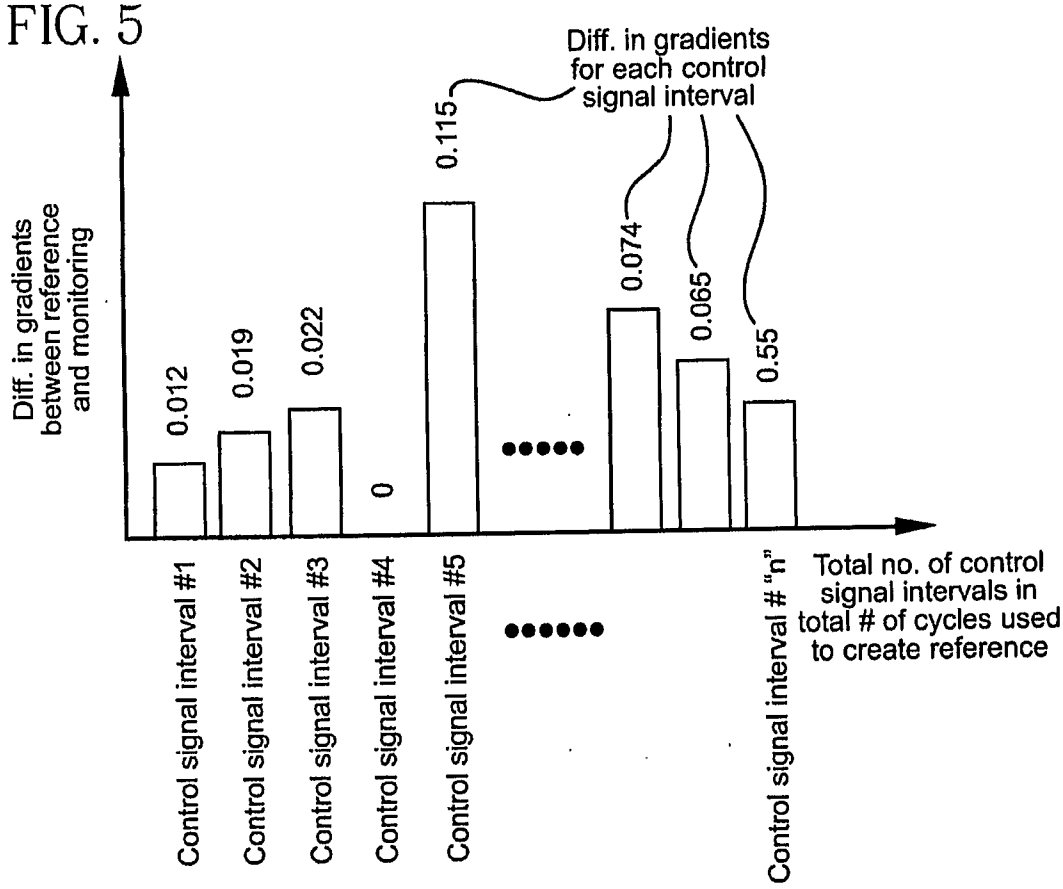

Diff. in gradients between reference and monitoring
Diff. in gradients for each control signal interval
0.012
0.019
0.022
0
0.115
0.074
0.065
0.55
Control signal interval #1
Control signal interval #2
Control signal interval #3
Control signal interval #4
Control signal interval #5
Control signal interval # "n"
Total no. of control signal intervals in total # of cycles used to create reference

