(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
22 February 2007 (22.02.2007)

PCT

(10) International Publication Number
WO 2007/021419 A1

(51) International Patent Classification:
G05B 23/02 (2006.01)

(21) International Application Number:
PCT/US2006/027541

(22) International Filing Date: 14 July 2006 (14.07.2006)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
11/205,745 17 August 2005 (17.08.2005) US

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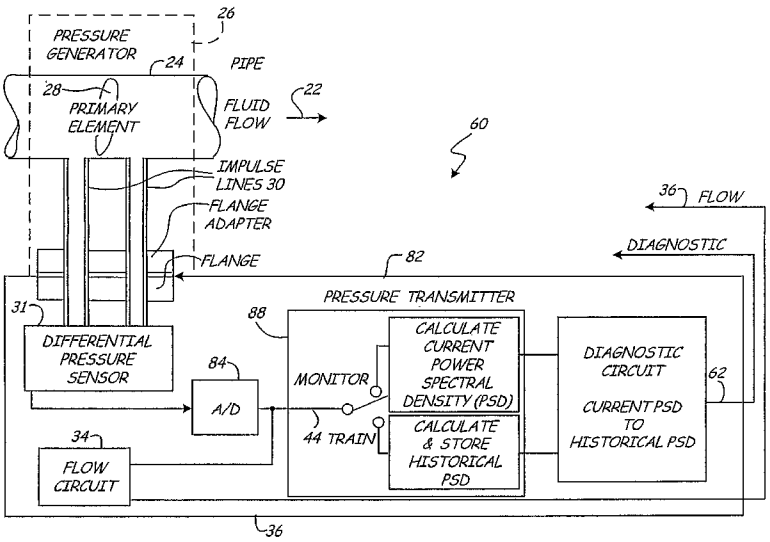
(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) **Title:** PROCESS VARIABLE TRANSMITTER WITH DIAGNOSTICS



(57) **Abstract:** A process variable transmitter (60, 82, 230, 232, 234, 238) with diagnostics based on power spectral density (PSD) analysis of a process variable sensor signal is provided. In one embodiment, the process variable transmitter (60, 82, 230, 232, 234, 238) is a pressure transmitter (82) and the diagnostics are used to diagnose impulse line obstruction or impending obstruction. Other diagnostics are also useful such as diagnosing primary element degradation. The sensor signal is digitized and the digitized signal is transferred into the frequency domain. The power of the frequencies on the sensor signal is examined to provide the enhanced diagnostics. In one aspect diagnostics are generated directly with the sensor PSD data. In another aspect, the PSD analysis is used to tune a filter in order to enhance traditional diagnostic algorithms.

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PROCESS VARIABLE TRANSMITTER WITH DIAGNOSTICS

BACKGROUND OF THE INVENTION

Process variable transmitters are used in industrial process control environments and couple to the process fluid and provide measurements relative to the process. Process variable transmitters can be configured to monitor one or more process variables associated with fluids in a process plant such as slurries, liquids, vapors and gasses in chemical, pulp, petroleum, gas, pharmaceutical, food and other fluid processing plants. The monitored process variables can be pressure, temperature, flow, level, pH, conductivity, turbidity, density, concentration, chemical composition or other properties of fluids. Process variable transmitter includes one or more sensors that can be either internal to the transmitter or external to the transmitter, depending on the installation needs of the process plant. Process variable transmitters generate one or more transmitter outputs that represent the sensed process variable. Transmitter outputs are configured for transmission over long distances to a controller or indicator via communication busses 242. In typical fluid processing plants, a communication buss 242 can be a 4-20 mA current loop that powers the transmitter, or a fieldbus connection, a HART protocol communication or a fiber optic connection to a controller, a control system or a readout. In transmitters powered by a 2 wire loop, power must be kept low to provide intrinsic safety in explosive atmospheres.

One type of process variable transmitter is known as a pressure transmitter. Typically, a pressure transmitter will be coupled to the process fluid through impulse lines. Pressure transmitter operation can easily deteriorate if one or both of the impulse lines becomes plugged.

Disassembly and inspection of the impulse lines is one method used to detect and correct plugging of lines. Another known method for detecting plugging is to periodically add a "check pulse" to the measurement signal from a pressure transmitter. This check pulse causes a control system connected to the transmitter to disturb the flow. If the pressure transmitter fails to accurately sense the flow disturbance, an alarm signal is generated indicating line plugging. Another known method for detecting plugging is sensing of both static and differential pressures. If there is inadequate correlation between oscillations in the static and differential pressures, then an alarm signal is generated indicating line plugging. Still another known method for detecting line plugging is to sense static pressures and pass them through high pass and low pass filters. Noise signals obtained from the filters are compared to a threshold, and if variance in the noise is less than the threshold, then an alarm signal indicates that the line is blocked.

These known methods use techniques which can increase the complexity and reduce reliability of the devices. Moreover, while these methods can sometimes detect a plugged impulse line, they generally cannot detect when deposits begin to collect within the impulse line, but do not yet plug the impulse line.

Thus, operation may continue even though the pressure transmitter's ability to sense pressure has been compromised to some extent. There is thus a need for a better diagnostic technology providing more predictive, less reactive maintenance for reducing cost or improving reliability.

SUMMARY OF THE INVENTION

A process variable transmitter with diagnostics based on power spectral density (PSD) analysis of a process variable sensor signal is provided. In one embodiment, the process variable transmitter is a pressure transmitter and the diagnostics are used to diagnose impulse line obstruction or impending obstruction. Other diagnostics are also useful such as diagnosing primary element degradation. The sensor signal is digitized and the digitized signal is transferred into the frequency domain. The power of the frequencies on the sensor signal is examined to provide the enhanced diagnostics. In one aspect diagnostics are generated directly with the sensor PSD data. In another aspect, the PSD analysis is used to tune a filter in order to enhance traditional diagnostic algorithms.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an illustration of a typical fluid processing environment for a diagnostic pressure transmitter.

FIG. 2 is a pictorial illustration of an embodiment of a differential pressure transmitter used in a fluid flow meter that diagnoses the condition of its impulse lines and/or primary element.

FIG. 3 is a block diagram of a fluid flow meter that provides diagnostics in accordance with embodiments of the present invention.

FIGS. 4 - 6 are graphs illustrating PSD analysis of sensor data being indicative of impulse piping obstruction.

FIG. 7 is a flow chart of a method of training a process variable transmitter for PSD-based diagnostics in accordance with embodiments of the present invention.

FIG. 8 is a flow chart of a method of selecting digital filter characteristics based upon a PSD analysis in accordance with an embodiment of the present invention.

FIG. 9 is a flow chart of a method of performing PSD-based diagnostics in accordance with embodiments of the present invention.

FIG. 10 is a graph of amplitude versus frequency versus time of a process variable signal.

FIG. 11 is a block diagram of a discrete wavelet transformation.

FIG. 12 is a graph showing signals output from a discrete wavelet transformation.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Embodiments of the present invention generally perform a spectral analysis to generate diagnostic information relative to a process variable transmitter. This analysis is described as occurring within a microprocessor system within the process variable transmitter, but can be performed by any suitable processing system. The processing system 88 can perform a wavelet transformation, discrete wavelet

transformation, Fourier transformation, or use other techniques to determine the spectrum of the sensor signal. The power of the distributed frequencies is determined by monitoring such a converted signal over time. One example of this is the power spectral density (PSD). The power spectral density can be defined as the power (or variance) of a time series and can be described as how the power (or variance) of a time series is distributed with frequency. For example, this can be defined as the Fourier transform of an auto-correlation sequence of the time series. Another definition of power spectral density is the squared modulus of the Fourier transform of the time series, scaled by an appropriate constant term.

In FIG. 1, a typical environment for diagnostic flow or pressure measurement is illustrated at 220. Process variable transmitters such as flow meter 230, level (pressure) transmitters 232, 234 on tank 236 and integral orifice flow meter 238 are shown connected to control system 240.

In Fig. 1, integral orifice flow meter 238 is provided with a diagnostic output which is also coupled along the communication bus 242 connected to it. Control system 240 can be programmed to display the diagnostic output for a human operator, or can be programmed to alter its operation when there is a diagnostic warning from flow meter 238. Control system 240 controls the operation of output devices such as control valve 244, pump motors or other controlling devices.

In Fig. 2, an exploded view of a typical diagnostic transmitter 82 according to the present invention is shown generally. Transmitter 82 includes

a flange 83 for receiving a differential pressure, a differential pressure sensor 31, electronics including an analog to digital converter 84, a microprocessor system 88, a digital to analog converter 96, and a digital communications circuit 100. Transmitter 82 is bolted to flange adapter 87. In embodiments shown herein, sensor 31 can comprise an absolute, gage, differential or other type of pressure sensor. Embodiments of the invention are useful in a number of applications, but are particularly advantageous where a process device is coupled to the process through impulse piping. Microprocessor 88 is programmed with diagnostic algorithms, which will be explained in greater detail below. Flange adapter 87 connects to impulse pipes which, in turn, connect to flow around a primary flow element (not shown in FIG. 2). The arrangement of transmitter 82 of FIG. 2 is explained in more detail in FIG. 3.

