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(54) **CROSS CORRELATION DIAGNOSTICS TOOL FOR VIBRATION ANALYSIS**

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(60) Provisional application No. 60/633,481, filed on Dec. 6, 2004.

(51) **Int. Cl.**
G06F 11/30 (2006.01)
G21C 17/00 (2006.01)

(52) **U.S. Cl.** **702/183**

(58) **Field of Classification Search** 702/183
See application file for complete search history.

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(57) **ABSTRACT**

A system and method for detecting and analyzing anomalies in a machine during operation. The system and method includes at least one sensor associated with a component on the machine, a transducer configured to be positioned about the component, and a test station for receiving signals from the at least one sensor and the transducer, and correlating the signals to determine a source of an anomaly.

11 Claims, 5 Drawing Sheets

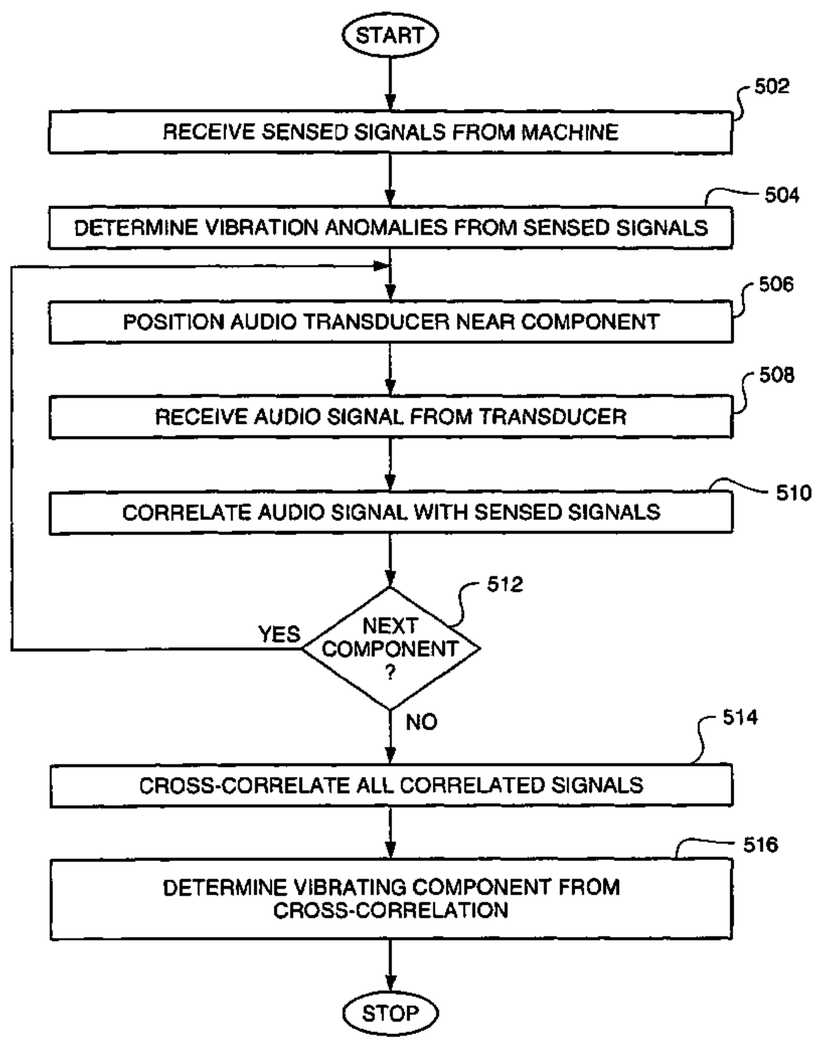


Fig. 1

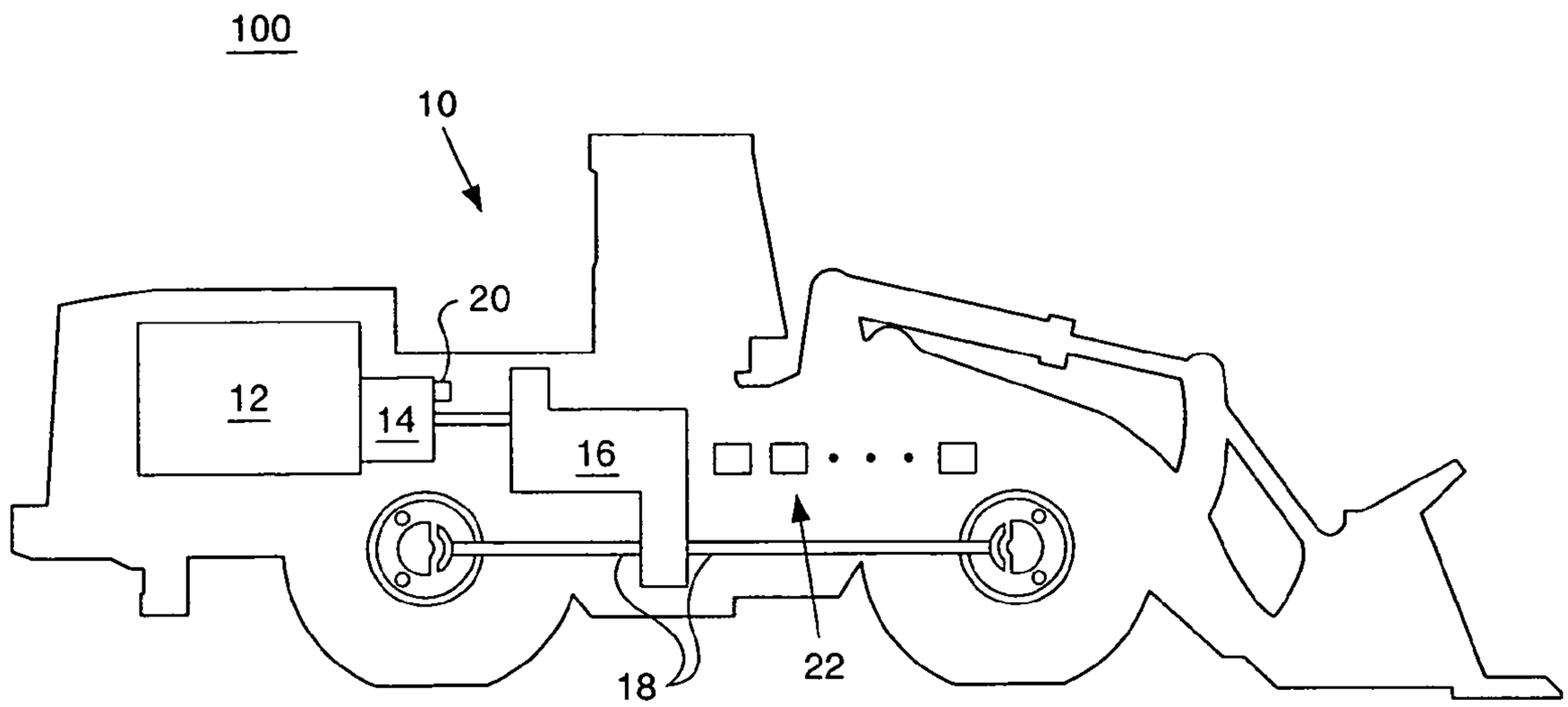
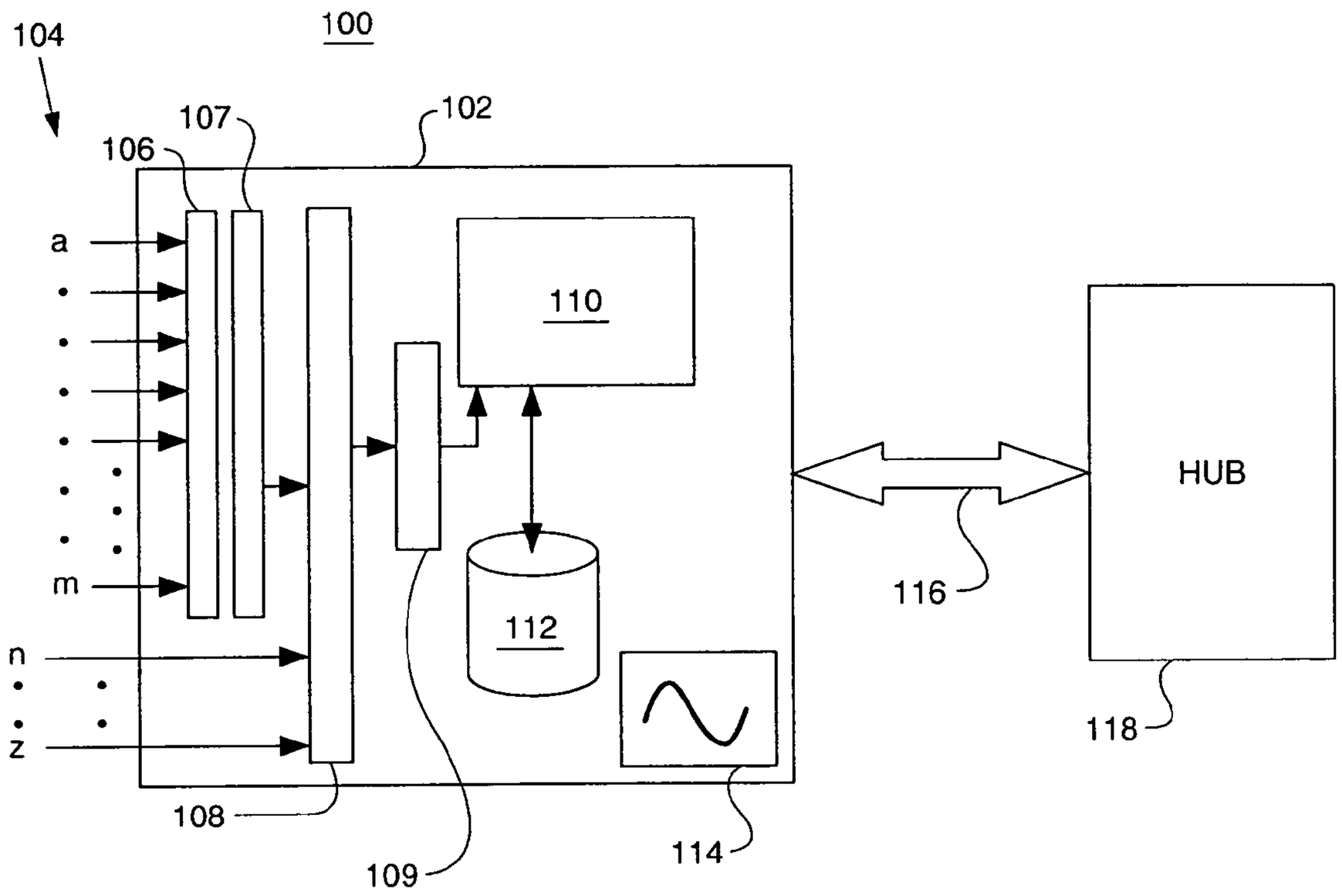


