(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 0 741 858 B1

(12) **EUROPEAN PATENT SPECIFICATION**

(45) Date of publication and mention of the grant of the patent:
12.08.1998 Bulletin 1998/33

(21) Application number: **95908616.6**

(22) Date of filing: **17.01.1995**

(51) Int Cl.[6]: **G01D 18/00**, G01D 3/02, G01D 3/028

(86) International application number:
PCT/US95/00835

(87) International publication number:
WO 95/20141 (27.07.1995 Gazette 1995/32)

(54) **TRANSMITTER WITH IMPROVED COMPENSATION**

WANDLER MIT VERBESSERTER KOMPENSATION

TRANSDUCTEUR A COMPENSATION AMELIOREE

(84) Designated Contracting States:
DE FR GB

(30) Priority: **25.01.1994 US 186288**

(43) Date of publication of application:
13.11.1996 Bulletin 1996/46

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EP-A- 0 363 958

- **PATENT ABSTRACTS OF JAPAN vol. 14 no. 367 (M-1008) ,9 August 1990 & JP,A,02 133215 (MITSUBISHI ELECTRIC CORP) 22 May 1990,**

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EP 0 741 858 B1

Description

BACKGROUND OF THE INVENTION

This invention relates to a technique for compensating a sensed variable, where the variable can be representative of position as in a process automation application, or representative of some other physical variable such as pressure, temperature, pH, optical intensity as in a process control industry application. More particularly, the invention applies to devices, such as transmitters, actuators and positioners, which compensate a sensed variable to provide an output representative of the variable.

There is a need to improve the accuracy with which measurement transmitters and devices with actuated outputs, such as a positioner, compensate outputs representative of process variables. Measurement transmitters sense process variables such as pressure, temperature, flow, pH, position, displacement, velocity and the like in a process control or process automation installation. Transmitters have analog-to-digital (A/D) converters for digitizing sensor outputs representative of sensed process variable and a compensation circuit for compensating the repeatable errors in the digitized process variable outputs. Temperature is one of the main sources of the error. The compensation circuit typically comprises a microprocessor which calculates the compensated process variable output with long polynomial functions selected to fit the error characteristics of the sensor over a span of pressures. Constants in the long polynomial function are individually selected to each sensor. During manufacture, individual testing of each sensor generates a set of characterization constants related to the sensor errors which is later stored in a transmitter EEPROM. Using this compensation scheme, process variables can typically be corrected to an accuracy of .05% over the span of the primary process variable which the transmitter measures. For example, known pressure transmitters having a span of 0 to 3810 mm (150 inches) of water provide corrected pressures within .05% accuracy. Limited electrical power and limited time to compute the output make it difficult to complete more complex computation needed to improve accuracy.

Errors in the operating characteristic of the sensor can be a complex, sometimes non-linear function of many variables. The primary variable (the variable which is compensated), contributes directly to the error, while secondary process variables (which affect the measurement of the primary process variables) contribute indirectly to the error. As the need for accuracy increases, contributions of secondary variables become significant. Current approaches solve this quandary with high order polynomials in multiple process variables, but the resulting equation is arithmetically ill-conditioned and sensitive to the manner in which the polynomial is computed, in that overflows may occur. One transmitter compensation equation is an eleventh order polynomial with approximately 100 terms in three variables, which must be calculated each time the transmitter outputs a process variable. Generating characterization constants for these high order polynomials is costly and time consuming. Furthermore, this approach cannot optimally capture the real behavior of the non-linear process variables, which interact nonlinearly.

In addition to concerns of software and computational complexity, power consumption is critical for transmitters which receive all their operating power over the same wires used for communication. Furthermore, some "intrinsically safe" areas where transmitters are installed limit the transmitter's available power. The finite current budget not only limits the number and complexity of the calculations, but impacts the functionality able to be incorporated in the transmitter. For example, A/D converters could convert digitized sensor outputs more rapidly if more power were available, thereby increasing the transmitter update rate. An EEPROM large enough to accommodate all the characterization constants also consumes power which would otherwise provide additional functionality.

There is thus a need for an accurate method for compensating process variables which is computationally simple and requires small numbers of stored characterization constants, so as to consume a reduced amount of power and provide excess power for additional functionality and increased update rates in the transmitter.

SUMMARY OF THE INVENTION

In an embodiment, a measurement transmitter has a sensor for sensing a process variable (PV) such as pressure and digitizing means for digitizing an output representative of the sensed PV. The sensor senses the PV within a span of PV values. A memory inside the transmitter stores at least two membership functions, each membership function having a non-zero value over a predetermined region of the PV span and a substantially zero value over the remainder of the span. The memory also stores a set of compensation formulas, each formula corresponding to a membership function. A selection circuit in the transmitter selects those membership functions which have a non-zero ordinate at the value of the digitized PV and a correction circuit provides at least one correction value, each correction value calculated from a compensation formula corresponding to a selected membership function. A weighting circuit weights each correction value by the ordinate of the corresponding selected membership function, and combines the multiplicands to provide a compensated PV. The compensated PV is coupled to a control circuit connecting the transmitter to a control system.

A second embodiment includes a sensor for sensing a primary PV such as differential pressure, and other sensors

for sensing secondary PVs such as line pressure and temperature. A set of converters digitize the sensed PVs. Each of the variables is assigned at least one membership function, with at least one of the variables having assigned at least two single dimensional membership functions. The membership functions having a substantially non-zero ordinate at the digitized PV values are selected, and compensation formulas corresponding to the selected membership functions are retrieved from a memory. An FAND circuit forms all unique three element combinations of the ordinates and provides the "rule strength" or minimum of the each of the combinations. A weighting circuit function perform in substantially the same way as described above to provide a compensated primary PV, which is formatted and coupled to a two wire circuit.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a sketch of a field mounted transmitter shown in a process control installation;
FIG. 2 is a block diagram of a transmitter made according to the present invention;
FIGS. 3A-C are plots of the three membership functions A-C respectively and FIG. 3D is a plot of the all three membership functions A-C, all shown as a function of uncompensated normalized pressure;
FIG. 4 is a flowchart of compensation circuit 58 in FIG. 2;
FIG. 5 is a block diagram of compensation circuit 58 with an alternative embodiment of membership function selection circuit 64;
FIG. 6 is a plot of a multidimensional membership functions;
FIG. 7 is a plot of the error as a function of pressure for two differential pressure sensors A and B.

TABLE 1 shows constants K_1 through K_{10} for each of the three regions.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In FIG. 1, a pressure transmitter shown generally at 2 transmits an output representative of pressure to a digital control system (DCS) 4 via a two wire current loop shown generally at 6. A fluid 8 in a tank 10 flows through pipe 12 into a series of other pipes 14, 16 and 18, all containing fluid 8. Measurement transmitter 2 senses the pressure difference across an orifice plate 20 situated in the flow of fluid 8. The pressure difference is representative of the flow rate of fluid 8 in pipe 12. A valve 22 located downstream from transmitter 2 controls the flow in pipe 12 as a function of commands received from DCS unit 4 over another two wire loop 24. DCS unit 4 is typically located in a control room away from the process control field installation and in an explosion-proof and intrinsically safe area, whereas transmitter 2 and valve 22 are mounted directly onto pipe 12 in the field.

In FIG. 2, transmitter 2 is shown with two terminals 50, 52 which are couplable to two terminals of DCS 4 over twisted wire pair 6. DCS 4 is modeled as a resistance and a power supply in series and is shown generally at 4. Transmitter 2 has a sensor section 54 including a capacitance based differential pressure sensor 54A, an absolute pressure sensor 54B and a temperature sensor 54C. Transmitter 2 senses differential pressures between 0 and 6350 mm (250 inches) of water. However, the types of process variables which transmitter 2 measures may include ones representative of position, volumetric flow, mass flow, temperature, level, density, displacement, pH, turbidity, dissolved oxygen and ion concentration. Analog output from sensors 54A-C is coupled to converter circuit 56, which includes voltage or capacitance based analog-to-digital (A/D) converters which can be of the type disclosed in U.S. Patents 4,878,012, 5,083,091, 5,119,033 and 5,155,455, assigned to the same assignee as the present invention. Each of converters 56A-C generates a serial bitstream of 10 to 16 bits representative of the corresponding digitized process variable (PV) onto a bus connected to compensation circuit 58.

Compensation circuit 58 uses fuzzy logic to provide an output representing a compensated PV and typically comprises a microprocessor such as a Motorola 68HC05 with integrated memory. Circuit 58 compensates the errors in the digitized signal representing differential pressure with the digitized signals representing absolute pressure, temperature and differential pressure. Compensation circuit 58 is based on the premise that compensation is most accurately modelled by segmenting the variables to be compensated into multiple regions which overlap each other, where each region has assigned to it a simplified compensation formula optimized for that region and a membership function which can be multidimensional. The "strength" of the formula in the region is variable throughout the region and is described by the ordinate of the membership function at the value of the variable to be compensated. The ordinate of the membership function is typically a number between 0 and 100 percent, indicating the extent to which the value of the variable to be compensated can be modeled by the compensation formula assigned to the selected region. Compensation is determined by first selecting the regions which include the value of the variable to be compensated, and selecting the membership functions and compensation formulas corresponding to each selected region. The next step is to provide a set of correction values, by calculating each of the compensation formulas at the value of the variable to be compensated, and determining the strength of each correction value from the corresponding membership function. Finally,

a compensation value is provided by combining the correction values, as weighted by the strength of the membership function at the variable value to be compensated.