FIG. 3 is a block diagram showing a fluid flow meter 60 adapted to sense fluid flow 22 in pipe 24. Fluid flow meter 60 includes a pressure generator 26 that includes a primary element 28 and impulse lines 30 that couple pressures generated in the fluid flow around the primary element 28 to a differential pressure sensor 31 in a pressure transmitter 82. The term "pressure generator" as used in this application means a primary element (e.g., an orifice plate, a pitot tube averaging pitot tubing, a nozzle, a venturi, a shedding bar, a bend in a pipe or other flow discontinuity adapted to cause a pressure drop in flow) together with impulse pipes or impulse passageways that couple the pressure drop from locations near the primary element to a location

outside the flow pipe. The spectral characteristics of this pressure presented by this defined "pressure generator" at a location outside the flow pipe to a connected pressure transmitter 82 can be affected by the condition of the primary element as well as by the condition of the impulse pipes. The connected pressure transmitter 82 can be a self-contained unit, or it can be fitted with remote seals as needed to fit the application. A flange 83 on the pressure transmitter 82 (or its remote seals) couples to a flange adapter 87 on the impulse lines 30 to complete the pressure connections. Pressure transmitter 82 couples to a primary flow element 28 via impulse lines 30 to sense flow. The pressure transmitter 82 comprises a differential pressure sensor 31 adapted to couple to the impulse lines 30 via a flange arrangement. An analog to digital converter 84 couples to the pressure sensor 31 and generates a series of digital representations of the sensed pressure. These digital representations are used by flow circuit 34 to compute flow and provide an indication of flow along line 36.

In one embodiment of the present invention, analog-to-digital converter is a known Sigma-Delta converter providing 22 conversions per second. In this embodiment, each converted digital representation of the process variable becomes a data point for Power Spectral Density (PSD) analysis. Preferably, a 32 point Fast Fourier Transform (FFT) is applied to the digital process data points to generate PSD information. Since the PSD analysis operates using a known analog-to-digital converter operating in a known manner, this embodiment of the present invention can be implemented wholly in software by adapting the

operation of microprocessor system 88. Thus, embodiments of the present invention can be applied to process variable transmitters that are currently installed in the field, or already manufactured, without having to modify their circuitry. Algorithms for performing the PSD analysis are set forth below.

Sigma-Delta converters are often used in the process measurement and control industry due to their fast conversion times and high accuracy. Sigma-Delta converters generally employ an internal capacitor charge pumping scheme that generates a digital bitstream that is analyzed, generally by counting positive 1's over a set interval. For example, one Sigma-Delta converter currently in use provides a bitstream signal consisting of 50% 1's to indicate the minimum pressure measurement, and 75% 1's to indicate the maximum pressure measurement. The digital bitstream is generally filtered to remove or attenuate fluctuating components prior to determination of the flow rate. The filtered data is then used with well-known equations to compute either the mass flow rate or the volumetric flow rate.

In accordance with another embodiment of the present invention, the digital bitstream within the analog-to-digital converter is used directly for PSD analysis. This bitstream usually has a frequency that is many orders of magnitude higher than the conversion frequency. For example, a known Sigma-Delta converter provides a digital bitstream that has a frequency of approximately 57 kHz. While those skilled in the art will recognize many ways in which PSD analysis can be performed upon the digital bitstream, a preferred method is as follows. For a given interval, such as

ten seconds, digital data from the bitstream is collected and saved. In the example above, 10 seconds of 57 kHz data yields 570,000 stored bits. The DC component can be optionally removed from the stored data by subtracting the average bit value (Number of 1's divided by the total number of bits) from each stored bit. Next, power spectral density is computed on the adjusted data. This is preferably done using a 65536 point FFT and a Hanning Window size of 65536. The size of the FFT was chosen because it is the power of 2 closest to the sampling bit frequency, and given a duration of ten seconds, it provides acceptable averaging of the spectrum. However, other sizes may be used in accordance with embodiments of the present invention.

Power spectral density, Fi, can be calculated using Welch's method of averaged periodograms for a given data set. The method uses a measurement sequence *x(n)* sampled at *fs* samples per second, where *n = 1, 2, ...N* . A front end filter with a filter frequency less than *fs/2* is used to reduce aliasing in the spectral calculations. The data set is divided into $F_{k,i}$ as shown in Eq. 1:

$$F_{k,i} = (1/M) \left| \sum_{n=1}^{M} x_k(n)\, e^{-j2\pi i \Delta f n} \right|^2 \qquad \text{Eq. 1}$$

There are $F_{k,i}$ overlapping data segments and for each segment, a periodogram is calculated where M is the number of points in the current segment. After all

periodograms for all segments are evaluated, all of them are averaged to calculate the power spectrum:

$$Fi = (1/L) \sum_{k=1}^{L} F_{k,i} \qquad \text{Eq. 2}$$

Once a power spectrum is obtained for a training mode, this sequence is stored in memory, preferably EEPROM, as the baseline power spectrum for comparison to real time power spectrums. Fi is thus the power spectrum sequence and i goes from 1 to N which is the total number of points in the original data sequence. N, usually a power of 2, also sets the frequency resolution of the spectrum estimation. Therefore, Fi is also known as the signal strength at the i^{th} frequency. The power spectrum typically includes a large number points at predefined frequency intervals, defining a shape of the spectral power distribution as a function of frequency.

In the performance of diagnostics using power spectral density, a relatively larger sample of the spectral density at baseline historical conditions and a relatively smaller sample of the spectral density at monitoring conditions are compared. The relatively smaller sample allows for a real time indication of problems in about 1 second. An increase in the related frequency components of the power spectrum can indicate the degradation of one or both impulse lines, and/or of the primary element. FIGS. 4-6 illustrate PSD data from a digital bitstream. These figures show three different impulse line conditions: fully open; partially obstructed with 0.0135 inch

diameter holes; and substantially obstructed with 0.005 inch holes. As can be seen from FIGS. 5 and 6, integrating the bitstream data from 1 to 10 Hertz, and/or from 10 - 30 Hertz provides an effective indication of impulse line plugging.

Microprocessor system 88 receives the series of digital representations (either individual digital conversions, or digital bitstream, or any combination thereof. Microprocessor system 88 has an algorithm stored therein that compares PSD data during a monitoring mode with PSD data acquired during a training mode. This comparison allows the process variable transmitter to detect fault that can affect the process variable measurement. This fault can be the plugging of impulse lines in a pressure transmitter, the deterioration of a primary element, or any other factor. System 88 generates diagnostic data 62 as a function of the current data set relative to the historical. A digital to analog converter 96 coupled to the microprocessor system 88 generates an analog transmitter output 98 indicative of the sensed flow rate. A digital communication circuit 100 receives the diagnostic data 94 from the microprocessor system 88 and generates a transmitter output 102 indicating the diagnostic data. The analog output 98 and the diagnostic data 102 can be coupled to indicators or controllers as desired.

FIG. 7 is a flow diagram of a method of training a process variable transmitter for diagnostics in accordance with embodiments of the present invention. Method 250 begins at Start block 252. Block 252 can be executed anytime that there is a relative certainty that the process variable

transmitter is fully functional and coupled to a process that is operating within specifications. Usually block 252 will be initiated by a technician, but block 252, in some circumstances, may be initiated remotely. Method 250 continues at block 254 where process value data is received. This data can include a plurality of digital indications. These indications can be individually converted process variable conversions; bits in a bitstream within an analog-to-digital converter; or any combination thereof. At block 256, an FFT is performed on the digital data. This FFT can be done in accordance with any known methods. Moreover, alternate methods for analyzing spectral components of the data can be performed instead of, or in addition to, FFT at block 256. At block 258, the power of the FFT's is calculated. This power information is then stored in the process variable transmitter. At step 260, the method determines if sufficient training has occurred. This can be done by checking whether sufficient time has passed, whether sufficient training data has been acquired, or any other suitable method. If training is not done, method 260 returns to block 254 and training continues. However, if training is determined to be complete at step 260, method 250 will end and the final set of power data Fi will be stored in nonvolatile memory within the process variable transmitter.

While many embodiments of the present invention employ PSD analysis of process sensor data for providing diagnostics directly, one embodiment does not. FIG. 8 illustrates a method of selecting digital filter parameters using PSD analysis. Method

270 begins by executing a training method 272, which is preferably identical to method 250. At block 274, the power of the frequencies is examined. At block 276, digital filter frequencies are chosen based upon an analysis of the power spectral density. The choice of frequencies includes selecting which "bins" in the FFT to use. The question is not only which bins to use, but also how many bins to use. This choice can be as simple as selecting one bin, or more complex. For example, non-adjoining bins could be selected; adjoining bins could be selected; all bins that contribute to the whole could be selected and weighed based on their respective magnitudes; or any combination thereof. Choosing bins can be done using a number of criteria. For example, the bin(s) with the most power could be selected; the bin(s) with the most variance in power could be selected; the bin(s) with the least variance in power could be selected; the bin(s) with the least magnitude could be selected; the bin(s) with the highest standard deviation could be selected; the bin(s) with the lowest standard deviation could be selected; or a group of adjacent bins with similar magnitudes could be selected. Once the bins are selected, the corresponding filter characteristics are used to digitally filter the sensor data, as indicated at block 278. The so filtered data can then be used for more effective process measurement and/or diagnostics. Thus, the filter characteristics can be chosen dynamically based upon PSD analysis of the sensor data. The filtered data could even be used with known statistical line plugging algorithms and techniques in accordance with embodiments of the present invention.