FIG. 2



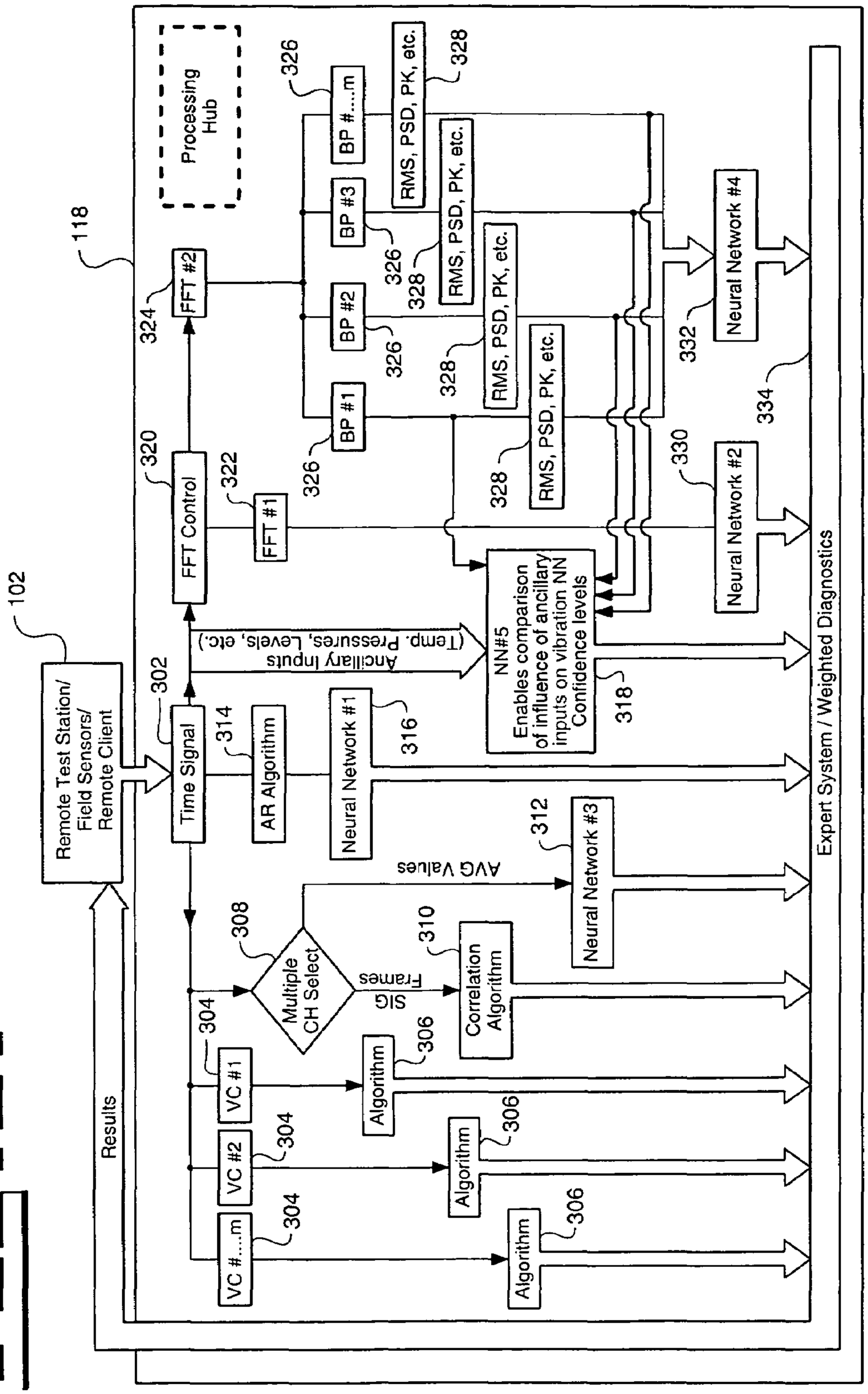

118
Processing Hub
326
BP #....m
328
RMS, PSD, PK, etc.
BP #3
RMS, PSD, PK, etc.
326
328
FFT #2
324
BP #2
RMS, PSD, PK, etc.
326
328
BP #1
RMS, PSD, PK, etc.
326
328
332
Neural Network #4
334
330
Neural Network #2
320
FFT Control
322
FFT #1
102
Remote Test Station/ Field Sensors/ Remote Client
302
Time Signal
314
AR Algorithm
Neural Network #1
316
Ancillary Inputs (Temp. Pressures, Levels, etc.)
NN#5 Enables comparison of influence of ancillary inputs on vibration NN Confidence levels
318
Expert System / Weighted Diagnostics
AVG Values
312
Neural Network #3
308
Multiple CH Select
Frames
SIG
310
Correlation Algorithm
304
VC #1
VC #2
VC #....m
304
304
306
Algorithm
306
Algorithm
306
Algorithm
Results