A membership function selection circuit 64 selects which membership function is non-zero at the digitized P,T,L value and outputs signals representative of the selected membership functions on bus 64B. Circuit 64 also outputs ordinates of the selected membership functions at the digitized P,T,L values (the "rule strengths") at bus 64A. As a general rule, compensation circuit 58 includes at least two single dimensional membership functions for differential pressure, each overlapping the other. If more than one variable is used for compensation, there has to be at least two membership functions for one of the variables. FIGS. 3A-C show differential pressure membership functions A, B and C, each of which have a non-zero value over a different predetermined range of uncompensated pressures within the span. The variable to be compensated (differential pressure) is compensated by the all three variables (P, T and L), but only P is assigned membership functions. (In the most general case, each variable is assigned multiple membership functions.) Membership function A, shown as a solid line in FIG. 3A, has a non-zero value between 0 and 50% span and a zero value thereafter. Membership function B, shown as a dotted line in FIG. 3B, has a non-zero value between 0 and 100% span and a zero value elsewhere. Membership function C, shown as a solid line in FIG. 3C, has a non-zero value between 50% and 100% span and a zero elsewhere. FIG. 3D shows membership functions A, B and C plotted as a function of normalized pressure span. The non-zero segments of membership functions A, B and C define Regions 1, 2 and 3, respectively. The form of the equations need not be the same for each of the regions. The preferred form of the compensation formula for Regions 1-3 to meet the required accuracy with the metal cell DP sensor is given by Equation 1, which has a second order term as its highest term and requires no more that ten characterization constants.

$$P_{CORRECTED}(P,T,L) = K_1 + K_2P + K_3T + K_4L + K_5P^2 + K_6T^2 + K_7L^2 + K_8PL + K_9TP + K_{10}LT \quad (1)$$

Compensation formula evaluation circuit 66 evaluates and provides a correction value for each of the compensation formulas corresponding to the selected membership functions. The set of characterization constants for each of Regions 1-3 are stored in memory 68 and given below in TABLE 1.

	REGION 1	REGION 2	REGION 3
K_1	-2.5152	-3.4206	-7.1604
K_2	278.5154	283.4241	293.4994
K_3	-4.1357	-2.3884	-0.3094
K4	2.4908	2.5038	2.7488
K_5	-3.4611	-10.5786	-17.4490
K_6	-4.1901	-5.6594	-6.9354
K_7	-0.1319	-0.1589	-0.2082
K_8	11.9573	11.8335	11.4431
K_9	-9.3189	-10.3664	-11.5712
K_{10}	1.1318	1.2281	1.3502

Memory 68 is a non-volatile memory containing membership functions, compensation formulas and characterization constants for the compensation formulas. Combining function circuit 70 receives the correction values and the rule strengths and provides a compensated P process variable according to the equation given by:

$$P_{comp} = \frac{\Sigma_{i-1}^{N} w_i f_{P_i}(P,T,L)}{\Sigma_{i-1}^{N} w_i} \quad (2)$$

where N is the number of selected regions, w_i is the rule strength for the ith region, $f_i(P,T,L)$ is the correction value from

the compensation formula corresponding to the ith region and P_{comp} represents the compensated differential pressure.

Output circuit 62 receives and formats the compensated differential pressure PV and couples it to terminals 50, 52 for transmission over process control loop 6. Output circuit 62 may be realized in several ways. A first alternative is a digital-to-analog circuit where the compensated PV is converted to an analog current representative of the compensated PV and is thereafter coupled onto current loop 6. A second alternative is a fully digital transmission, such as Fieldbus, of the compensated PV onto loop 6. A third implementation superimposes a digital signal representative of the PV on an analog current alsq representative of the PV, such as in the HART® protocol.

The number and the functional form of the membership functions are determined by the compensation accuracy required (e.g. .05% accuracy) and the sensor's operating characteristics. For example, a sensor with a significant amount of error which must be compensated requires more membership functions than does a sensor which substantially meets the required amount of accuracy. Membership functions for the sensor which needs more compensation may each have a different functional form (e.g. exponential, gaussian, polynomial, constant, cubic spline, gaussian and logarithmic).

Consider a pressure of approximately 30% of span, corresponding to an applied pressure of 1905 mm (75.0 inches) of water, indicated on FIG. 3D by a solid vertical line and included in the non-zero segments of membership function A and B. Membership functions A and B, corresponding to Regions 1 and 2 are the "selected membership functions". The values of the two membership functions at 30% of span are .359 and .641, respectively. The compensation formulas for Region 1 and 2 are given by Equation 3 and 5:

$$f_{P_1}(P,T,L) = -2.512 + 278.5154P - 4.137T + 2.4908L - 3.4611P^2 - 4.1901T^2 - 0.1319L^{**}2 + 11.9573PL - 9.3189TP + 1.1318LT \quad (3)$$

$$f_{P_2}(P,T,L) = -3.4206 + 283.4241P - 2.3884T + 2.5038L - 10.5786P^2 - 5.694T^{**}2 - 0.1589L^{**}2 + 11.8335PL - 10.3664TP + 1.2281LT \quad (5)$$

Correction values from Equation 3 and 5 are 1910 and 1907 mm (75.188 and 75.070 inches) of water, respectively. The compensated pressure is provided by a combining function, given by Equation 2 above, and is 1908 mm (75.112 inches) of water, simplified from:

$$P_{comp} = \frac{.359(75.188) + .641(75.070)}{.359 + .641} \quad (7)$$

The T and L values substituted into the above equation correspond to room temperature and atmospheric line pressure.

Rather than executing a single eleventh order polynomial as in the prior art, only two second order polynomials are computed. The resulting correction value from the second order function is insensitive to the manner in which computation takes place (e.g. no overflows), requires less execution time, takes fewer characterization constants and provides more space in memory for additional software functionality in transmitter 2. Another benefit of a fuzzy logic implementation of compensation circuit 58 is to capture the effect of non-linear interaction between variables, which is difficult to model in a prior art single polynomial compensation scheme. The types of variables adapted for use in the disclosed compensation scheme are not limited to sensed PVs. The variable may be a time dependent variable, such as the first or second derivative, or the integral, of the variable. In this case, the corresponding membership function would be arranged to provide minimal compensation when the derivative is large (i.e. the magnitude of the compensation is insignificant compared to the magnitude of the pressure change, so it is adequate to approximately compensate the primary PV). Optimal value stem actuation by a positioner or actuator, such as in a pick and place machine, requires a sensed position and may include a velocity and an acceleration. Another type of variable is a "history dependent" variable, where effects of hysteresis are taken into account. History dependent PVs include information about the previous measurements taken with the specific sensor in transmitter 2. For example, extreme overpressurization of a capacitive based pressure sensor modifies its capacitance as a function of pressure in subsequent measurements. Different compensation formulas apply depending on the severity and frequency of the overpressurization. Another type of variable is a "position dependent" variable, where the value of the variable changes with position, such as in a diaphragm having one stiffness when bowed and another stiffness in the absence of applied pressure. Another type of variable is a "device dependent" variable, where the membership functions and compensation formulas

change with the materials used to manufacture transmitter 2. For example, a sensor sensing pressure within a low pressure range has different compensation requirements than does a high range pressure sensor. Similarly, a pressure sensor with a diaphragm made of HASTELLOY® has different error characteristics, and hence requires different compensation, than does one made of MONEL®.

The present invention solves inaccuracies in a prior art compensation technique called piecewise linear fitting. In piecewise linear fitting, the span of the variable of interest is segmented into two or more ranges, and a linear equation is selected for each range which optimally fits each of the ranges. Unfortunately, there are typically small discontinuities, or mismatches, at the boundaries between the separately compensated ranges. The present compensation scheme, with the overlapping membership functions, provides a smooth transition between ranges of the variable of interest.

In FIG. 4, a flowchart of the functions in compensation circuit 58 is disclosed. The process variables P,T,L are sensed and digitized in blocks 200 and 202 respectively. A counter for counting the number of regions is initialized in block 204. A decision block 206 retrieves the ith membership function from a memory block 208 and determines whether the digitized P,T,L value is in the ith region described by the ith membership function. If the digitized point is included in the region, a computation block 210 retrieves appropriate compensation formulas and characterization constants from memory 208 to compute the ordinate value of a membership function $f_{mi}(P,T,L)$ and a correction value $f_{ci}(P,T,L)$ computed from the ith compensation formula, or otherwise increments the region counter i. Decision block 212 causes the loop to re-execute until all the regions which include the digitized P,T,L point are selected. Then block 214 computes the compensated differential pressure as indicated.

FIG. 5 details an alternative embodiment of membership function selection circuit 64. Exactly as in FIG. 2, fuzzy compensation circuit 58 receives digitized differential pressure (P), digitized absolute line pressure (L) and digitized temperature (T), and uses those three variables to provide a compensated differential pressure. The three main functional blocks are a rule strength circuit 302, a compensation formula evaluation circuit 304 and a combining circuit 306. However, in this alternative embodiment, all of the three variables (P,T,L) are assigned multiple membership functions. In particular, differential pressure is assigned four membership functions defined as f_{p1}, f_{p2}, f_{p3} and f_{p4}; temperature is assigned three membership functions defined as f_{t1}, f_{t2}, and f_{t3}; and absolute pressure is assigned two membership functions defined as f_{l1} and f_{l2}. Circuit 58 is preferably implemented in a CMOS microprocessor (with adequate on-chip memory), so as to conserve power in the transmitter, which receives power solely from the current loop.