FIG. 9 is a flow chart of a method of performing PSD-based diagnostics in accordance with embodiments of the present invention. Many factors can affect the digital bitstream and thus the process variable. The impulse lines can become clogged and/or the primary element can become eroded or fouled. Method 280 begins at block 282, where training occurs. Block 282 is preferably identical to training method 250 described with respect to FIG. 7. Once training has completed, method 280 moves to block 284 where the process value data is calculated. Again, this data can be a set of individual analog-to-digital converted readings from converter 84, or the data include all or part of a digital bitstream generated within converter 84. At block 286, the data is converted into the frequency domain, preferably using FFT. At block 288, the power of the FFT's is calculated yielding a set Fi of power spectral data related to the process variable. At block 290, the set Fi is compared to the stored training data set Fi. This comparison can take many forms. For example, the comparison can include examining the sum of the magnitudes for selected spectral ranges. The comparison can also include comparing the standard deviation and mean of Fi compared to the standard deviation and mean of Fi. Yet another comparison includes comparing frequency ranges that are consistently of a higher or lower magnitude. Referring back to FIG. 6, using digital bitstream data, the "fully open" condition would correspond to the training set Fi. Thus, comparing the integral of the bitstream spectrum from a selected frequency range can show that when the impulse lines are beginning to clog, the integral of the spectrum drops

substantially. One frequency range that has worked well in testing is between 10 and 40 Hz. However, a range between 10 and 30 Hz is also believed to be beneficial. Finally, there appears to be useful information provided in the 30 - 40 Hz range that may also be useful for detecting partial, or full, impulse line plugging. The difference between Fi and Fi as indicated by the integral of a selected spectrum can be compared to a preselected threshold to determine if a fault exists. At block 292, fault determination is performed based upon the comparison(s) in block 290. If a fault is revealed, control passes to block 294 where the fault is indicated, and process variable transmitter operation can be optionally halted. This fault indication can be a local indication such as a device alarm, or an indication communicated to a remote entity such as a control room or operator. The fault indication may indicate a current critical fault, or it may indicate an impending fault. If no fault is found, control returns to block 284 and the method continues to monitor the process device operation.

Any of the methods can be stored on a computer-readable medium as a plurality of sequences of instructions, the plurality of sequences of instructions including sequences that, when executed by a microprocessor system in a pressure transmitter cause the pressure transmitter to perform a diagnostic method relative to a primary element and impulse lines couplable to the transmitter.

In one embodiment, microprocessor system 88 includes signal preprocessor which is coupled to sensor 31 through analog to digital converter 84 which

isolates signal components in the sensor signal such as frequencies, amplitudes or signal characteristics which are related to a plugged impulse line 30 or degraded primary element 28. The signal preprocessor provides an isolated signal output to a signal evaluator in microprocessor 88. The signal preprocessor isolates a portion of the signal by filtering, performing a wavelet transform, performing a Fourier transform, use of a neural network, statistical analysis, or other signal evaluation techniques. Such preprocessing is preferably implemented in microprocessor 88 or in a specialized digital signal processor. The isolated signal output is related to a plugged or plugging impulse line 30 or degraded primary element 28 sensed by sensor 31.

The signal components are isolated through signal processing techniques in which only desired frequencies or other signal characteristics such as amplitude are identified and an indication of their identification is provided. Depending upon the strength signals to be detected and their frequency, signal preprocessor can comprise a filter, for example a band pass filter, to generate the isolated signal output. For more sensitive isolation, advanced signal processing techniques are utilized such as a Fast Fourier transform (FFT) to obtain the spectrum of the sensor signal. In one embodiment, the signal preprocessor comprises a wavelet processor which performs a wavelet analysis on the sensor signal as shown in FIGS. 10, 11 and 12 using a discrete wavelet transform. Wavelet analysis is well suited for analyzing signals which have transients or other non-stationary characteristics in the time domain. In

contrast to Fourier transforms, wavelet analysis retains information in the time domain, i.e., when the event occurred.

Wavelet analysis is a technique for transforming a time domain signal into the frequency domain which, like a Fourier transformation, allows the frequency components to be identified. However, unlike a Fourier transformation, in a wavelet transformation the output includes information related to time. This may be expressed in the form of a three dimensional graph with time shown on one axis, frequency on a second axis and signal amplitude on a third axis. A discussion of wavelet analysis is given in On-Line Tool Condition Monitoring System With Wavelet Fuzzy Neural Network, by L. Xiaoli et al., 8 JOURNAL OF INTELLIGENT MANUFACTURING pgs. 271-276 (1997). In performing a continuous wavelet transformation, a portion of the sensor signal is windowed and convolved with a wavelet function. This convolution is performed by superimposing the wavelet function at the beginning of a sample, multiplying the wavelet function with the signal and then integrating the result over the sample period. The result of the integration is scaled and provides the first value for continuous wavelet transform at time equals zero. This point may be then mapped onto a three dimensional plane. The wavelet function is then shifted right (forward in time) and the multiplication and integration steps are repeated to obtain another set of data points which are mapped onto the 3-D space. This process is repeated and the wavelet is moved (convolved) through the entire signal. The wavelet function is then scaled, which changes the frequency

resolution of the transformation, and the above steps are repeated.

Data from a wavelet transformation of a sensor signal from sensor 31 is shown in FIG. 10. The data is graphed in three dimensions and forms a surface 300. As shown in the graph of FIG. 10, the sensor signal includes a small signal peak at about 1 kHz at time t_1 and another peak at about 100 Hz at time t_2. Through subsequent processing by the signal evaluator, surface 300 or portions of surface 300 are evaluated to determine impulse piping or primary element degradation.

The continuous wavelet transformation described above requires extensive computations. Therefore, in one embodiment, microprocessor system 88 performs a discrete wavelet transform (DWT) which is well suited for implementation in microprocessor system. One efficient discrete wavelet transform uses the Mallat algorithm, which is a two channel sub-band coder. The Mallet algorithm provides a series of separated or decomposed signals which are representative of individual frequency components of the original signal. FIG. 11 shows an example of such a system in which an original sensor signal S is decomposed using a sub-band coder of a Mallet algorithm. The signal S has a frequency range from 0 to a maximum of f_{MAX}. The signal is passed simultaneously through a first high pass filter having a frequency range from 1/2 f_{MAX} to f_{MAX}, and a low pass filter having a frequency range from 0 to 1/2 f_{MAX}. This process is called decomposition. The output from the high pass filter provides "level 1" discrete wavelet transform coefficients. The level 1

coefficients represent the amplitude as a function of time of that portion of the input signal which is between 1/2 f_{max} and f_{MAX}. The output from the 0 - 1/2 f_{max} low pass filter is passed through subsequent high pass (1/4 f_{max} - 1/2 f_{max}) and low pass (0 - 1/4 f_{max}) filters, as desired, to provide additional levels (beyond "level 1") of discrete wavelet transform coefficients. The outputs from each low pass filter can be subjected to further decompositions offering additional levels of discrete wavelet transformation coefficients as desired. This process continues until the desired resolution is achieved or the number of remaining data samples after a decomposition yields no additional information. The resolution of the wavelet transform is chosen to be approximately the same as the sensor or the same as the minimum signal resolution required to monitor the signal. Each level of DWT coefficients is representative of signal amplitude as a function of time for a given frequency range. Coefficients for each frequency range are concatenated to form a graph such as that shown in FIG. 10.

In some embodiments, padding is added to the signal by adding data to the sensor signal near the borders of windows used in the wavelet analysis. This padding reduces distortions in the frequency domain output. This technique can be used with a continuous wavelet transform or a discrete wavelet transform. "Padding" is defined as appending extra data on either side of the current active data window, for example, extra data points are added which extend 25% of the current window beyond either window edge. In one embodiment, the padding is generated by repeating a

portion of the data in the current window so that the added data "pads" the existing signal on either side. The entire data set is then fit to a quadratic equation which is used to extrapolate the signal 25% beyond the active data window.

FIG. 12 is an example showing a signal S generated by sensor 31 and the resultant approximation signals yielded in seven decomposition levels labeled level 1 through level 7. In this example, signal level 7 is representative of the lowest frequency DWT coefficient which can be generated. Any further decomposition yields noise. All levels, or only those levels which relate impulse piping or primary element degradation are provided.

Microprocessor 88 evaluates the isolated signal received from the signal preprocessing and in one embodiment, monitors an amplitude of a certain frequency or range of frequencies identified and provides a diagnostic output if a threshold is exceeded. Signal evaluator can also comprise more advanced decision making algorithms such as fuzzy logic, neural networks, expert systems, rule based systems, etc. Commonly assigned U.S. Patent No. 6,017,143 describes various decision making systems which can be implemented in signal evaluator 154 and is incorporated herein by reference.

Microprocessor 88 performs diagnostics related to the impulse piping or primary element using information derived from the differential pressure sensor 31. The following describes a number of embodiments for realizing a diagnostic circuit. The diagnostic circuit can provide a residual lifetime estimate, an indication of a failure, an indication of

an impending failure or a calibration output which is used to correct for errors in the sensed process variable.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes can be made in form and detail without departing from the spirit and scope of the invention. For example, various function blocks of the invention have been described in terms of circuitry, however, many function blocks may be implemented in other forms such as digital and analog circuits, software and their hybrids. When implemented in software, a microprocessor performs the functions and the signals comprise digital values on which the software operates. A general purpose processor programmed with instructions that cause the processor to perform the desired process elements, application specific hardware components that contain circuit wired to perform the desired elements and any combination of programming a general purpose processor and hardware components can be used. Deterministic or fuzzy logic techniques can be used as needed to make decisions in the circuitry or software. Because of the nature of complex digital circuitry, circuit elements may not be partitioned into separate blocks as shown, but components used for various functional blocks can be intermingled and shared. Likewise with software, some instructions can be shared as part of several functions and be intermingled with unrelated instructions within the scope of the invention. The diagnostic output can be a predictive indicator of a future failure, such as the future partial or complete

plugging of an impulse line. The diagnostics can be applied to impulse piping and/or primary elements. Finally, although various embodiments of the present invention have been described with respect to a pressure transmitter, embodiments of the present invention can be practiced with any process device where a sensor is coupled to the process device through an analog-to-digital converter.

WHAT IS CLAIMED IS:

1. A process variable transmitter for coupling to a process and providing an indication of a variable of the process over a communication bus, the process variable transmitter comprising:

a process variable sensor coupleable to the process to provide an analog indication of the variable;

an analog-to-digital converter coupled to the process variable sensor and providing digital information indicative of the analog indication provided by the sensor; and

output circuitry configured to provide an output related to the process variable;

a microprocessor system coupled to the analog-to-digital converter and configured to calculate power spectral density of the digital information and responsively generate diagnostic information based on the power spectral density.