FIG-3-

Fig. 4

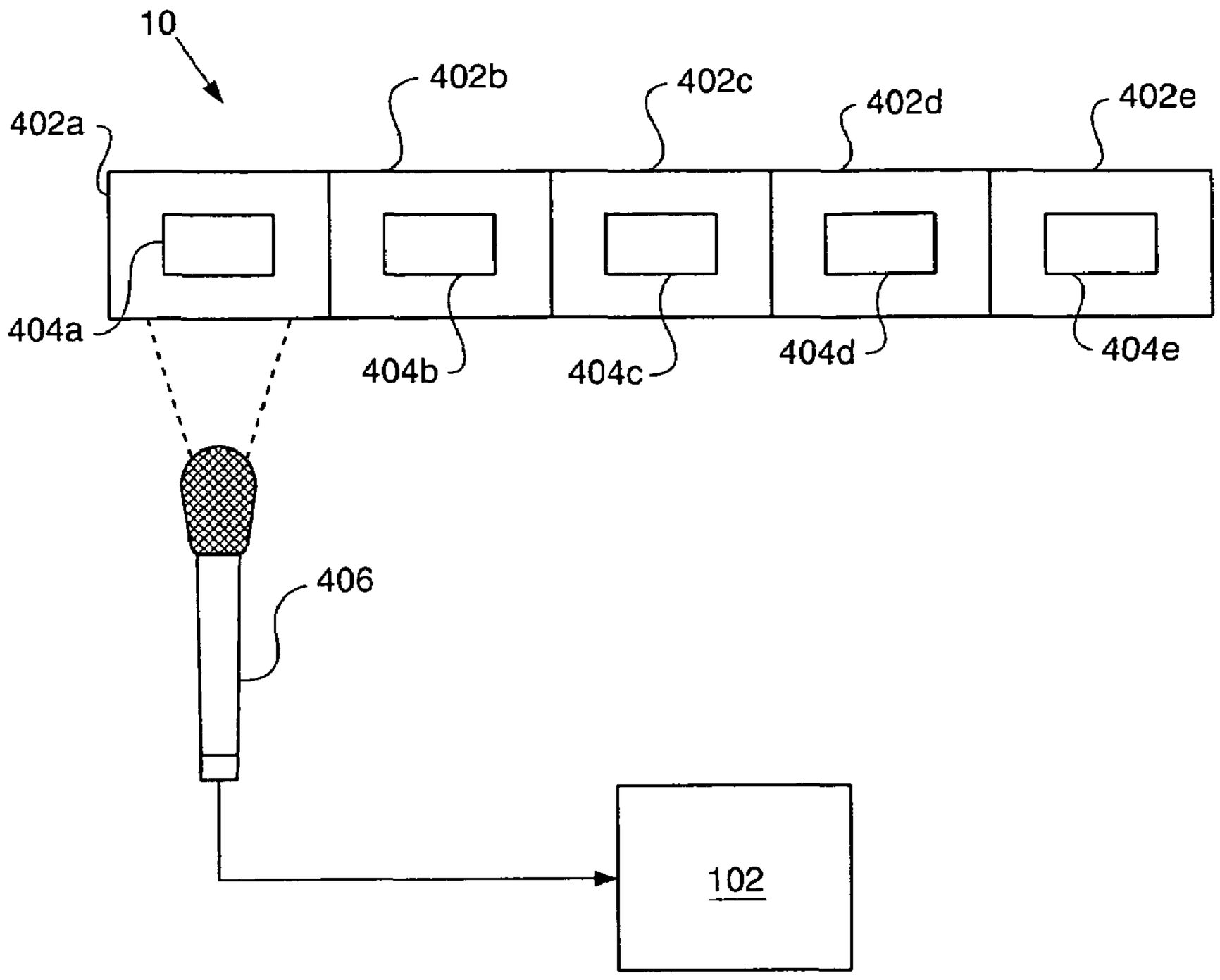
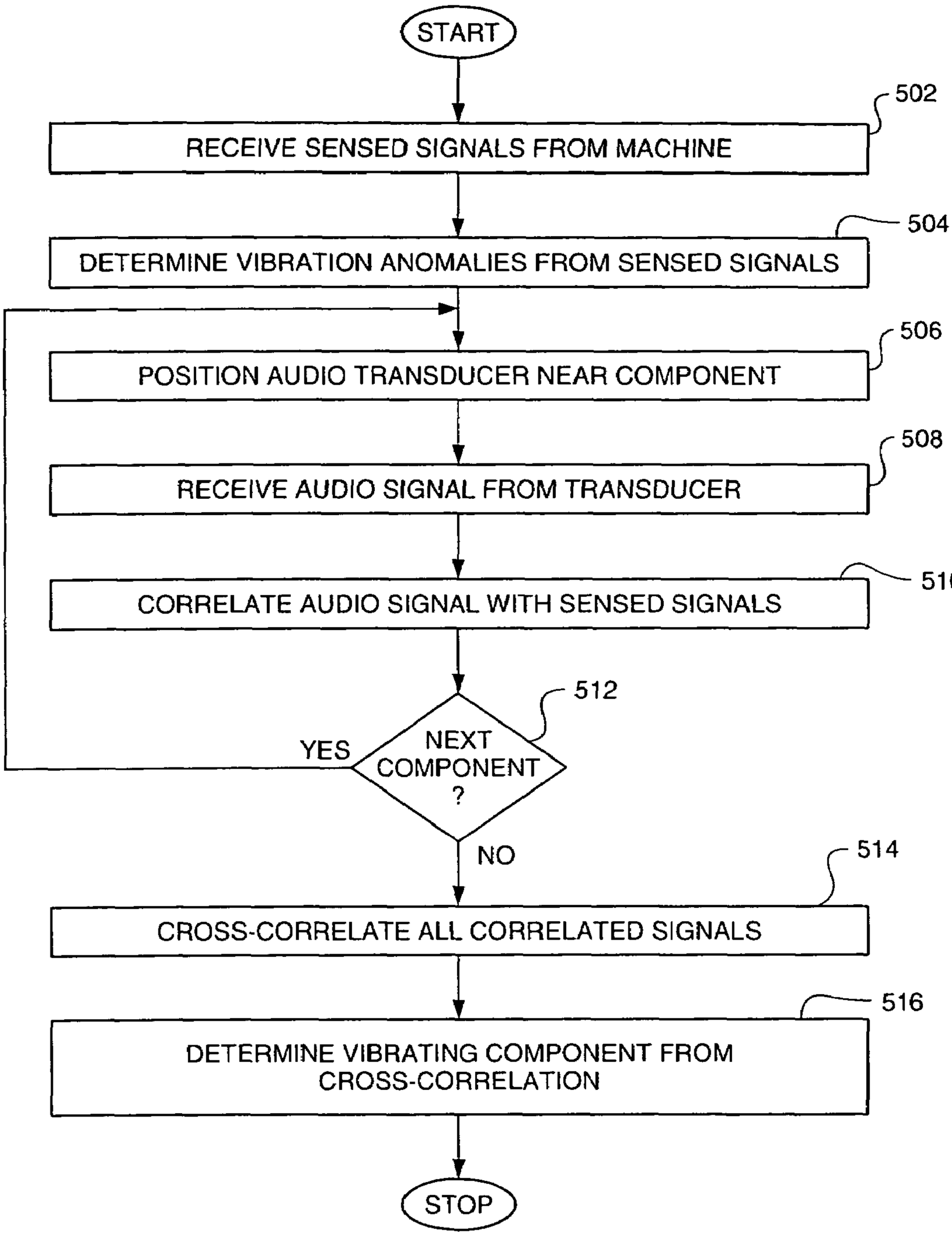