Circuit 310 receives the digitized P value and selects those membership functions which have a non-zero ordinate at the digitized P value. Because the non-zero portions of the membership functions may overlap, there is usually more that one selected membership function for each digitized PV. When the membership functions overlap each other by 50%, 2^N equations are computed where N is the number of variables which are divided into more than one membership function. The output of circuit 310 is the ordinate of each of the selected membership functions corresponding to the digitized P value, and is labelled at 310A. For example, if the digitized P value were included in the non-zero portion of three of the four P membership functions, then circuit 310 outputs three values, each value being an ordinate of the three selected membership functions corresponding to the digitized P value. Specifically for $P = p_0$, bus 310A includes the ordinates: $[\, f_{p2}(p_0), f_{p3}(p_0), f_{p4}(p_0)\,]$. At about the same time so as to be effectively simultaneous, circuit 312 receives the digitized T value and selects temperature membership functions having a non-zero value at the digitized T value. If the digitized T value were included in the non-zero portion of two of the three T membership functions, then circuit 312 outputs two values on bus 312A, each value being an ordinate of a selected membership function. Specifically for $T = t_0$, bus 312A includes the ordinates: $[\, f_{t2}(t_0), f_{t3}(t_0)\,]$. In similar fashion, circuit 314 receives the digitized L value and selects absolute pressure membership functions having a non-zero value at the digitized L value. If the digitized L value were included in both of the two L membership functions, then circuit 314 outputs two values on bus 314A, each value being an ordinate of a selected membership function. Specifically for $L = l_0$, bus 314A includes the ordinates: $[\, f_{l1}(l_0), f_{l2}(l_0)\,]$.

Fuzzy AND circuit 316 forms all unique three element combinations of the ordinates it receives from circuits 310-314 (where each combination includes one value from each of the three busses 310A, 312A and 314A) and outputs the fuzzy AND (the minimum) of each of the unique combinations on a bus 316A. For the set of P, T and L values from the example above, the set of unique membership function ordinate combinations is:

$[\, f_{p2}(p_0)\, f_{t2}(t_0)\, f_{l1}(l_0)\,]$
$[\, f_{p2}(p_0)\, f_{t2}(t_0)\, f_{l2}(l_0)\,]$
$[\, f_{p2}(p_0)\, f_{t3}(t_0)\, f_{l1}(l_0)\,]$
$[\, f_{p2}(p_0)\, f_{t3}(t_0)\, f_{l2}(l_0)\,]$
$[\, f_{p3}(p_0)\, f_{t2}(t_0)\, f_{l1}(l_0)\,]$
$[\, f_{p3}(p_0)\, f_{t2}(t_0)\, f_{l2}(l_0)\,]$
$[\, f_{p3}(p_0)\, f_{t3}(t_0)\, f_{l1}(l_0)\,]$
$[\, f_{p3}(p_0)\, f_{t3}(t_0)\, f_{l2}(l_0)\,]$
$[\, f_{p4}(p_0)\, f_{t2}(t_0)\, f_{l1}(l_0)\,]$

$[f_{p4}(p_0)\ f_{t2}(t_0)\ f_{l2}(l_0)]$
$[f_{p4}(p_0)\ f_{t3}(t_0)\ f_{l1}(l_0)]$
$[f_{p4}(p_0)\ f_{t3}(t_0)\ f_{l2}(l_0)]$

The effect of the fuzzy AND circuit 316 is to take single variable membership functions for P, T and L and create multivariable membership functions in P-T-L space. Although it cannot be rendered graphically, circuit 316 creates in P-T-L space a set of 24 three-variable membership functions from the four P, three T and two L single-dimensional membership functions. There are 24 compensation formulas corresponding to the 24 membership functions. In general, the number of multivariable membership functions created is equal to the product of the number of membership functions defined for each individual variable. FIG. 6 gives an example of multivariable membership functions in two variables, P and T. Twelve overlapping pentahedrally shaped two-variable membership functions are defined in P-T space from four triangularly shaped P membership functions and three triangularly T membership functions. Each multivariable membership function corresponds to a compensation formula, and the ordinate of the multivariable membership function (the output of the fuzzy AND) is called a "rule strength" which describes the extent to which the compensated pressure can be modelled with the corresponding compensation formula.

Circuit 316 selects those compensation formulas corresponding to each "rule strength" output on bus 316B. Bus 316B has as many signals in it as there are compensation formulas. A "one" value corresponding to a specific compensation formula indicates that it is selected for use in compensation formula evaluation circuit 304. In our specific example, each of the twelve rule strengths defines a point on the surface of twelve separate pentahedrons, so that twelve compensation formulas (out of a total of 24) are selected.

Memory 308 stores the form and the characterization constants for each of the compensation formulas. Compensation formula evaluation circuit 304 retrieves the constants for the selected compensation formulas indicated via bus 316B from memory 308, and calculates a correction value corresponding to each of the selected compensation formulas. Combining circuit 306 receives the correction values and the rule strengths for each of the selected regions and weights the correction values by the appropriate rule strength. The weighted average is given by Equation 4. The characterization constants stored in memory 308 are the result of a weighted least squares fit between the actual operating characteristics of the sensor and the chosen form of the compensation formula for that compensation formula. (The weighted least squares fit is performed during manufacture, rather than operation of the unit.) The weighted least squares fit is given by:

$$b = P^{-1}s \tag{8}$$

where **b** is a nx1 vector of calculated characterization coefficients, **P** is the nxn weighted covariance matrix of the input data matrix **X** and **s** is the nx1 weighted covariance vector of **X** with **y**. The data matrix **X** is of dimension mxn where each row is one of m data vectors representing one of the m (P,T,L) characterization points.

In an alternate embodiment of compensation circuit 58 shown in FIG. 5, FAND circuit 316 is obviated and membership function circuits 310-314 are replaced by three explicitly defined three dimensional membership functions having the form of a radial basis function given generally by:

$$R_i(X) = \exp\left[-\frac{|X - x_j|^2}{\sigma_i^2}\right] \tag{9}$$

In the radial basis function, **X** is a three dimensional vector whose components are the digitized P, T and L values, $\mathbf{x}_i$ is a three dimensional vector defining the center of the function in P-T-L space, and σ controls the width of the function. A set of multidimensional membership functions, such as with radial basis functions, effectively replaces the function of FAND circuit 316, since the FAND circuit provides a set of multidimensional membership functions from sets of single dimensional membership functions.

The present invention is particularly suitable when used in a transmitter with dual differential pressure sensors. FIG. 7 shows the sensor error on the respective y axes 400,402 plotted as a function of sensed differential pressure on x axes 404,406 for two pressure sensors A and B (labelled), each connected as shown for pressure sensor 54A in FIG. 2. Sensor A senses a wide range of pressures between 0 and 6895 x 10^3Pa (1000 PSI), while sensor B senses pressure over a tenth of the other sensor's span; from 0 to 689.5 x 103 Pa (100 PSI). The error for sensor A is greater at any given pressure than the error for sensor B at the same pressure. A dual sensor transmitter as described here has an output representative of the converted output from sensor B at low pressures, but switches to an output representative of the converted output from sensor A over higher pressures. The present compensation

scheme provides a smooth transmitter output when the transmitter switches between the sensors A and B. In the same fashion as disclosed in FIG3A-D, the output from sensor A is treated as one process variable and output from sensor B is treated as another process variable. As disclosed, each process variable has assigned to it a membership function and a compensation formula, which indicate the extent to which the process variable can be modelled by the compensation formula. A correction value is provided from computing each of the two compensation formulas, and a combining function weights the correction values and provides a compensated pressure. This is a preferred compensation scheme for dual sensor transmitters in that output from both sensors is used throughout a switchover range of pressures, (i.e. no data is discarded for pressures measured within the switchover range) with the relative weighting of the output from each sensor defined by each sensor's membership function. This applicability of the present compensation scheme to dual sensors applies equally well to transmitters having multiple sensors sensing the same process variable, and to transmitters with redundant sensors where each sensor senses a range of PVs substantially the same as the other.

The present invention can be applied to devices outside of the process control and process automation industry, and for example could be used to compensate control surface position in an airplane. The type of variables used in the compensation circuit can be other than PVs, the compensation formulas and membership functions can be of forms other than polynomials, and the combining function can be a non-linear averaging function.

Claims

1. A measurement transmitter, comprising:

   conversion means (54,56) including a first sensor for sensing a variable PV within a first span of PV values and for providing a first digitized output representative of the sensed PV;
   a memory (68) for storing at least two membership functions for the first sensor, each membership function having a non-zero value over a predetermined region of the first PV span and a substantially zero value over the remainder of the first span;
   selection means (64) for selecting those membership functions which have a non-zero value at the first digitized PV;
   correction means (66) for providing at least one correction value, each correction value calculated from a compensation formula stored in the memory (68) which corresponds to a selected membership function;
   weighting means (70) for weighting each correction value by its corresponding selected membership function, and for combining the weighted correction values to provide a compensated PV; and
   an output circuit (62) for coupling the compensated PV to a control circuit.