2. The transmitter of claim 1, wherein the transmitter is a pressure transmitter coupleable to the process via a plurality of impulse lines.

3. The transmitter of claim 2, wherein the diagnostics are indicative of a condition of the impulse lines.

4. The transmitter of claim 3, wherein the diagnostics are indicative of partial plugging of at least one impulse line.

5. The transmitter of claim 4, wherein the diagnostics indicate a time when the impulse lines will become completely plugged.

6. The transmitter of claim 1, wherein the analog-to-digital converter provides the digital information as a plurality of discrete digitized conversion values.

7. The transmitter of claim 6, wherein the discrete digitized values are provided at a frequency of about 22 times per second.

8. The transmitter of claim 1, wherein the digital information includes digital bitstream data.

9. The transmitter of claim 8, wherein the bitstream data is provided at a frequency in excess of about 55 kHz.

10. The transmitter of claim 9, wherein the digital information is transferred to the frequency domain using a Fast Fourier Transform (FFT).

11. The transmitter of claim 10, wherein the power spectral density is computed using a Hanning window size of approximately 65536.

12. The transmitter of claim 11, wherein the diagnostic information is based on an integral of the power of frequencies ranging from about 1 to about 10 Hz.

13. The transmitter of claim 11, wherein the diagnostic information is based on an integral of the power of frequencies ranging from about 10 to about 30 Hz.

14. The transmitter of claim 11, wherein the diagnostic information is based on an integral of the power of frequencies ranging from about 10 to about 40 Hz.

15. The transmitter of claim 11, wherein the diagnostic information is based on an integral of the power of frequencies ranging from about 30 to about 40 Hz.

16. The transmitter of claim 1, wherein the digital information is transferred into the frequency domain using wavelet analysis.

17. The transmitter of claim 1, wherein the diagnostic information is generated based on a comparison of power spectral density information Fi with baseline power spectral density information Fi.

18. The transmitter of claim 17, wherein the comparison includes comparing the deviation in the sum of the magnitudes over selected frequencies.

19. The transmitter of claim 17, wherein the comparison includes comparing the standard deviation of the magnitudes over selected frequencies.

20. The transmitter of claim 17, wherein the baseline power spectral density is obtained during a training session.

21. The transmitter of claim 1, wherein the diagnostic information includes an indication of a fault.

22. The transmitter of claim 21, wherein the fault indication is a local fault indication.

23. The transmitter of claim 21, wherein the fault indication is transmitted over the communication buss.

24. The transmitter of claim 21, wherein the fault indication predicts a future event.

25. A method of predictively diagnosing a process variable transmitter having an analog-to-

digital converter coupled to a process variable sensor that is coupled to a process, the method comprising:

obtaining a plurality of digital data from the analog-to-digital converter;

calculating power spectral density of the plurality of digital data;

comparing the calculated power spectral density with baseline power spectral density;

generating a predictive diagnostic output based upon the comparison.

26. The method of claim 25, wherein the plurality of digital data include a plurality of digitized conversions.

27. The method of claim 25, wherein the plurality of digital data includes digital bitstream data.

28. The method of claim 25, wherein the diagnostic output is indicative of a condition of at least one impulse line.

29. A process variable transmitter for coupling to a process and providing an indication of a variable of the process over a communication buss, the process variable transmitter comprising:

a process variable sensor coupleable to the process to provide an analog indication of a variable of the process;

an analog-to-digital converter coupled to the process variable sensor and providing digital information indicative of the analog indication provided by the sensor; and

microprocessor means for generating a process value and for generating a diagnostic output using power spectral density analysis.

30. A method of configuring a digital filter in a process variable transmitter, the method comprising:

a process variable sensor coupleable to the process to provide an analog indication of a variable of the process;

a analog-to-digital converter coupled to the process variable sensor and providing digital information indicative of the analog indication provided by the sensor;

a microprocessor system coupled to the analog-to-digital converter, The microprocessor system providing digital filtering of the analog-to-digital converter using configurable filter characteristics; and

wherein the configurable filter characteristics are chosen based on a power spectral density analysis performed during a training session.

31. The method of claim 30, wherein the filtered digital information is used to provide a process variable output.

32. The method of claim 30, wherein the filtered digital information is used to provide a diagnostic output.

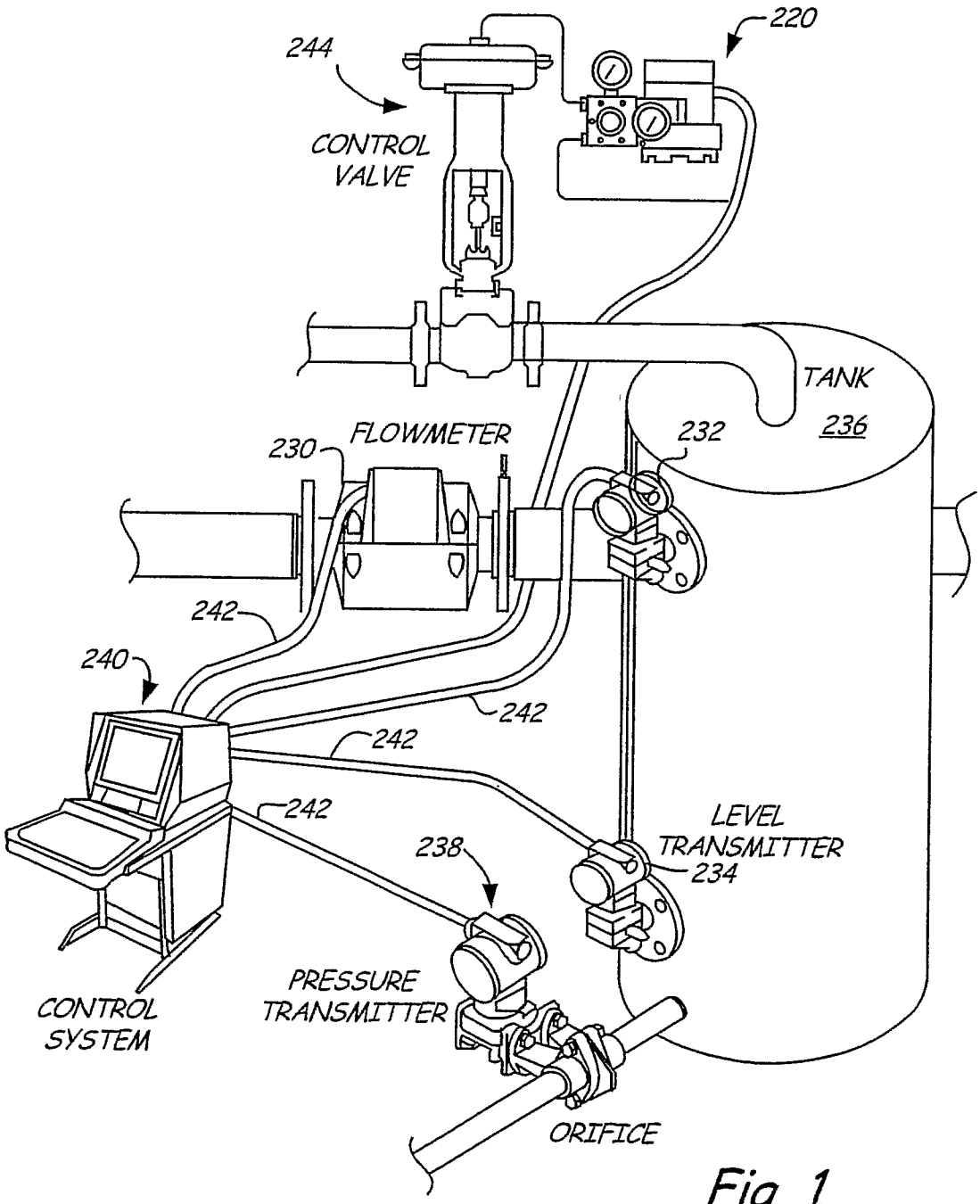
220
244
CONTROL VALVE
TANK
236
FLOWMETER
230
232
242
240
242
242
242
LEVEL TRANSMITTER
234
238
PRESSURE TRANSMITTER
CONTROL SYSTEM
ORIFICE