FIG. 6

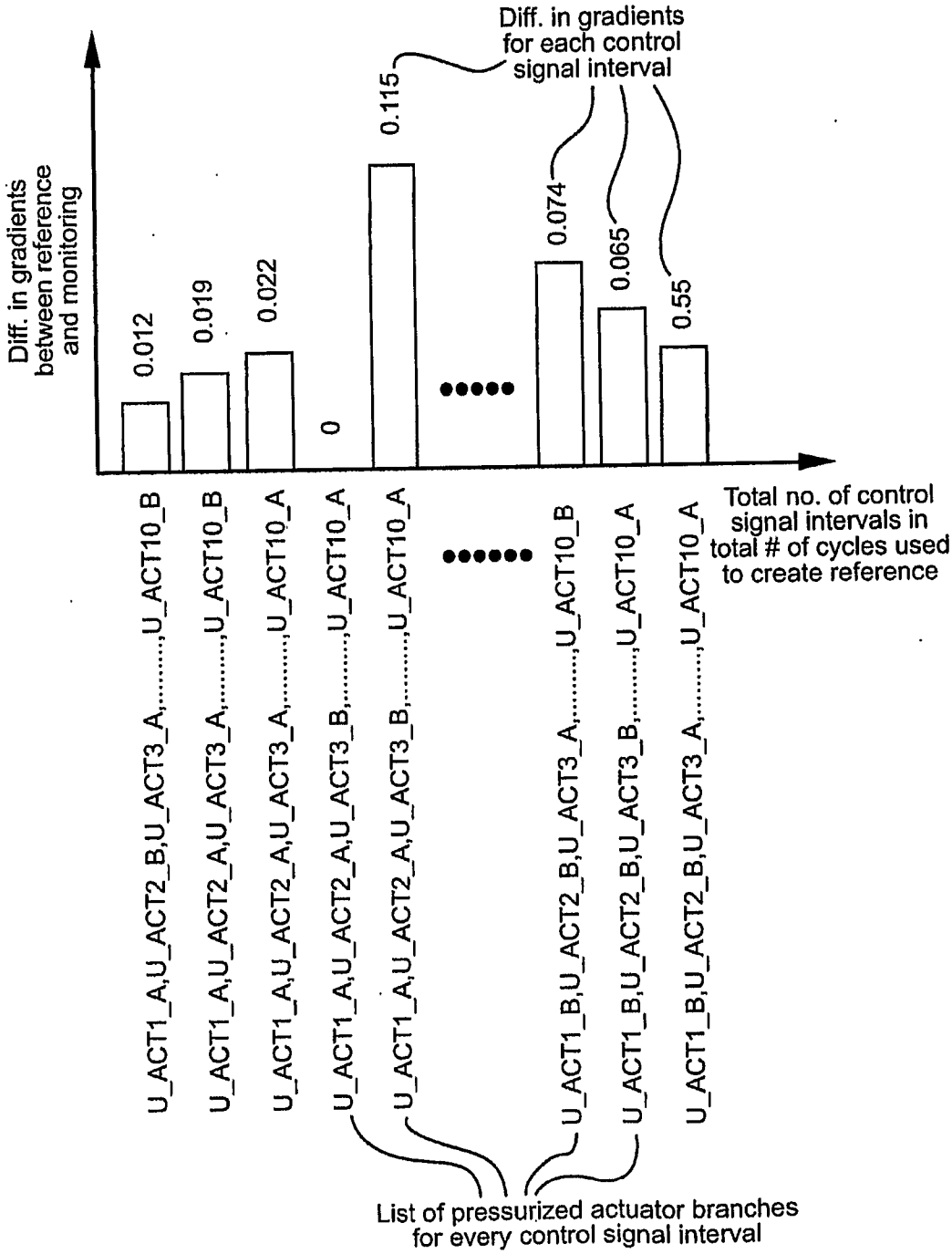

Diff. in gradients between reference and monitoring
Diff. in gradients for each control signal interval
0.012
0.019
0.022
0
0.115
0.074
0.065
0.55
Total no. of control signal intervals in total # of cycles used to create reference
U_ACT1_A,U_ACT2_B,U_ACT3_A,.....,U_ACT10_B
U_ACT1_A,U_ACT2_A,U_ACT3_A,.....,U_ACT10_B
U_ACT1_A,U_ACT2_A,U_ACT3_A,.....,U_ACT10_A
U_ACT1_A,U_ACT2_A,U_ACT3_B,.....,U_ACT10_A
U_ACT1_A,U_ACT2_A,U_ACT3_B,.....,U_ACT10_A
U_ACT1_B,U_ACT2_B,U_ACT3_A,.....,U_ACT10_B
U_ACT1_B,U_ACT2_B,U_ACT3_B,.....,U_ACT10_A
U_ACT1_B,U_ACT2_B,U_ACT3_A,.....,U_ACT10_A
List of pressurized actuator branches for every control signal interval