2. The transmitter of claim 1 where non-zero regions of the membership functions overlap each other.

3. The transmitter of any of the preceding claims where at least one membership function is triangularly shaped.

4. The transmitter of any of the preceding claims where at least one membership function is a gaussian function.

5. The transmitter of any of the preceding claims where the weighting means combine the correction values according to a weighted average.

6. The transmitter of any of the preceding claims where at least one of the compensation formulas is a polynomial function.

7. The transmitter of any of the preceding claims where the PV is one of a set of PVs representative of differential pressure, position, volumetric flow, mass flow, temperature, level, density, displacement, pH, turbidity, dissolved oxygen and ion concentration.

8. The transmitter of any of claims 1-6 where the sensed PV comprises differential pressure and there are three membership functions for the differential pressure, the membership functions each having a center point corresponding to a maximum value of the membership function, where the center points are evenly spaced along the first span of PV values.

9. The transmitter of any of claim 1-6 where there are three membership functions each overlapping at least one other membership function by 50%.

10. The measurement transmitter of any of claims 1-6, where the conversion means (54,56) further includes a second sensor for sensing the PV within a second span of PV values and for providing a second digitized output representative of the sensed PV; and

where the memory (68) further comprises at least two membership functions for the second sensor, each membership function having a non-zero value over a predetermined region of the second PV span and a substantially zero value over the remainder of the second span; and
where the selection means (64) further comprises means for selecting those membership functions which have a non-zero value at the second digitized PV.

11. The measurement transmitter of claim 10 where the first range is substantially the same as the second range.

12. The measurement transmitter of claim 10 where the first range is larger than the second range.

13. A method for calculating compensated process variables, comprising:

sensing a variable PV representative of a process, the PV taking on values within a predetermined span of PV values;
converting the sensed PV to a digitized PV;
storing at least two membership functions, each membership function having a non-zero value over a predetermined region of the PV span and a substantially zero value over the remainder of the span;
storing a set of compensation formulas, each formula corresponding to a membership function;
selecting those membership functions which have a non-zero value at the digitized PV;
providing at least one correction value, each correction value calculated from a compensation formula corresponding to a selected membership function;
weighting each correction value by its corresponding selected membership function, and combining the weighted correction values to provide a compensated PV; and coupling the compensated PV to a control circuit.

Patentansprüche

1. Ein Meßwertgeber, der folgendes aufweist:

eine Umwandlungsvorrichtung (54, 56), die einen ersten Sensor zur Erfassung einer variablen PV oder Prozeßvariablen innerhalb eines ersten Meßbereichs von PV-Werten und zur Erzeugung eines ersten digitalisierten Ausgangssignals aufweist, das die erfaßte PV wiedergibt;

einen Speicher (68) zum Speichern von mindestens zwei Mitgliedsfunktionen für den ersten Sensor, wobei jede Mitgliedsfunktion über einen vorher festgelegten Bereich des ersten PV-Meßbereichs einen Nicht-Nullwert und über den restlichen ersten Meßbereich einen Wert mit im wesentlichen Null aufweist;

eine Auswahlvorrichtung (64) zum Auswählen dieser Mitgliedsfunktionen, die an der ersten digitalisierten PV einen Nicht-Nullwert aufweisen;

eine Berichtigungsvorrichtung (66) zur Erzeugung mindestens eines Berichtigungswerts, wobei jeder Berichtigungswert aus einer im Speicher (68) gespeicherten Kompensationsformel berechnet wird, die einer ausgewählten Mitgliedsfunktion entspricht;

eine Gewichtungsvorrichtung (70) zur Gewichtung jedes Berichtigungswerts durch seine entsprechende ausgewählte Mitgliedsfunktion und zur Kombination der gewichteten Berichtigungswerte zur Erzeugung einer kompensierten PV; und

ein Ausgangs-Schaltkreis (62) zum Leiten der kompensierten PV zu einem Steuer-Schaltkreis.

2. Meßwertgeber nach Anspruch 1, dadurch gekennzeichnet, daß sich Nicht-Null-Bereiche der Mitgliedsfunktionen gegenseitig überlappen.

3. Meßwertgeber nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, daß mindestens eine Mit-

gliedsfunktion dreieckig geformt ist.

4. Meßwertgeber nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, daß mindestens eine Mitgliedsfunktion eine Gauß'sche Funktion ist.

5. Meßwertgeber nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, daß die Gewichtungsvorrichtung die Berichtigungswerte gemäß einem gewichteten Durchschnitt kombiniert.

6. Meßwertgeber nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, daß mindestens eine der Kompensationsformeln eine Polynomfunktion ist.

7. Meßwertgeber nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, daß die PV eine aus einem Satz PVs ist, die Differenzdruck, Position, volumetrische Strömung, Mengenfluß, Temperatur, Pegel, Dichte, Verdrängung, pH, Trübheit, gelösten Sauerstoff und Ionenkonzentration wiedergeben.

8. Meßwertgeber nach einem der Ansprüche 1-6, dadurch gekennzeichnet, daß die erfaßte PV Differenzdruck aufweist und es drei Mitgliedsfunktionen für den Differenzdruck gibt, wobei die Migliedsfunktionen je einen Mittelpunkt aufweisen, der einem maximalen Wert der Mitgliedsfunktion entspricht, daß die Mittelpunkte entlang des ersten Meßbereichs der PV-Werte gleichmäßig beabstandet sind.

9. Meßwertgeber nach einem der Ansprüche 1-6, dadurch gekennzeichnet, daß es drei Mitgliedsfunktionen gibt, von denen jede mindestens eine andere Mitgliedsfunktion um 50 % überlappt.

10. Meßwertgeber nach einem der Ansprüche 1-6, dadurch gekennzeichnet, daß die Umwandlungsvorrichtung (54, 56) weiterhin einen zweiten Sensor zur Erfassung der PV innerhalb eines zweiten Meßbereichs von PV-Werten und zur Erzeugung eines zweiten digitalisierten Ausgangssignals aufweist, das die erfaßte PV wiedergibt; und

    daß der Speicher (68) weiterhin mindestens zwei Mitgliedsfunktionen für den zweiten Sensor aufweist, wobei jede Mitgliedsfunktion über einen vorher festgelegten Bereich des zweiten PV-Meßbereichs einen Nicht-Nullwert und über den restlichen zweiten Meßbereich einen im wesentlichen Nullwert aufweist; und

    daß die Auswahlvorrichtung (64) weiterhin eine Vorrichtung zum Auswählen dieser Mitgliedsfunktionen aufweist, die an der zweiten digitalisierten PV einen Nicht-Nullwert aufweisen.

11. Meßwertgeber nach Anspruch 10, dadurch gekennzeichnet, daß der erste Bereich im wesentlichen derselbe wie der zweite Bereich ist.

12. Meßwertgeber nach Anspruch 10, dadurch gekennzeichnet, daß der erste Bereich größer ist als der zweite Bereich.

13. Ein Verfahren zur Berechnung von kompensierten Prozeßvariablen, das folgendes aufweist:

    Erfassung einer variablen PV, die ein Verfahren wiedergibt, wobei die PV Werte innerhalb eines vorher festgelegten Meßbereichs von PV-Werten annimmt;

    Umwandlung der erfaßten PV in eine digitalisierte PV;

    Speichern von mindestens zwei Mitgliedsfunktionen, wobei jede Mitgliedsfunktion über einen vorher festgelegten Bereich des PV-Meßbereichs einen Nicht-Nullwert und über den restlichen Meßbereich einen im wesentlichen Nullwert aufweist;

    Speichern eines Satzes von Kompensationsformeln, wobei jede Formel einer Mitgliedsfunktion entspricht;

    Auswählen dieser Mitgliedsfunktionen, die an der digitalisierten PV einen Nicht-Nullwert aufweisen;

    Erzeugung mindestens eines Berichtigungswerts, wobei jeder Berichtigungswert aus einer Kompensationsformel berechnet wird, die einer ausgewählten Mitgliedsfunktion entspricht;

Gewichtung jedes Berichtigungswerts durch seine entsprechende ausgewählte Mitgliedsfunktion und Kombination der gewichteten Berichtigungswerte zur Erzeugung einer kompensierten PV; und

Leiten der kompensierten PV zu einem Steuer-Schaltkreis.

Revendications

1. Unité de transmission de mesures, comprenant :

   des moyens de conversion (54, 56) incluant un premier détecteur pour détecter une variable PV, dans un premier intervalle de valeurs de PV, et délivrer une première sortie numérisée représentative de la variable PV détectée;
   une mémoire (68) pour mémoriser au moins deux fonctions d'appartenance relatives au premier détecteur, chaque fonction d'appartenance ayant une valeur non-nulle sur une région prédéterminée du premier intervalle de valeurs de PV et une valeur pratiquement nulle sur le reste du premier intervalle;
   des moyens de sélection (64) pour sélectionner les fonctions d'appartenance qui ont une valeur non-nulle au niveau de la première variable PV numérisée;
   des moyens de correction (66) pour délivrer au moins une valeur de correction, chaque valeur de correction étant calculée à partir d'une formule de compensation mémorisée dans la mémoire (68) qui correspond à une fonction d'appartenance sélectionnée;
   des moyens de pondération (70) pour pondérer chaque valeur de correction par la fonction d'appartenance sélectionnée qui lui correspond, et combiner les valeurs de correction pondérées afin de délivrer une variable PV compensée; et
   un circuit de sortie (62) pour envoyer la variable PV compensée vers un circuit de commande.