Fig. 1

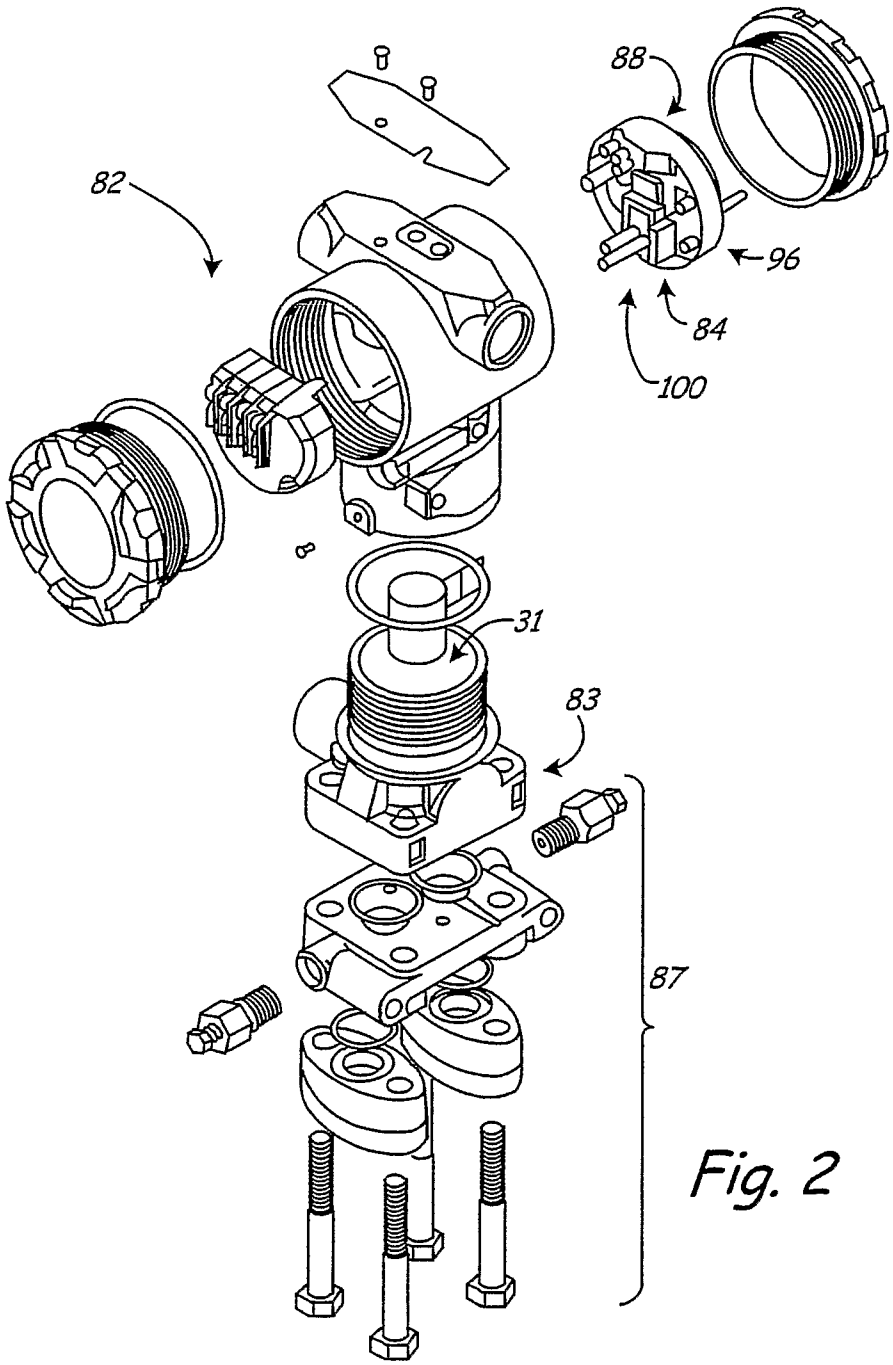

Fig. 2

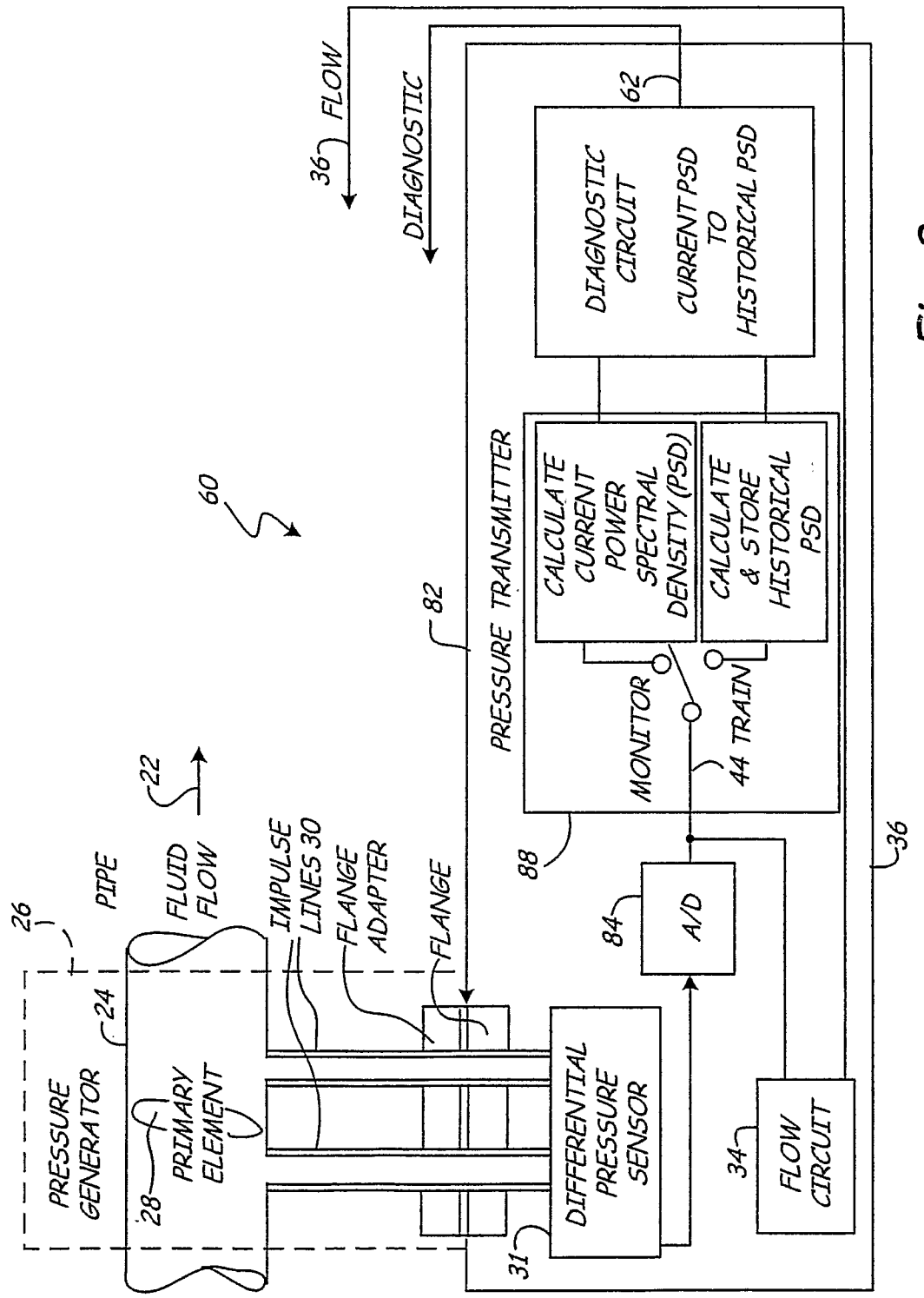
PRESSURE GENERATOR
PRIMARY ELEMENT
28
24
26
PIPE
FLUID FLOW
22
IMPULSE LINES 30
FLANGE ADAPTER
FLANGE
60
82
PRESSURE TRANSMITTER
88
DIFFERENTIAL PRESSURE SENSOR
31
84
A/D
MONITOR
44 TRAIN
CALCULATE CURRENT POWER SPECTRAL DENSITY (PSD)
CALCULATE & STORE HISTORICAL PSD
DIAGNOSTIC CIRCUIT
62
CURRENT PSD TO HISTORICAL PSD
DIAGNOSTIC
36
FLOW
34
FLOW CIRCUIT
36

Fig. 3

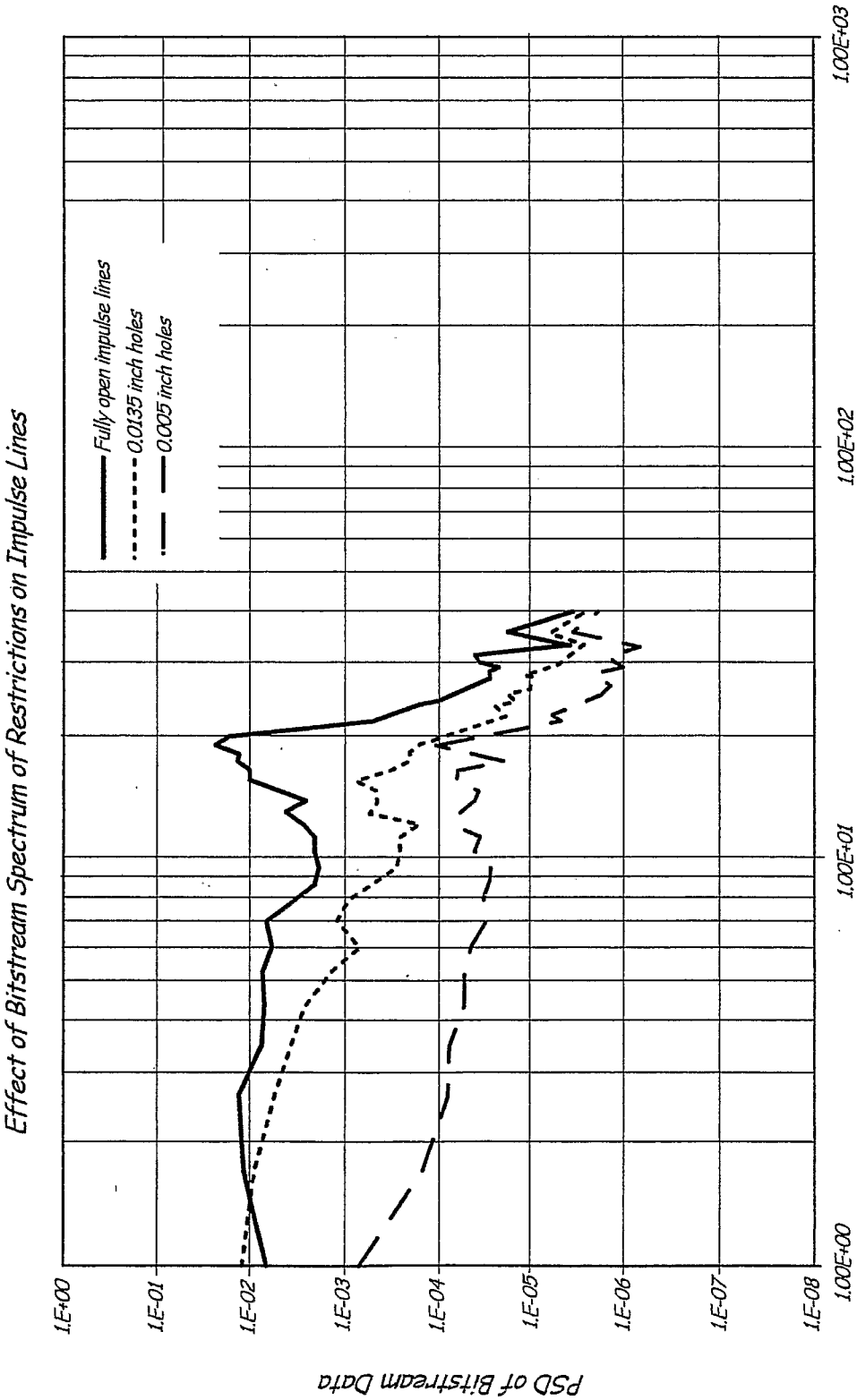
Effect of Bitstream Spectrum of Restrictions on Impulse Lines
Fully open impulse lines
0.0135 inch holes
0.005 inch holes
PSD of Bitstream Data
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.00E+00
1.00E+01
1.00E+02
1.00E+03
Frequency (Hz)