Fig. 5


START
RECEIVE SENSED SIGNALS FROM MACHINE
502
DETERMINE VIBRATION ANOMALIES FROM SENSED SIGNALS
504
POSITION AUDIO TRANSDUCER NEAR COMPONENT
506
RECEIVE AUDIO SIGNAL FROM TRANSDUCER
508
CORRELATE AUDIO SIGNAL WITH SENSED SIGNALS
510
NEXT COMPONENT ?
512
YES
NO
CROSS-CORRELATE ALL CORRELATED SIGNALS
514
DETERMINE VIBRATING COMPONENT FROM CROSS-CORRELATION
516
STOP

CROSS CORRELATION DIAGNOSTICS TOOL FOR VIBRATION ANALYSIS

This application is a continuation-in-part of U.S. patent application Ser. No. 11/197,707, filed Aug. 4, 2005 now U.S. Pat. No. 7,194,383, which in turn claims benefit under 35 U.S.C. § 119(e) of U.S. Provisional Application No. 60/633,481, entitled "Vibration Analysis System and Method for a Machine", filed Dec. 6, 2004.

TECHNICAL FIELD

This invention relates generally to a system and method for analyzing vibration related data for a machine and, more particularly, to a system and method for testing and analyzing vibration relevant data for a rotating machine using traditional vibration analysis techniques in cooperation with artificial intelligence.

BACKGROUND

Rotating machinery is used in many applications. For example, machines such as mobile machines, e.g., on and off road vehicles, construction machines, earthworking machines, and the like, employ principles of rotation to function. Engines, motors, drive trains, ground engaging components such as wheels or tracks, and the like rotate to enable the machines to perform work tasks.

The efficiency and life expectancy of rotating machinery may be analyzed and determined by resort to a study of vibrations present in the machine components. Friction forces between moving parts, compounded by irregularities in component tolerances, serve to cause vibrations in the machines. An analysis of the vibrations may aid in determining, in real time and non-intrusively, the health of the machines, even to the point of predicting component life and potential breakdowns.

Vibration analysis, including related concepts of sound and ultrasonic analysis, has long been of interest in monitoring and diagnosing machine health. However, vibration analysis techniques have typically proven to be lacking by either providing questionable results or providing data that cannot be readily interpreted and understood.

Efforts have been made to use artificial intelligence techniques to test and analyze vibration of machines. For example, U.S. Pat. Nos. 5,566,092, 5,566,273, 5,602,761, 5,854,993, 6,236,950 and 6,539,319, all assigned to the present assignee, disclose variations in techniques for using neural networks to perform testing and analysis of machines, particularly with respect to vibration characteristics of the machines. Although the techniques embodied in the above patents have resulted in some degree of success, it is desired that further techniques be developed which offer greater reliability, robustness and precision in testing and analysis.

The present invention is directed to overcoming one or more of the problems as set forth above.

SUMMARY OF THE INVENTION

In one aspect of the present invention a system for detecting and analyzing anomalies in a machine during operation is disclosed. The system includes at least one sensor associated with a component on the machine, a transducer configured to be positioned about the component, and a test station for receiving signals from the at least one sensor and the transducer, and correlating the signals to determine a source of an anomaly.

In another aspect of the present invention a method for detecting and analyzing anomalies in a machine during operation is disclosed. The method includes the steps of receiving sensed signals from the machine, receiving audio signals from a transducer positioned about components on the machine, correlating audio signals received with respect to each component with corresponding sensed signals associated with each component, cross-correlating all correlated signals, and determining a location of an anomaly based on the cross-correlation.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a diagrammatic illustration of a machine that may be used with the present invention;

FIG. **2** is a block diagram depicting an aspect of the present invention;

FIG. **3** is a detailed block diagram of a processing hub suited for use with the system of FIG. **2**;

FIG. **4** is a diagrammatic illustration of another embodiment of the present invention; and

FIG. **5** is a flow diagram depicting a method associated with another embodiment of the present invention.

DETAILED DESCRIPTION

Referring to the drawings in general, a system **100** and method for detecting and analyzing anomalies in a machine **10** during operation is shown. Anomalies may refer to vibration related characteristics of the machine **10**, in particular to vibration related characteristics of rotating components of the machine **10**.

Referring to FIG. **1** in particular, a machine **10** is embodied as a wheel loader, typically used for earthworking and construction purposes. The wheel loader depiction is merely for exemplary purposes, in that machines of a variety of types, mobile and stationary, may be used with the present invention. For example, other types of wheeled machines and vehicles, tracked machines, power generators, machines for manufacturing, assembly, and storage, and various other types of machines, may all benefit from use of the present invention.

The exemplary machine **10** of FIG. **1** may include an engine **12**, a transmission **14**, a transfer unit **16** of some type, e.g., a transfer case, and a drive train **18**, all of which are well understood in the art. A common feature of the above listed components of the machine **10** is that all embody rotating movement of component parts, that may be prone to vibration within or outside of acceptable tolerances.

At least one vibration sensor **20** may be used to sense, either directly or through derivation, vibrations in the machine **10**. Vibration sensors **20** may include such devices as rotational speed sensors, accelerometers, and the like, and may be connected at various desired locations on the machine **10** to sense parameters indicative of vibration.

At least one other, non-vibration sensor **22** may be used to detect, either directly or indirectly, characteristics associated with the machine **10** that are not vibration related. Examples of non-vibration sensors **22** may include temperature sensors, humidity sensors, barometric pressure sensors, fluid level sensors, and the like.