FIG. 7

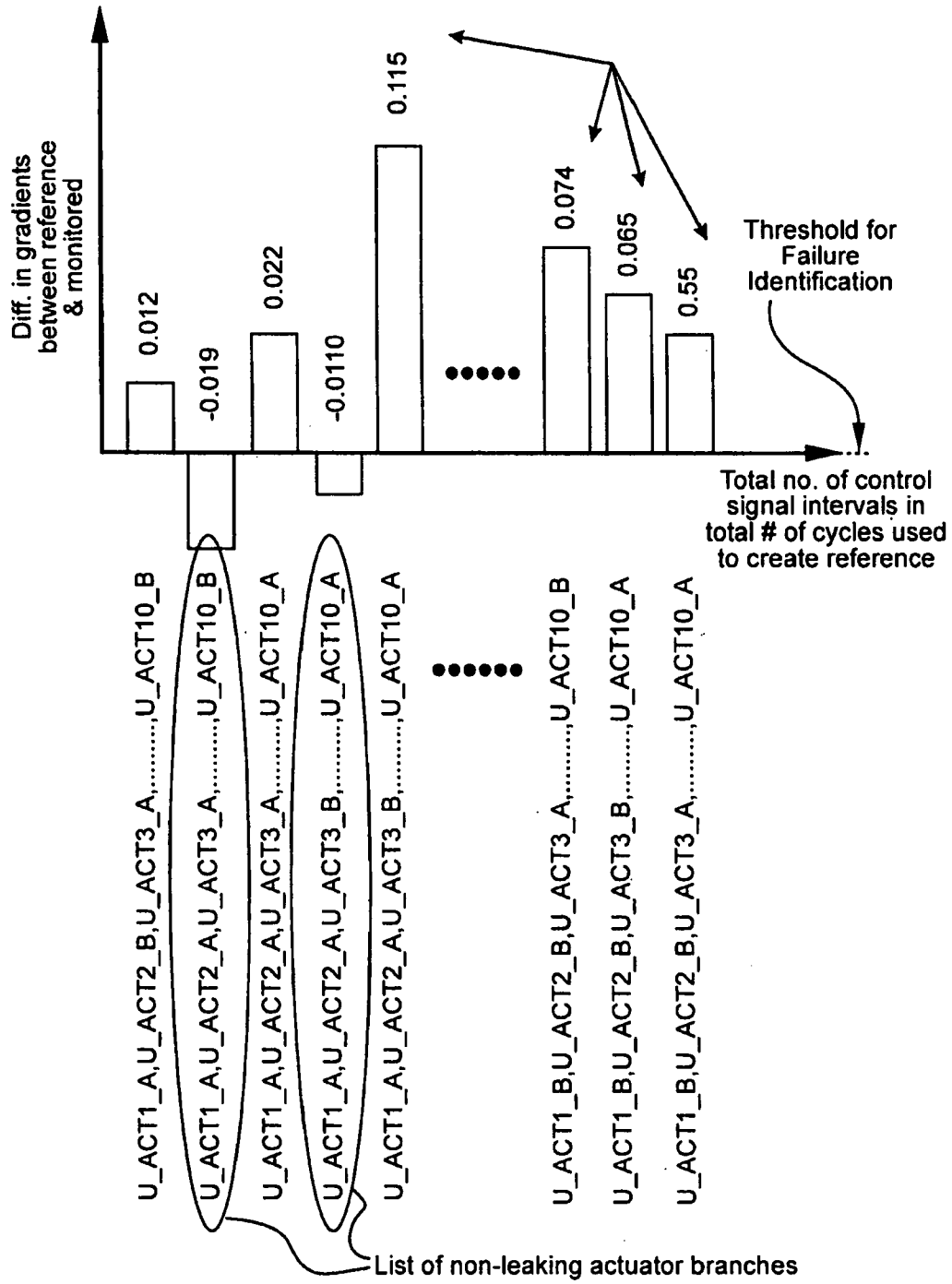