Fig. 4

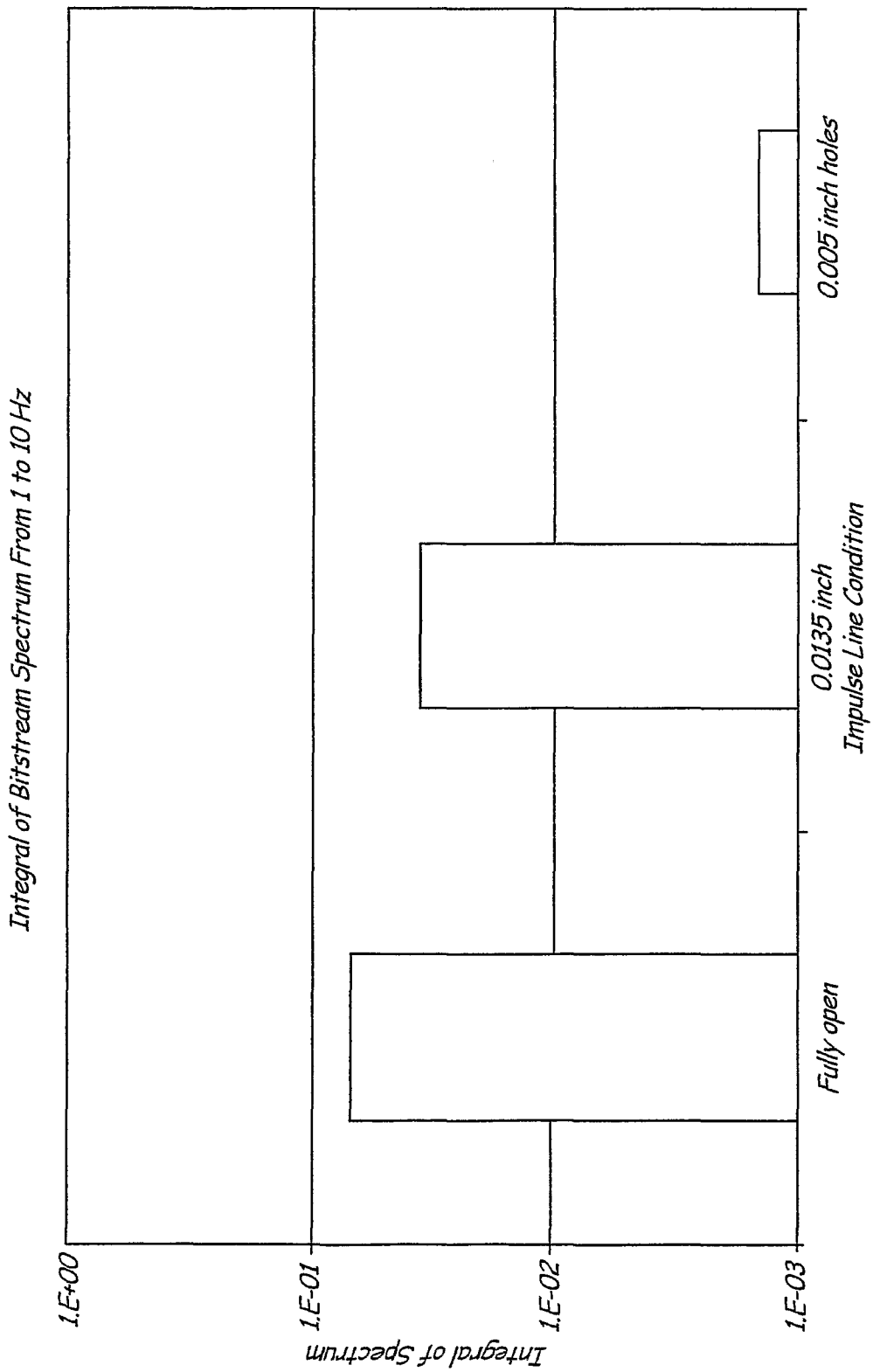
Integral of Bitstream Spectrum From 1 to 10 Hz
1.E+00
1.E-01
1.E-02
1.E-03
Integral of Spectrum
Fully open
0.0135 inch
Impulse Line Condition
0.005 inch holes

Fig. 5

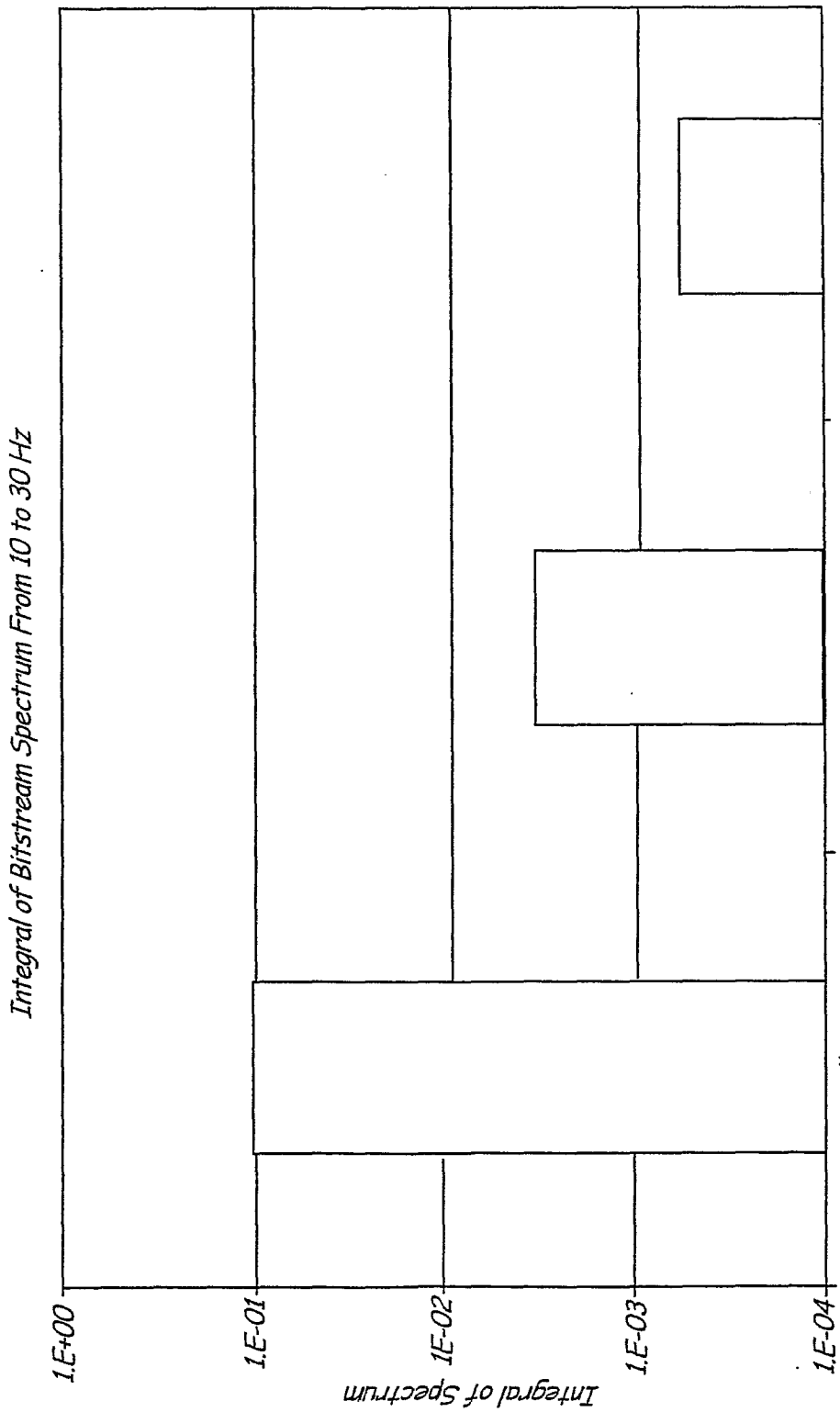
Integral of Bitstream Spectrum From 10 to 30 Hz
1.E+00
1.E-01
1E-02
1.E-03
1.E-04
Integral of Spectrum
Fully open
0.0135 inch holes
Impulse Line Condition
0.005 inch holes