2. Unité de transmission selon la revendication 1, dans laquelle les régions non-nulles des fonctions d'appartenance se chevauchent.

3. Unité de transmission selon l'une quelconque des revendications précédentes, dans laquelle au moins une fonction d'appartenance est de forme triangulaire.

4. Unité de transmission selon l'une quelconque 5 des revendications précédentes, dans laquelle au moins une fonction d'appartenance est une fonction gaussienne.

5. Unité de transmission selon l'une quelconque des revendications précédentes, dans laquelle les moyens de pondération combinent les valeurs de correction conformément à une moyenne pondérée.

6. Unité de transmission selon l'une quelconque des revendications précédentes, dans laquelle au moins l'une des formules de compensation est une fonction polynomiale.

7. Unité de transmission selon l'une quelconque 5 des revendications précédentes, dans laquelle la variable PV appartient à un ensemble de variables PV représentant une pression différentielle, une position, un débit volumique, un débit massique, une température, un niveau, une densité, un déplacement, un pH, une turbidité, une concentration en oxygène dissous et en ions.

8. Unité de transmission selon l'une quelconque des revendications 1 à 6, dans laquelle la variable PV détectée comprend une pression différentielle et dans laquelle trois fonctions d'appartenance sont utilisées pour la pression différentielle, les fonctions d'appartenance ayant chacune un point central correspondant à une valeur maximale de la fonction d'appartenance, les points centraux étant équidistants sur le premier intervalle de valeurs de PV.

9. Unité de transmission selon l'une quelconque des revendications 1 à 6, dans laquelle sont utilisées trois fonctions d'appartenance, chaque fonction chevauchant au moins 50% d'une autre fonction d'appartenance.

10. Unité de transmission de mesures selon l'une quelconque des revendications 1 à 6, dans laquelle les moyens de conversion (54, 56) comportent en outre un second détecteur pour détecter la variable PV dans un second intervalle de valeurs de PV et délivrer une seconde sortie numérisée représentative de la variable PV détectée; et

dans laquelle la mémoire (68) comprend en outre au moins deux fonctions d'appartenance relatives au second détecteur, chaque fonction d'appartenance ayant une valeur non-nulle sur une région prédéterminée du second intervalle de valeurs de PV et une valeur pratiquement nulle sur le reste du second intervalle; et
dans laquelle les moyens de sélection (64) comprennent en outre des moyens pour sélectionner les fonctions d'appartenance qui ont une valeur non-nulle au niveau de la seconde variable PV numérisée.

11. Unité de transmission de mesures selon la revendication 10, dans laquelle la première plage est pratiquement la même que la seconde plage.

12. Unité de transmission de mesures selon la revendication 10, dans laquelle la première plage est plus grande que la seconde plage.

13. Procédé pour calculer des variables de traitement compensées, consistant à :

détecter une variable PV représentative d'un traitement, la variable PV prenant des valeurs situées dans un intervalle prédéterminé de valeurs de PV;
convertir la variable PV détectée en une variable PV numérisée;
mémoriser au moins deux fonctions d'appartenance, chaque fonction d'appartenance ayant une valeur non-nulle sur une région prédéterminée de l'intervalle de valeurs de PV et une valeur pratiquement nulle sur le reste de l'intervalle;
mémoriser un ensemble de formules de compensation, chaque formule correspondant à une fonction d'appartenance;
sélectionner les fonctions d'appartenance qui ont une valeur non-nulle au niveau de la variable PV numérisée;
délivrer au moins une valeur de correction, chaque valeur de correction étant calculée à partir d'une formule de compensation correspondant à une fonction d'appartenance sélectionnée;
pondérer chaque valeur de correction par la fonction d'appartenance sélectionnée qui lui correspond et combiner les valeurs de correction pondérées afin de délivrer une variable PV compensée; et
envoyer la variable PV compensée vers un circuit de commande.