Referring to FIG. **2**, a block diagram illustrating an aspect of the system **100** is shown. The system **100** is depicted as having a remote test station **102** for on-site testing of the machine **10**, and a processing hub **118** that may be located

at a central point away from the test station **102**. For example, there may be many remote test stations **102** located at sites in which machines are also located, and a single processing hub **118** located at a central station away from the machine sites. Although the present disclosure describes the exemplary situation in which the test station **102** and the hub **118** are at separate locations, it is conceivable that the test station **102** and the hub **118** may be located at one site, perhaps even housed as one unit.

The test station **102** may include a plurality of sensed inputs **104**, for example from a variety of vibration and non-vibration sensors **20**,**22**. The sensed inputs **104** may be input to a signal conditioner **106**. The signal conditioner **106** may be used to perform functions such as providing proper biasing currents. The conditioned signals may then be routed through analog filters **107** for anti-aliasing. The signals may then be delivered to an I/O connector **108**, and then to an A/D converter card **109** for conversion from analog to digital. Sensed inputs **104***a–m* represent signals that are processed by the above steps. Alternatively, signals, as depicted by sensed inputs **104***n–z*, may not require the above conditioning and filtering and may be delivered directly to the I/O connector **108**.

A processor **110** may receive the conditioned data signals and perform additional processing. For example, a memory **112** may be accessed to store and retrieve data. The processor **110** may also prepare the data for delivery to the hub **118**, e.g., by selecting certain data, categorizing data, tabulating and partially analyzing raw data, and the like.

The remote test station **102** is powered by a power supply **114**, which may be an uninterruptible power supply (UPS) to protect the equipment and the received and compiled data from corruption caused by power interruptions.

A communications link **116** provides communications between the test station **102** and the hub **118**. The communications link **116** may be wired or wireless, depending on the overall system configuration and needs. Preferably, communications may be made by way of an Internet protocol for web access. However, other methods of communication may be used. For example, the communications link **116** may be wireless such as radio, microwave, or satellite, or may be wired such as via telephone line, coaxial cable, power transmission lines, and the like. In addition, the communications link **116** may be hard wired by way of dedicated wiring connections, or the test station **102** and the hub **118** may be connected together as one integrated unit. Associated transmit and receive equipment (not shown) is used to enable communications over the communications link **116**. By whatever medium used for communicating, the communications link **116** may be secured from access, such as by an encrypted Internet protocol, for example.

The processing hub **118** is enabled to receive data from one or more test stations **102**, process and analyze the data, and deliver the results of the analysis to the test stations **102**, or to other designated locations, e.g., to other sites which may be designated to receive out of tolerance or alarm condition messages by way of text messaging or email. Details of operation of the hub **118** may best be described with reference to FIG. **3**. The hub **118** may represent software within a computer. In this embodiment, the blocks in FIG. **3** represent various software functions.

In FIG. **3**, a block indicated as time signal **302** represents the test signal that is delivered to the hub **118** by way of the communications link **116**. The time signal **302** is processed prior to delivery by the test station **102** and may be analog to digital converted, encrypted, and delivered as a compacted test message, for example in Internet protocol. The time signal **302** may have many channels and many test steps for each channel. For example, the time signal **302** may have channels representative of each sensed signal being analyzed, and each channel may have test steps for multiple operating conditions of the machine **10**. More specifically, the machine **10** may be a transmission, the channels may represent signals received from a multitude of sensors which are configured to sense a corresponding multitude of characteristics of the transmission, e.g., vibrations, temperature, pressure, environmental conditions, and the like, and the test steps may be indicative of various operating modes of the transmission, e.g., first gear forward, second gear forward, and the like.

At least one virtual channel **304** is set up to receive the time signals **302** for delivery to at least one algorithm **306**. The virtual channels **304** may be compared in function to signal splitters, thus providing distinct routes for the time signals **302** to be sent. However, the virtual channels **304** have no physical connection to the world outside of the hub **118**. The time signals **302** may pass unaltered through each virtual channel **304** or, alternatively, one or more virtual channels **304** may be used to select desired components of the time signals **302**. The algorithms **306** may be used to process the time signals **302** for analysis using techniques such as correlation, co-variance, wavelet analysis, and the like.

A multiple channel selector **308** provides for selection of multiple channels for processing and analysis. The multiple channel selector **308** may provide more than one channel of the time signal **302** to an algorithm, such as a correlation algorithm **310**, to analyze the channels, in particular the results of interactions between the channels. For example, a channel indicative of a vibration signal of a sensor located on a component under test may be analyzed with consideration given to a channel indicative of a vibration signal of a sensor located elsewhere on the machine **10**.

The multiple channel selector **308** may also process the time signals **302**, e.g., for each of multiple channels, to prepare the signals for a neural network, such as neural network number three **312**. In particular, the multiple channel selector **308** may average values, e.g., peak amplitude or power, of the signals to provide points to neural network number three **312**.

The time signals **302** may also be delivered to an autoregression (AR) algorithm **314** for conversion to the frequency domain. The AR algorithm **314**, as is well known in the art, is a computationally efficient method for transferring signals from the time domain to the frequency domain. The transferred signals may then be delivered to a neural network, such as neural network number one **316** for analysis.

Various channels of the time signal **302** may represent ancillary sensors, i.e., signals from non-vibration sensors **22**. These ancillary sensor signals may be sent to a compensatory neural network, i.e., neural network number five **318**, for comparison of the influence of the ancillary characteristics on the analysis of vibration related signals. For example, ancillary characteristics such as temperature, pressure, fluid levels, ambient conditions, and the like, have an effect on machine vibrations. As such, an analysis of vibration signals may be made at a higher confidence level if these ancillary characteristics are taken into account.