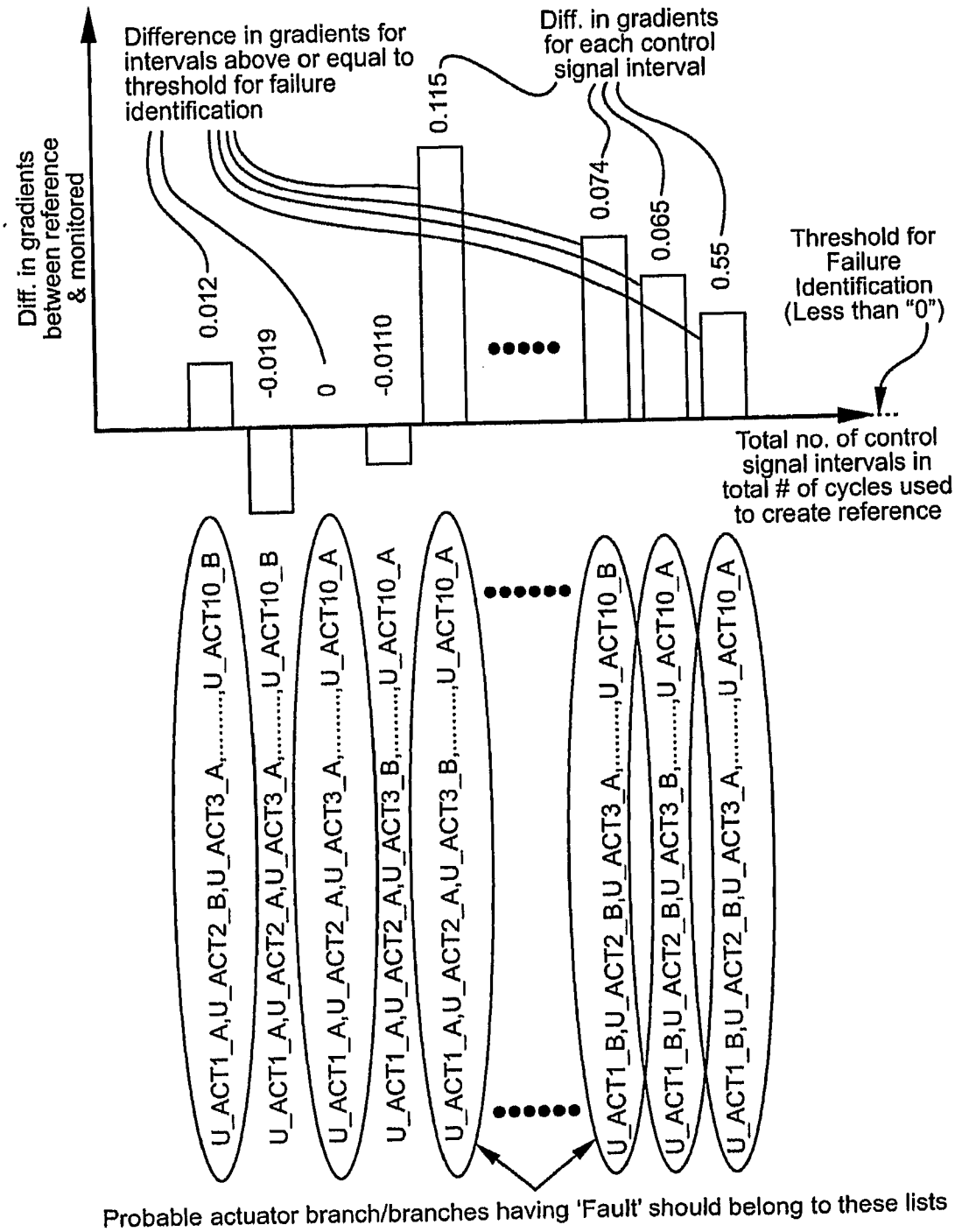