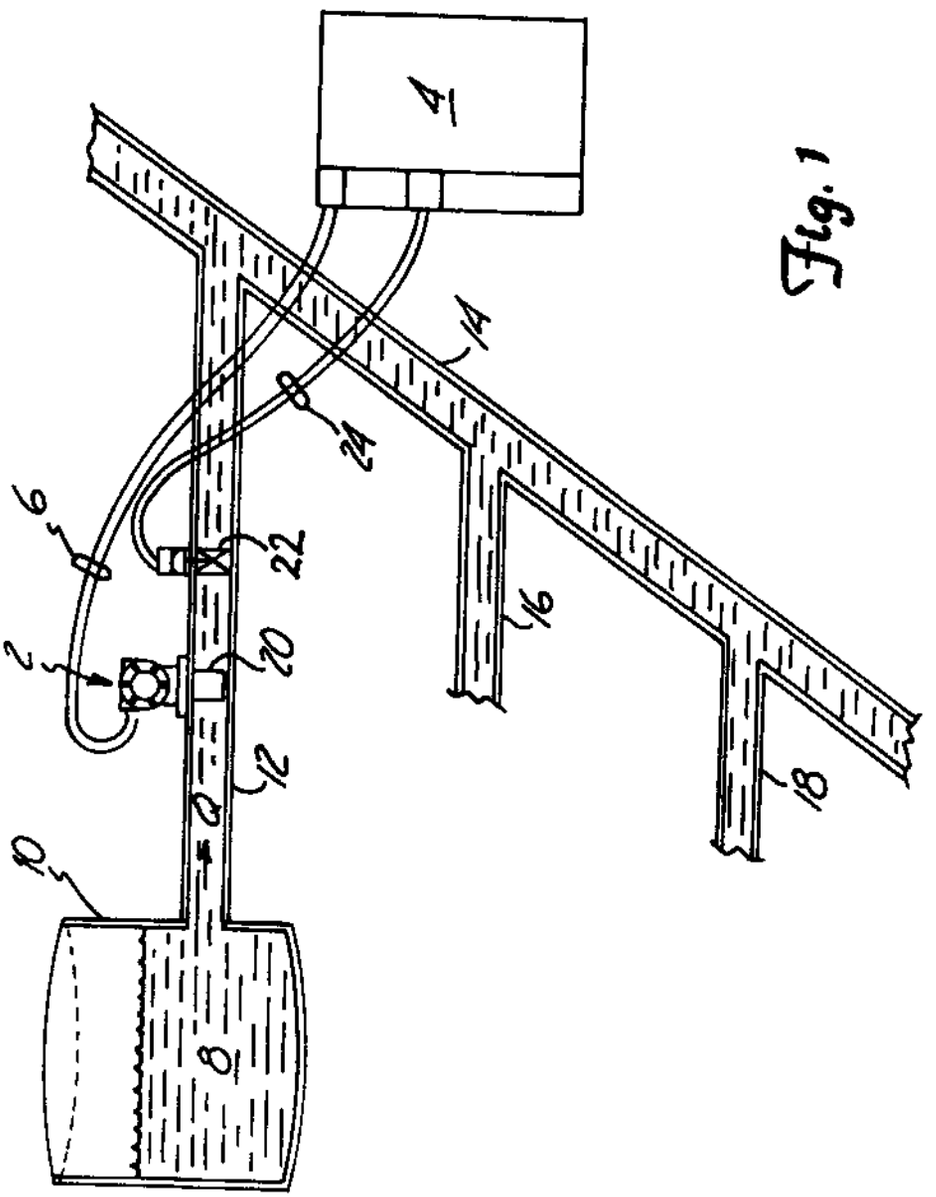


Fig. 1

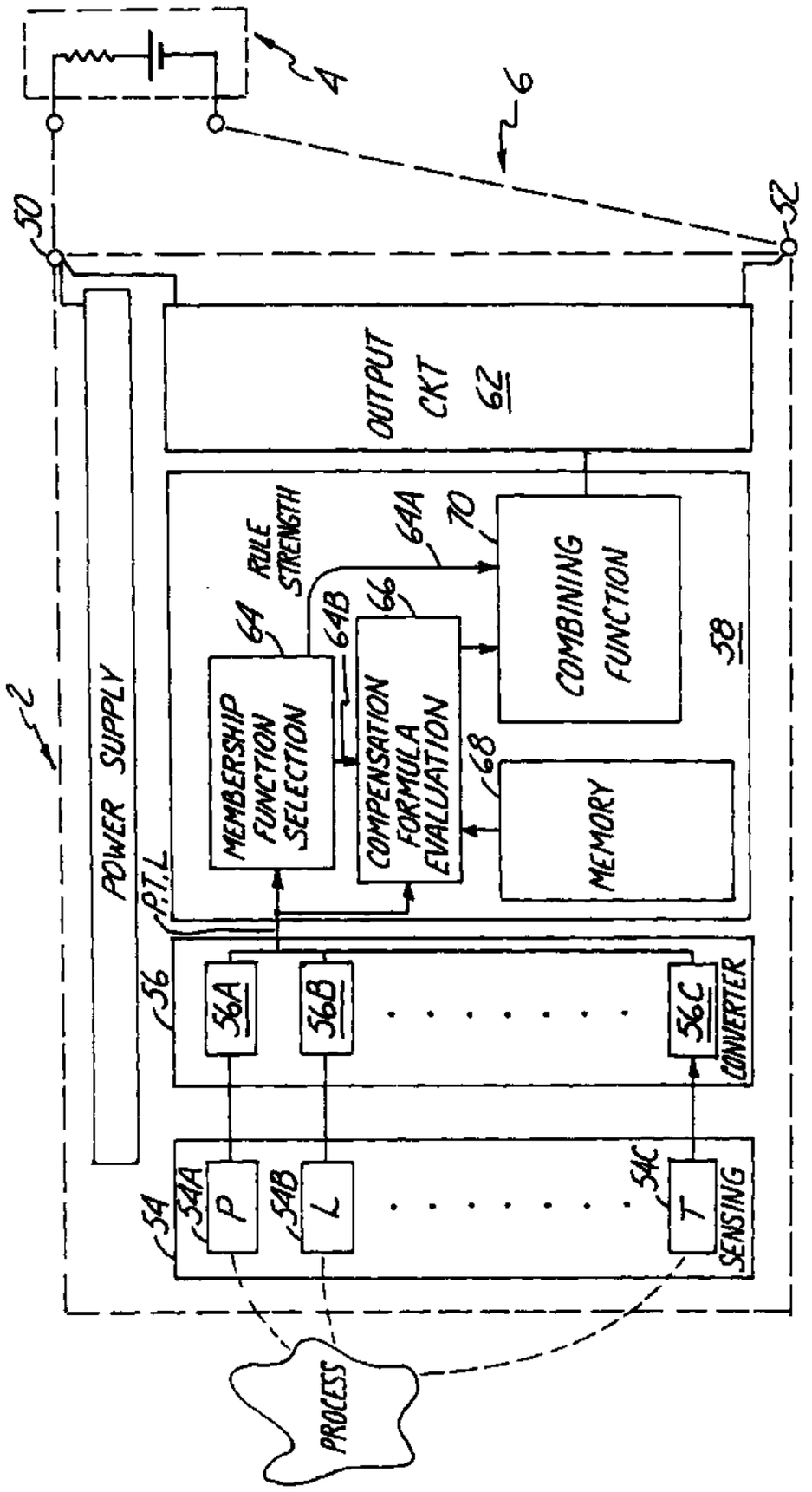

4
6
50
52
OUTPUT CKT 62
RULE STRENGTH
64A
70
64
64B
66
COMBINING FUNCTION
58
MEMBERSHIP FUNCTION SELECTION
COMPENSATION FORMULA EVALUATION
68
MEMORY
2
POWER SUPPLY
P.T.L
56
56A
56B
56C
CONVERTER
54
54A
P
54B
L
54C
T
SENSING
PROCESS

Fig. 2

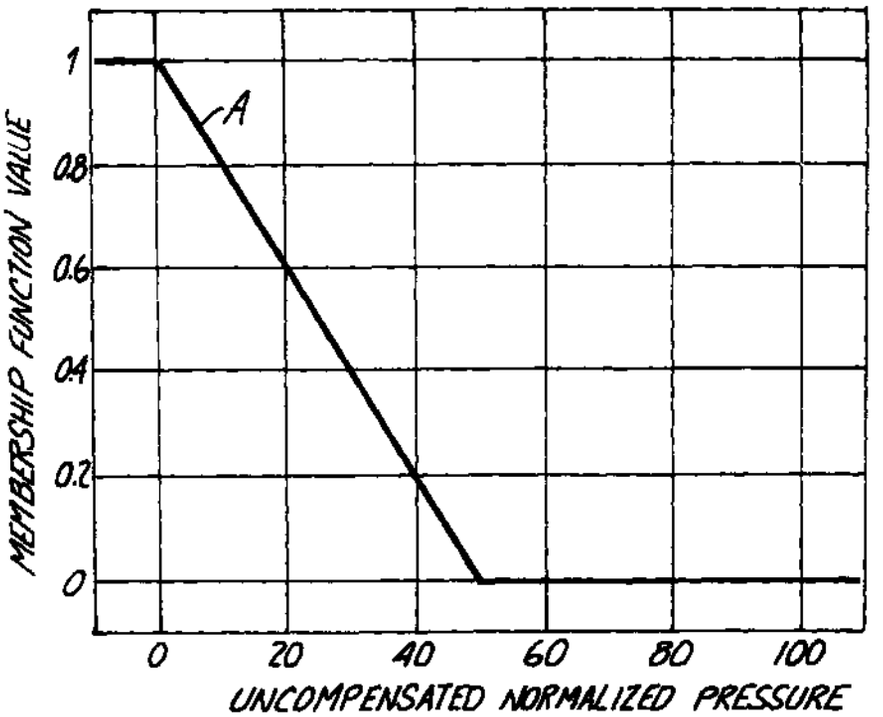

MEMBERSHIP FUNCTION VALUE
1
0.8
0.6
0.4
0.2
0
A
0
20
40
60
80
100
UNCOMPENSATED NORMALIZED PRESSURE

Fig.3A

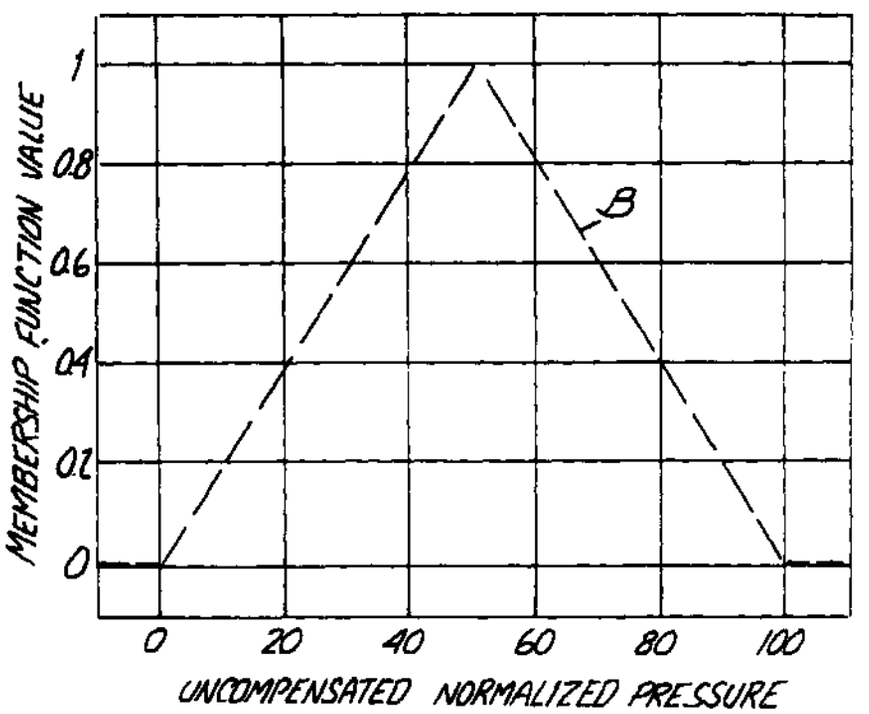

MEMBERSHIP FUNCTION VALUE
1
0.8
0.6
0.4
0.2
0
B
0
20
40
60
80
100
UNCOMPENSATED NORMALIZED PRESSURE

Fig.3B

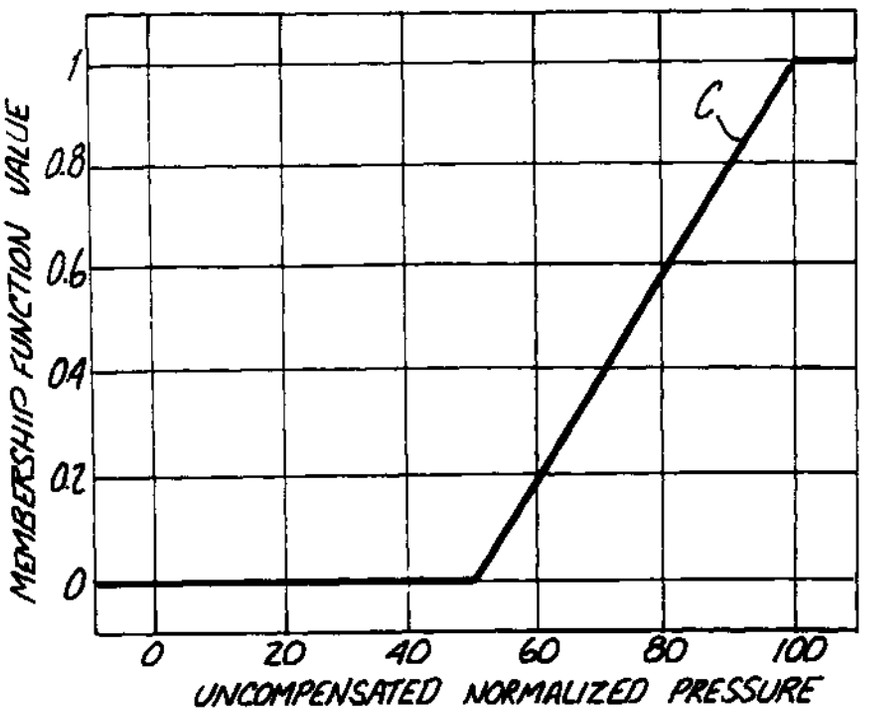
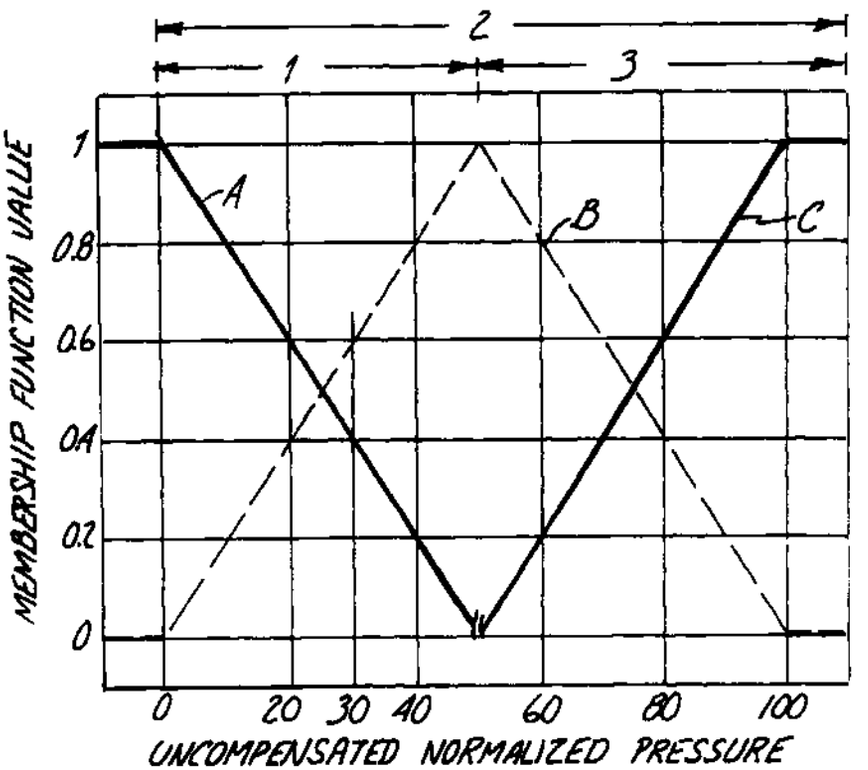