The time signals **302** may also be sent to an FFT (Fast Fourier Transform) control **320**, which may provide options such as the use of a truncated FFT, a decimated time waveform FFT, and the like. FFTs, such as FFT number one **322** and FFT number two **324**, convert the time domain signals to the frequency domain and may or may not

condense the number of frequency domain points to simplify the work of the neural networks.

The use of an FFT algorithm allows for processing of a time domain signal to produce a frequency domain signal which represents all frequency components present in the provided time-domain signal. Given the large number of data points in the frequency spectrum, it may take a significant amount of time to determine which frequencies are significant, and to determine what a normal level for these frequencies should be. The present invention may use an autostencil algorithm to automatically create a set of spectral divisions, based on the given frequency domain signal. Based on the dimensions of the division, new data signals may be passed through the divisions to perform diagnostic functions upon their content, such as the absolute maximum value of any frequency component contained therein, or the power, e.g., RMS value, of the data contained within the division.

A preferred algorithm may work by identifying key component frequency elements in the signal, creating a spectral division around the signal, scaling the height of the division as appropriate, and repeating until a series of divisions are created. The algorithm may first identify the highest amplitude frequency component that is not already part of an existing spectral division. The algorithm may then use a predefined or user configurable transfer function to create a spectral division around this frequency component. The transfer function serves to identify the width of the spectral division. The transfer function is typically an exponential curve. As variations in environmental variables, e.g., RPM, temperature, humidity, and the like, may cause a shift in frequencies, higher frequency components will typically be more greatly affected than lower frequency components. The exponential transfer function may serve to widen those spectral divisions at upper frequencies so that their content remains relatively stable. A similar exponential transfer function may exist to scale the height, e.g., thresholds, of the spectral division. This transfer function may then serve to scale down the thresholds of any spectral divisions present in higher frequency ranges as it takes a much higher force at higher frequencies to cause a significant change in amplitude of a frequency component than it would take at lower frequencies.

The process of identifying frequency components may repeat until certain criteria have been met. In a first embodiment, a fixed number of divisions, i.e., N number, may be requested, to identify the top N major components of the signal. In a second embodiment, the algorithm may run with the number of divisions N set to infinity to saturate the signal with divisions, thus ensuring that substantially all of the signal is covered by at least one division. A third embodiment may involve calculating a signal-to-noise ratio and a total power in the signal, and then a process begins of identifying divisions until all non-noise power in the signal is contained within defined spectral divisions.

The FFT points from FFT number one may be applied directly to a neural network such as neural network number two for vibration analysis.

The FFT points from FFT number two **324** may then be sent through a series of band pass filters (BPF) **326** configured in parallel so that the frequency domain may be split into bands of frequency packets. Each packet then may undergo further processing by way of frequency packet processors **328**. For example, a root mean square (RMS) value of each packet may be determined or a peak value (PK) of each packet may be determined. Alternatively, a power spectral density (PSD) or some other such value may be determined.

The points from the frequency packet processors **328** may then be applied to a neural network such as neural network number four **332** to analyze vibration characteristics of the machine **10** under test. Furthermore, the points may, in addition or alternatively, be applied to neural network number five **318**, i.e., the compensatory neural network, for inclusion of the influence of ancillary characteristics in the vibration analysis of the machine **10** under test. Preferably, the results of the compensatory neural network will have a higher confidence level due to the inclusion of factors that may have an effect on machine vibrations, that are not considered by typical vibration analysis techniques.

Each of the neural networks and algorithms used may be assigned an adjustable weighting factor during initial setup of the hub **118**, and during subsequent sessions in which the hub **118** is fine tuned for optimal performance. The process for setting up the hub **118** may employ the use of wizards which prompt for certain inputs, such as number and types of neural networks, BPF specifics, virtual channels and algorithms to be used, and the like. The resultant hub configuration may thus be customized for specific vibration analysis situations, and also may be altered periodically as desired. The hub **118** may be based on software which provides for drag and drop user configurability. For example, various selectable features such as BPFs, algorithms, neural networks, and the like, may be selected by dragging icons representative of such features to a portion of a display and dropping the icons to select them. By this technique, any desired number of features may be chosen. The selection of features may be made for each test step of each channel in the time signal **302**.

The above described algorithm, and other algorithms that may be used as well, may be used to identify a series of inputs that are applicable to a neural network. Part of the configuration process involves taking collected data, identifying it as a normal pattern, and training this normal pattern to all the neural networks contained within the processing hub **118**. When a new test plan is set up, or an existing test plan is updated or modified, each neural network present must potentially be reconfigured based on the most recent data collected. As a part of this process, each neural network present must be re-initialized, created, and trained. Subsequently, the normal pattern for each neural network must be identified, and each neural network must be trained with a new pattern.

The use of wizards may be used to fully automate this process, thus eliminating operator error, and significantly reducing the time required to get the processing hub **118** into operation. The wizards may identify each neural network present, regardless of the previous state of any neural network. Furthermore, the use of wizards may allow for test identification of normal samples, i.e., a sample being the full result of one test performed by the processing hub **118**. This may include the identification of multiple samples, having patterns which may then be combined to form a single input pattern. Once an input pattern is identified for each unique neural network, the network is blanked if necessary, initialized, and then trained to the normal pattern identified by the above procedure. The process may then be repeated for each neural network present, regardless of the size of the pattern, e.g., number of points.

An expert system **334** receives the weighted outputs from the chosen neural networks and algorithms, and responsively sums the weights for a final vibration analysis of the

machine **10**. If desired, conditioned packets from the BPFs **326**, e.g., RMS conditioned, may be sent directly to the expert system **334** to help establish confidence in the neural networks, in particular neural network number four **332**, and neural network number five **318**.

Referring to FIG. **4**, a block diagram illustrating another embodiment of the present invention is shown.

Machine **10** has a number of components **402***a–e*, such as pumps, drive train components, and the like. The components **402** may be connected together or may be separately located, for example adjacent each other. The components **402** may be rotating or non-rotating components, and may be a combination thereof. For example, components **402***b* and **402***d* may be rotating components, and components **402***a*, **402***c* and **402***e* may be non-rotating.