Diff. in gradients between reference & monitored
0.012
-0.019
0.022
-0.0110
0.115
0.074
0.065
0.55
Threshold for Failure Identification
Total no. of control signal intervals in total # of cycles used to create reference
U_ACT1_A,U_ACT2_B,U_ACT3_A,.....,U_ACT10_B
U_ACT1_A,U_ACT2_A,U_ACT3_A,.....,U_ACT10_B
U_ACT1_A,U_ACT2_A,U_ACT3_A,.....,U_ACT10_A
U_ACT1_A,U_ACT2_A,U_ACT3_B,.....,U_ACT10_A
U_ACT1_A,U_ACT2_A,U_ACT3_B,.....,U_ACT10_A
U_ACT1_B,U_ACT2_B,U_ACT3_A,.....,U_ACT10_B
U_ACT1_B,U_ACT2_B,U_ACT3_B,.....,U_ACT10_A
U_ACT1_B,U_ACT2_B,U_ACT3_A,.....,U_ACT10_A
List of non-leaking actuator branches

FIG. 8


Diff. in gradients between reference & monitored
Difference in gradients for intervals above or equal to threshold for failure identification
Diff. in gradients for each control signal interval
0.012
-0.019
0
-0.0110
0.115
0.074
0.065
0.55
Threshold for Failure Identification (Less than "0")
Total no. of control signal intervals in total # of cycles used to create reference
U_ACT1_A,U_ACT2_B,U_ACT3_A,.....,U_ACT10_B
U_ACT1_A,U_ACT2_A,U_ACT3_A,.....,U_ACT10_B
U_ACT1_A,U_ACT2_A,U_ACT3_A,.....,U_ACT10_A
U_ACT1_A,U_ACT2_A,U_ACT3_B,.....,U_ACT10_A
U_ACT1_A,U_ACT2_A,U_ACT3_B,.....,U_ACT10_A
U_ACT1_B,U_ACT2_B,U_ACT3_A,.....,U_ACT10_B
U_ACT1_B,U_ACT2_B,U_ACT3_B,.....,U_ACT10_A
U_ACT1_B,U_ACT2_B,U_ACT3_A,.....,U_ACT10_A
Probable actuator branch/branches having 'Fault' should belong to these lists