MEMBERSHIP FUNCTION VALUE
1
0.8
0.6
0.4
0.2
0
C
0
20
40
60
80
100
UNCOMPENSATED NORMALIZED PRESSURE

Fig.3C

Fig3D


2
1
3
MEMBERSHIP FUNCTION VALUE
1
0.8
0.6
0.4
0.2
0
A
B
C
0
20
30
40
60
80
100
UNCOMPENSATED NORMALIZED PRESSURE

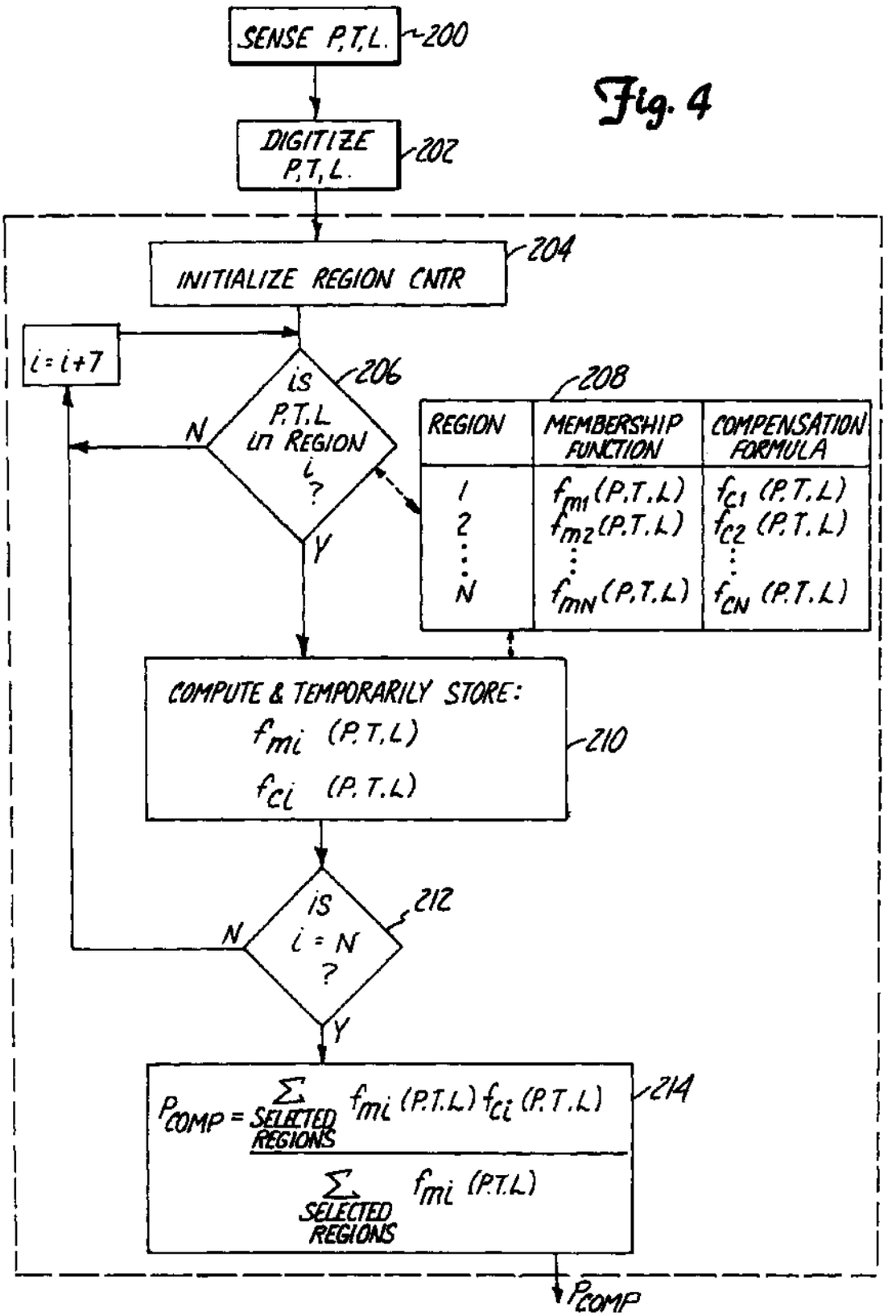

SENSE P,T,L.
200
DIGITIZE P,T,L.
202
INITIALIZE REGION CNTR
204
i = i+7
IS P,T,L IN REGION i ?
206
N
Y
208
REGION
MEMBERSHIP FUNCTION
COMPENSATION FORMULA
1
2
N
$f_{m1}(P,T,L)$
$f_{m2}(P,T,L)$
$f_{mN}(P,T,L)$
$f_{C1}(P,T,L)$
$f_{C2}(P,T,L)$
$f_{CN}(P,T,L)$
COMPUTE & TEMPORARILY STORE:
$f_{mi}(P,T,L)$
$f_{Ci}(P,T,L)$
210
IS i = N ?
212
N
Y
$P_{COMP} = \frac{\sum_{SELECTED\ REGIONS} f_{mi}(P,T,L)\, f_{Ci}(P,T,L)}{\sum_{SELECTED\ REGIONS} f_{mi}(P,T,L)}$
214
P_{COMP}