A plurality of sensors **404***a–e* may be located with respect to corresponding components **402***a–e*. The sensors **404** may be transducers, such as pressure transducers, having analog outputs. In one embodiment, one or more sensors **404** may be accelerometers. Each sensor **404** is configured and located to sense vibration anomalies from a corresponding component **402**. However, since vibrations generated by one component, e.g., component **402***b*, may induce further vibrations in other components, e.g., **402***a* and **402***c*, it is conceivable that all of sensors **404***a–c* may pick up vibration anomalies from their corresponding components **402***a–c*, even though only one component **402***b* is creating the vibrations. Thus, it is difficult to determine the concise origin of the vibrations.

A transducer **406** is configured to be movably positioned adjacent selected individual components. Since vibrations typically may generate audible sound signals which then travel through space, the transducer **406** may be a sound transducer, such as a microphone. In particular, a directional microphone may be used. The transducer **406** may be configured to pick up audio signals caused by vibrations, and then deliver electrical signals representative of the audio to the remote test station **102**. For discussion purposes, the remote test station **102** may be referred to as the test station **102**.

A method of operation of the embodiment of FIG. **4** is shown in the flow diagram of FIG. **5**.

In a first control block **502**, signals are sensed from the machine **10** and received by the test station **102**. The signals may originate from sensors **404**. In a second control block **504**, the test station **102** determines the presence of vibrations from the sensed signals.

In a third control block **506**, a transducer **406**, for example a microphone, is positioned near a component **402**, for example component **402***a*. A user may be prompted by the test station **102** to position the microphone or, alternatively, the user may position the microphone and then provide input to the test station **102** that component **402***a* is being monitored. In a fourth control block **508**, an audio signal is delivered from the transducer **406** to the test station **102**.

In a fifth control block **510**, the received audio signal is correlated with the sensed signals to determine the strongest correlation found between the transducer **406** and the sensor locations. Preferably, the transducer **406** is moved about the component **402** with respect to the location of the associated sensor **404** to find the strongest correlation between the audio signal and the sensed vibration signal.

A first decision block **512** indicates that the processes of control blocks **506–510** are repeated for each desired component, for example components **502***b*, **502***c*, and so forth.

In a sixth control block **514**, the test station **102** cross-correlates all of the correlated signals to find the strongest cross-correlation. In a seventh control block **516**, the test station **102** determines from the cross-correlation which component is most likely to be the source of vibration.

In an alternate embodiment, the data gathered by the test station **102** may be delivered to the processing hub **118** for further processing, and the cross-correlation function may be performed by the processing hub **118**.

INDUSTRIAL APPLICABILITY

The system **100** may be selected to operate in any one of several modes. For example, a first mode may be chosen in which the system **100** monitors the results of all configured test plan parameters, and outputs an alarm if a threshold of any selected parameter is exceeded. Notifications may be sent to any desired location by any desired means.

A second mode may include the features of the above described first mode, and further include alarm functions based on the outputs of any neural networks if preset confidence levels are exceeded.

A third mode may include features of the first and second modes, and may further include the ability for a test engineer to elect to have the system **100** make an intelligent prognosis based on the weighted results of any selected parameters, as well as any of the neural network confidence levels. The results, based on a combination of weights in any desired category, may be provided to an operator of the machine **10**, a test engineer at the hub **118**, a database for recordation, another specified location, or any combination thereof.

The use of the above described techniques and components in the hub **118** allows for greater confidence levels in the results and also enables vibration analysis with the use of neural networks which have no need for past historical data to achieve a reasonable level of reliability certainty.

Other aspects can be obtained from a study of the drawings, the disclosure, and the appended claims.

What is claimed is:

1. A method for detecting and analyzing anomalies in a machine during operation, including:

receiving sensed signals from the machine indicative of vibration;

receiving sensed signals from the machine indicative of non-vibration characteristics;

receiving audio signals from a transducer positioned about components on the machine;

correlating audio signals received from the transducer with sensed signals received from the machine indicative of vibration and non-vibration characteristics;

cross-correlating all correlated signals;

determining a location of an anomaly in the machine based on the cross-correlation; and

transmitting the determined location of the anomaly to a user at a desired location.

2. A method, as set forth in claim **1**, wherein determining a location of an anomaly includes the step of determining a location of a vibration emanating from a component.

3. A method, as set forth in claim **1**, wherein receiving audio signals from a transducer includes the step of receiving audio signals from a transducer as the transducer moves in relation to a component.

4. A method, as set forth in claim **1**, wherein correlating audio signals received from the transducer with sensed signals received from the machine indicative of vibration and non-vibration characteristics includes the step of correlating audio signals with sensed signals to find a location of a strongest correlation between the audio and sensed signals.

5. A method, as set forth in claim 4, wherein cross-correlating all correlated signals includes the step of determining a location of a strongest cross-correlation, the determined location being indicative of a component being a source of the anomaly.

6. An apparatus for detecting and analyzing anomalies in a machine during operation, comprising:

at least a first sensor configured to detect a parameter indicative of vibration;

at least a second sensor configured to detect a non-vibration parameter;

a transducer configured to receive audio signals related to components of the machine;

a first model to correlate the received audio signals with the detected vibration and non-vibration parameters; and

a second model to cross-correlate all correlated signals to determine a location of an anomaly in the machine based on the cross-correlation.

7. The apparatus of claim 6, wherein the second model is a neural network model.

8. The apparatus of claim 6, wherein the first model is an autoregression algorithm model.

9. The apparatus of claim 6, wherein the second model is a Fast Fourier Transform control model.

10. The apparatus of claim 6, wherein the non-vibration parameter includes temperature.

11. The apparatus of claim 6, wherein the non-vibration parameter includes humidity.

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