Fig. 6

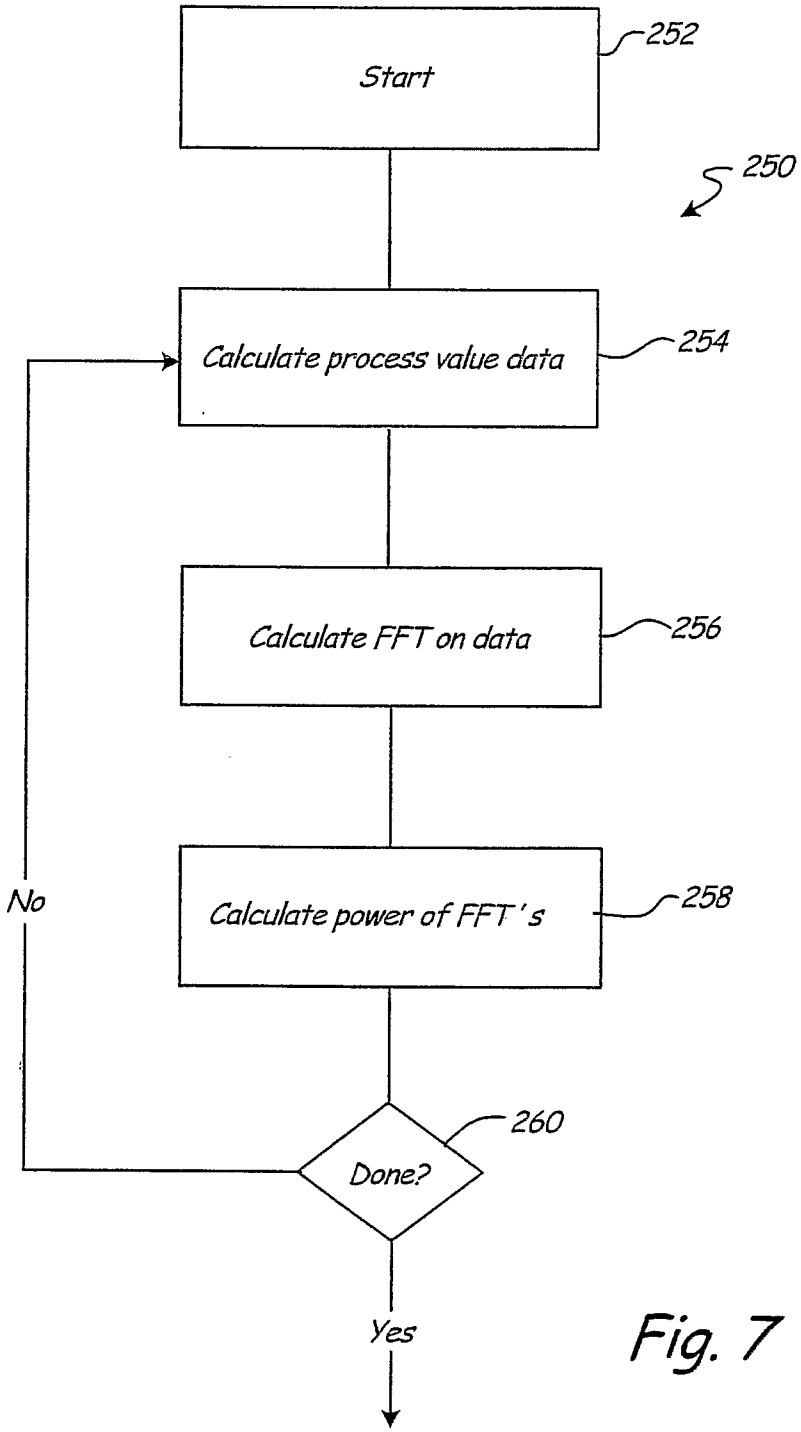
Start
252
250
Calculate process value data
254
Calculate FFT on data
256
Calculate power of FFT's
258
Done?
260
No
Yes

Fig. 7

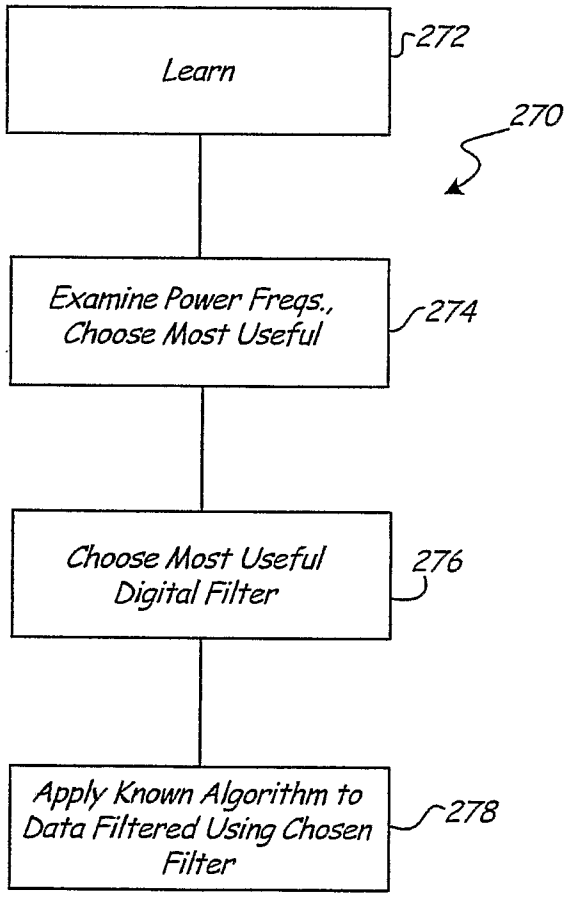
Learn
272
270
Examine Power Freqs., Choose Most Useful
274
Choose Most Useful Digital Filter
276
Apply Known Algorithm to Data Filtered Using Chosen Filter
278

Fig. 8

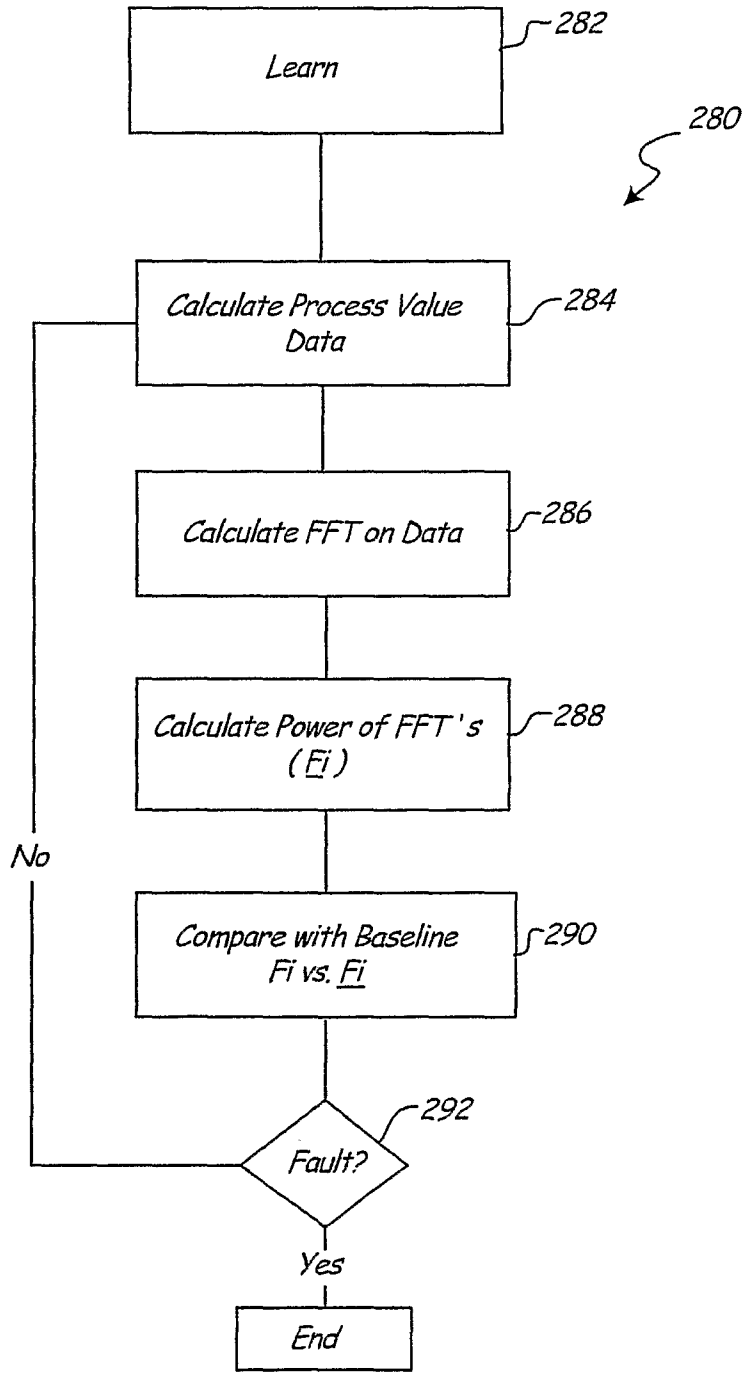
Learn
282
280
Calculate Process Value Data
284
Calculate FFT on Data
286
Calculate Power of FFT's (Fi)
288
No
Compare with Baseline Fi vs. Fi
290
Fault?
292
Yes
End