Fig. 4

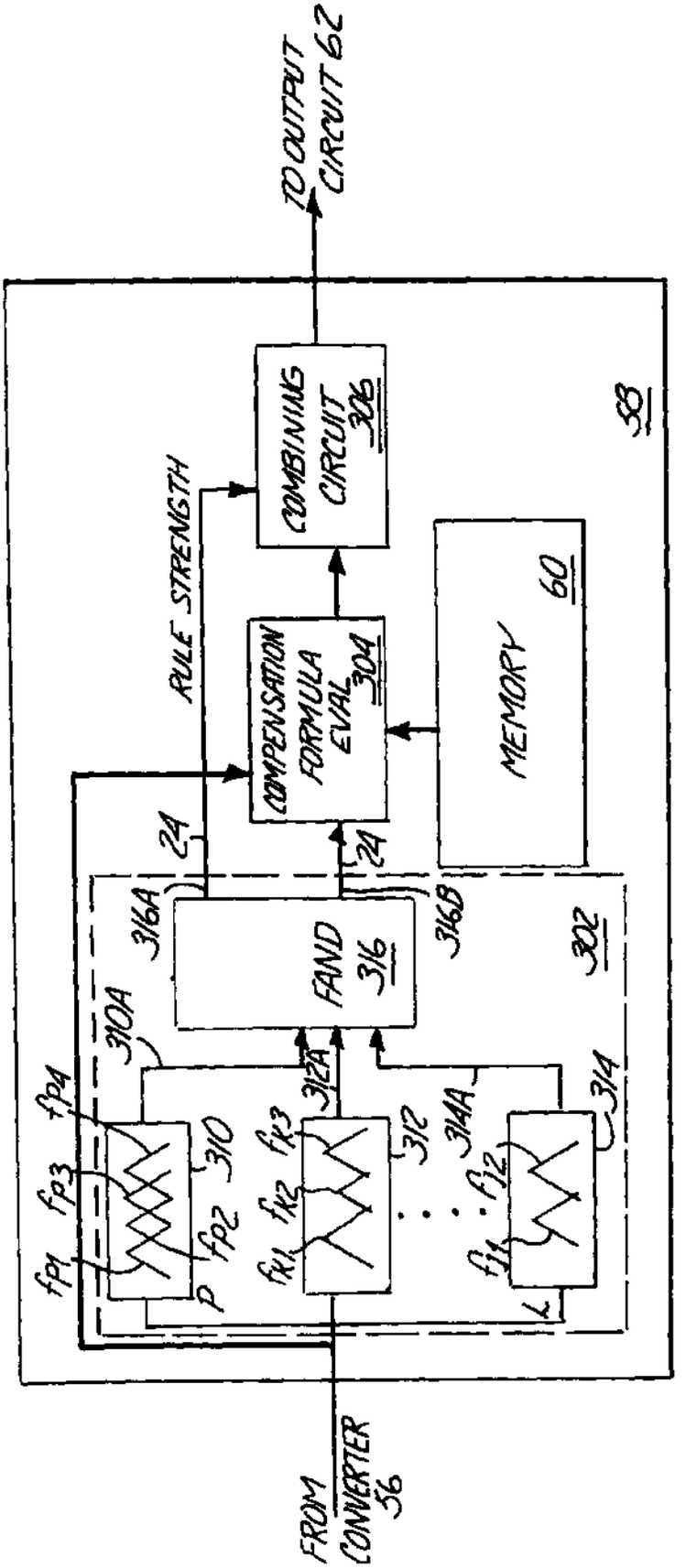

TO OUTPUT CIRCUIT 62
COMBINING CIRCUIT 306
RULE STRENGTH
COMPENSATION FORMULA EVAL 304
MEMORY 60
58
24
24
316A
316B
FAND 316
302
310A
312A
314A
310
312
314
fp1
fp2
fp3
fp4
fk1
fk2
fk3
fj1
fj2
P
L
FROM CONVERTER 56

Fig.5

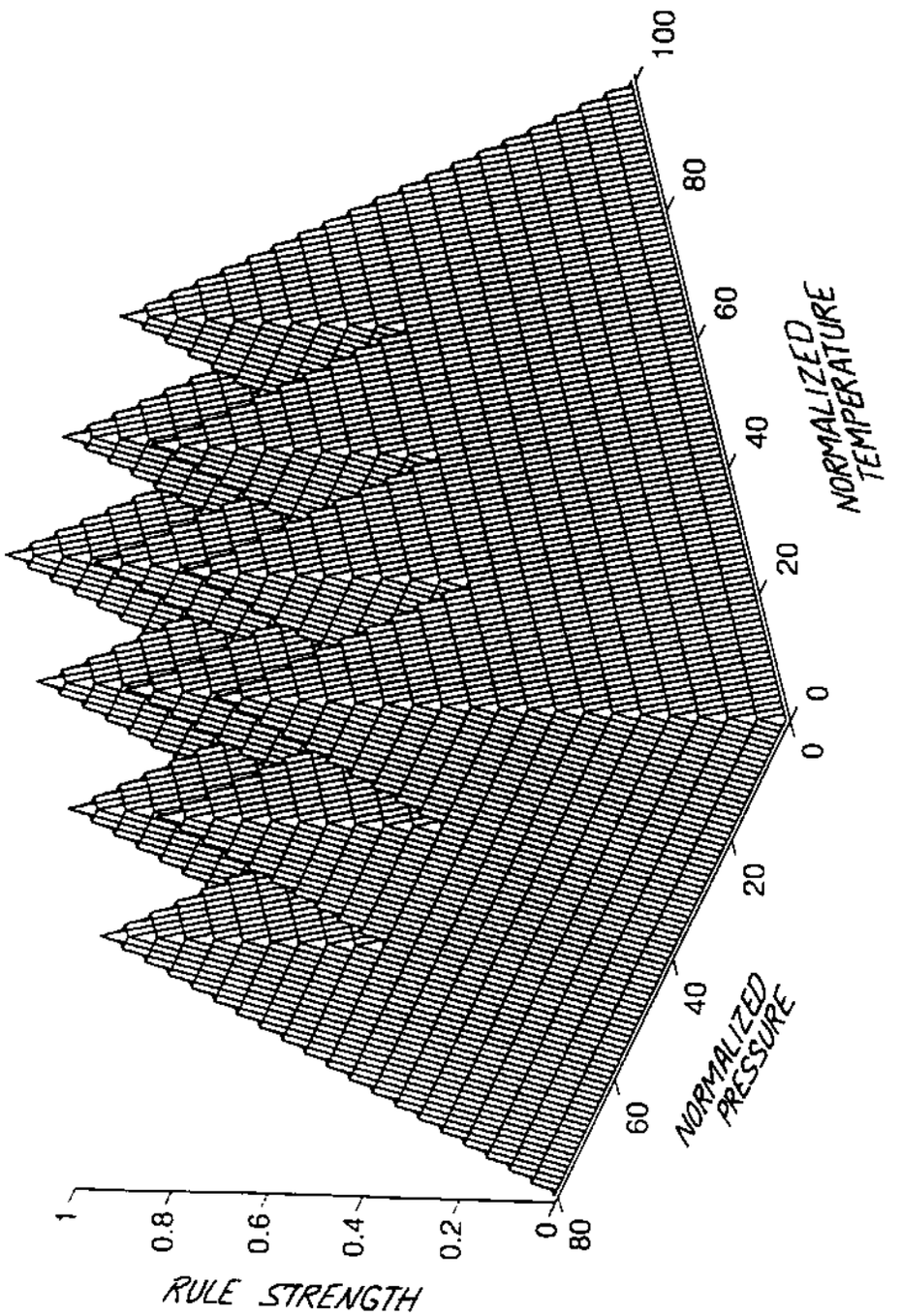

RULE STRENGTH
1
0.8
0.6
0.4
0.2
0
NORMALIZED PRESSURE
80
60
40
20
0
NORMALIZED TEMPERATURE
0
20
40
60
80
100

Fig. 6

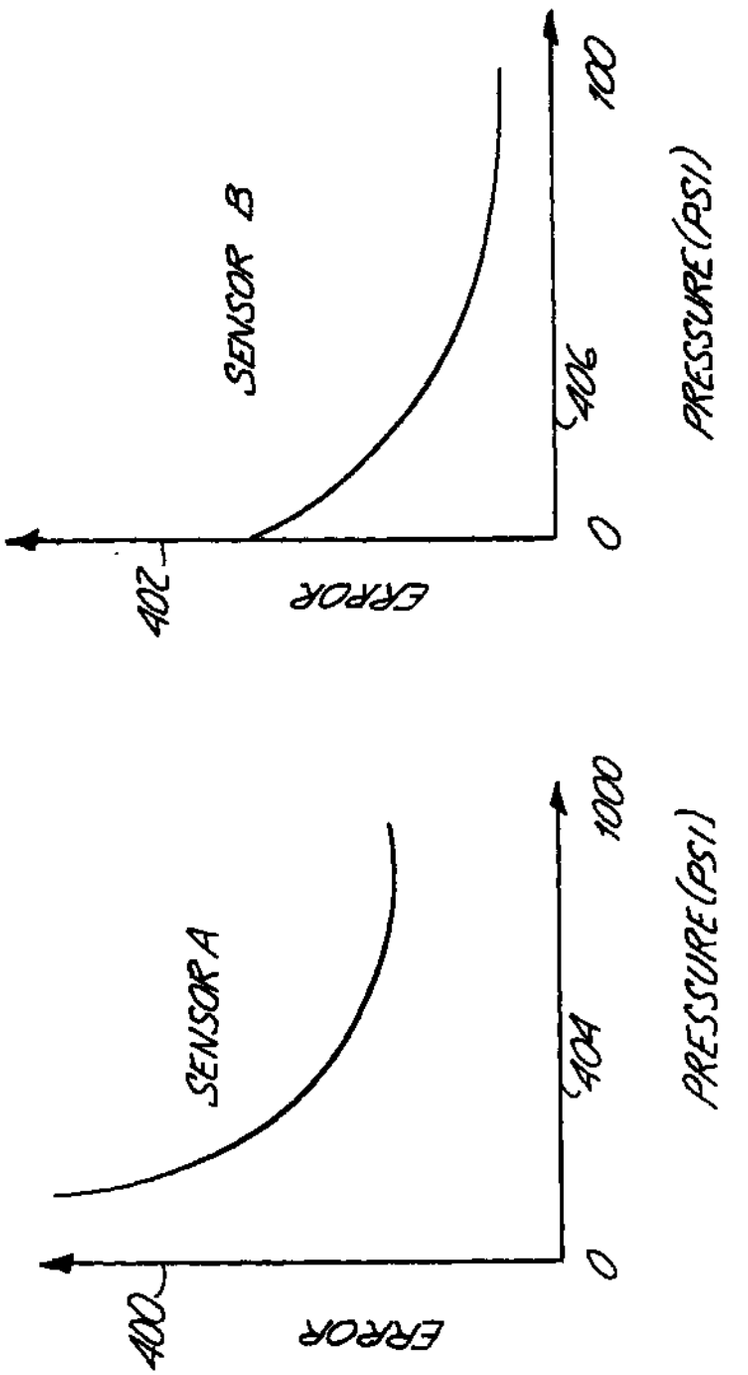

SENSOR B
ERROR
402
0
406
100
PRESSURE (PSI)
SENSOR A
ERROR
400
0
404
1000
PRESSURE (PSI)

Fig. 7