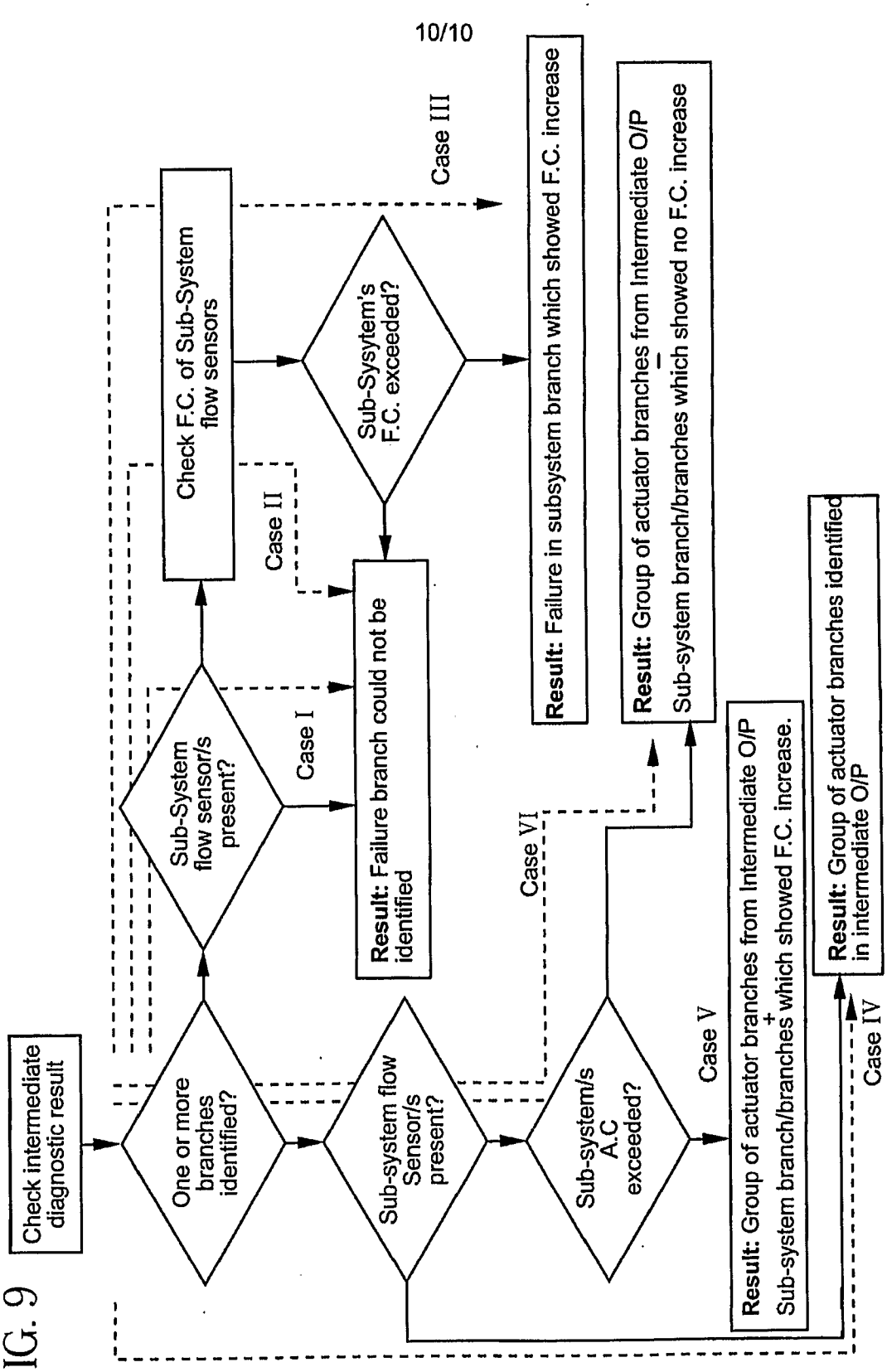

Check intermediate diagnostic result
One or more branches identified?
Sub-System flow sensor/s present?
Case I
Result: Failure branch could not be identified
Case II
Check F.C. of Sub-System flow sensors
Sub-Sysytem's F.C. exceeded?
Case III
Result: Failure in subsystem branch which showed F.C. increase
Sub-system flow Sensor/s present?
Case VI
Result: Group of actuator branches from Intermediate O/P
Sub-system branch/branches which showed no F.C. increase
Sub-system/s A.C exceeded?
Case V
Result: Group of actuator branches from Intermediate O/P
+
Sub-system branch/branches which showed F.C. increase.
Result: Group of actuator branches identified in intermediate O/P
Case IV

FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US07/03887

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G01F 17/00 (2007.10)
USPC - 702/51
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)
IPC(8) -G01F 17/00, G01F 23/00, G01L 07/00, G01N 11/00, G06F 19/00 (2007.10)
USPC - 702/51

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)
PUBWEST, MicroPatent, IP.com, DialogPro, IEEE XPLORE, GOOGLE SCHOLAR ADVANCED

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 7,031,850 B2 (KAMBLI et al) 18 April 2006 (18.04.2006) entire document	1-24
A	US 7,124,057 B2 (FORSTER et al) 17 October 2006 (17.10.2006) entire document	1-29
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