Fig. 9

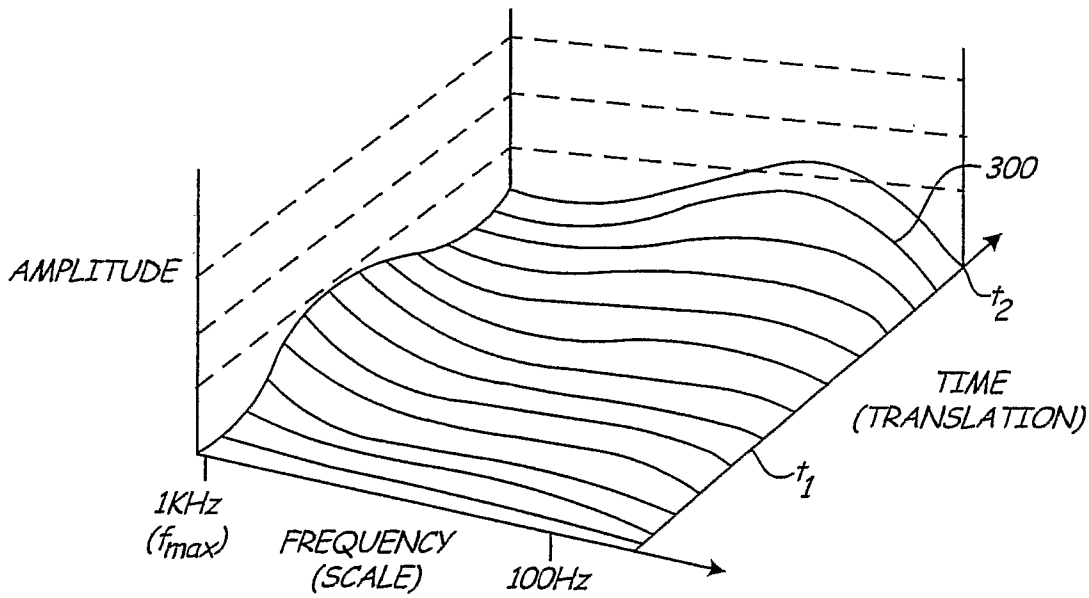
AMPLITUDE
1KHz
(f_{max})
FREQUENCY
(SCALE)
100Hz
t_1
t_2
300
TIME
(TRANSLATION)

Fig. 10

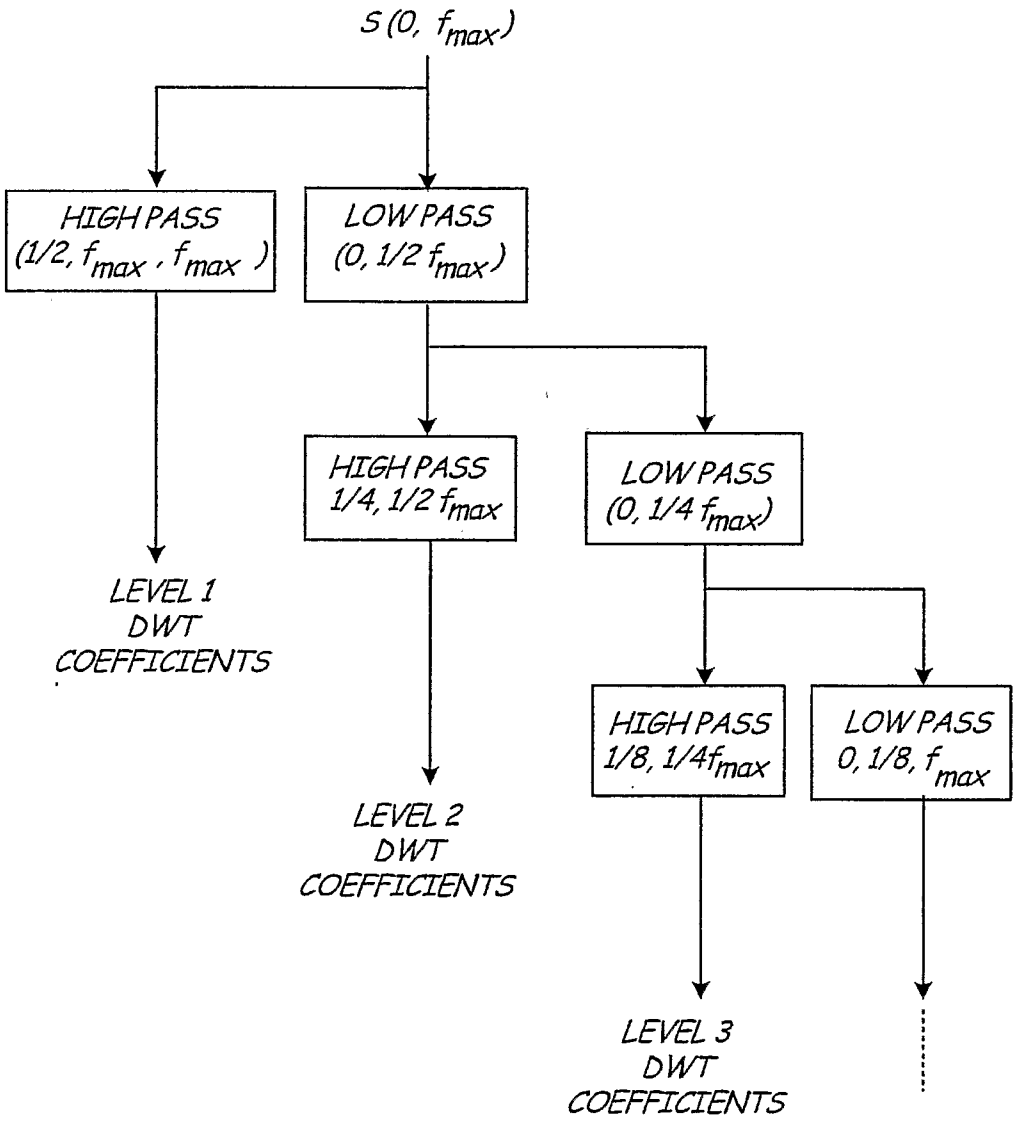
S (0, f_{max})
HIGH PASS (1/2, f_{max} , f_{max})
LOW PASS (0, 1/2 f_{max})
HIGH PASS 1/4, 1/2 f_{max}
LOW PASS (0, 1/4 f_{max})
HIGH PASS 1/8, 1/4f_{max}
LOW PASS 0, 1/8, f_{max}
LEVEL 1 DWT COEFFICIENTS
LEVEL 2 DWT COEFFICIENTS
LEVEL 3 DWT COEFFICIENTS

Fig. 11

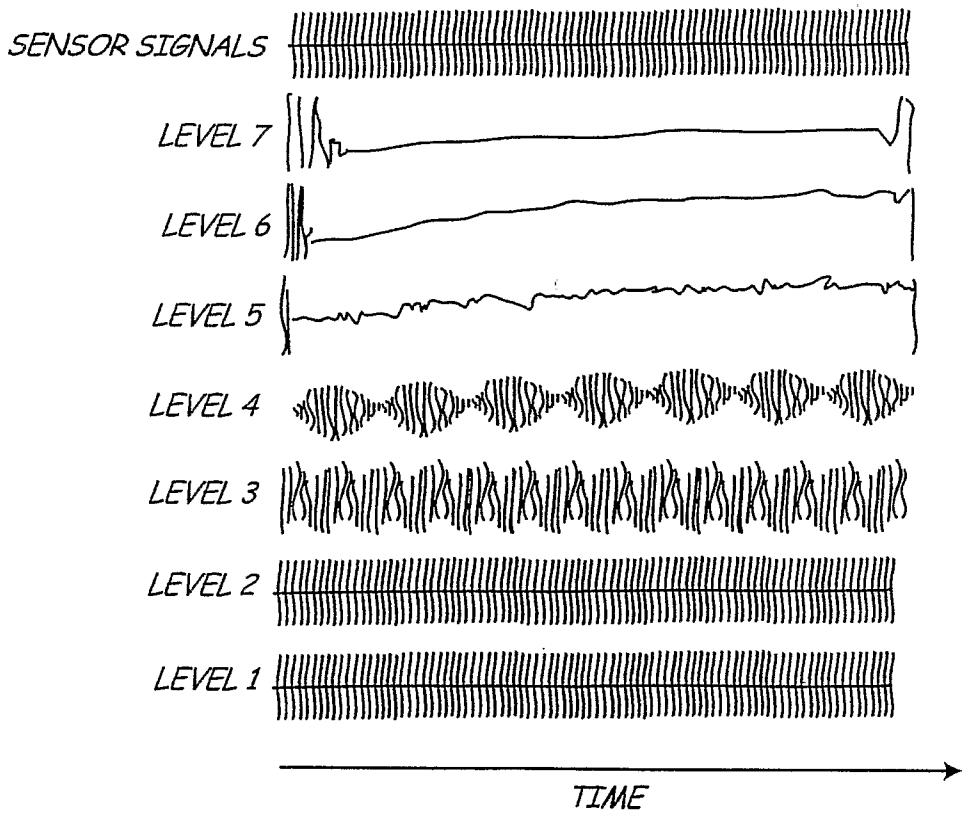
SENSOR SIGNALS
LEVEL 7
LEVEL 6
LEVEL 5
LEVEL 4
LEVEL 3
LEVEL 2
LEVEL 1
TIME

Fig. 12

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2006/027541

A. CLASSIFICATION OF SUBJECT MATTER
INV. G05B23/02

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)
G05B

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 practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 2002/029130 A1 (ERYUREK EVREN [US] ET AL) 7 March 2002 (2002-03-07) paragraph [0029] - paragraph [0032] paragraph [0060] - paragraph [0062]	1,2,17, 29-31 4,9,11
Y	US 6 654 697 B1 (ERYUREK EVREN [US] ET AL) 25 November 2003 (2003-11-25) column 9, line 28 - line 65	4,9
Y	EP 1 298 511 A1 (RELIANCE ELECTRIC TECHNOLOGIES [US]) 2 April 2003 (2003-04-02) paragraph [0065]	11
X	US 2004/249583 A1 (ERYUREK EVREN [US] ET AL) 9 December 2004 (2004-12-09) paragraph [0033] - paragraph [0054]	25,28

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
15 November 2006	05/12/2006

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	KELPERIS, K

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2006/027541

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2002029130 A1	07-03-2002	NONE	
US 6654697 B1	25-11-2003	NONE	
EP 1298511 A1	02-04-2003	DE 60203458 D1 DE 60203458 T2	04-05-2005 15-09-2005
US 2004249583 A1	09-12-2004	US 2006036404 A1	16-02-2006