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(54) Title: METHOD AND SYSTEM FOR OBTAINING VALID OSCILLATING COMPONENTS

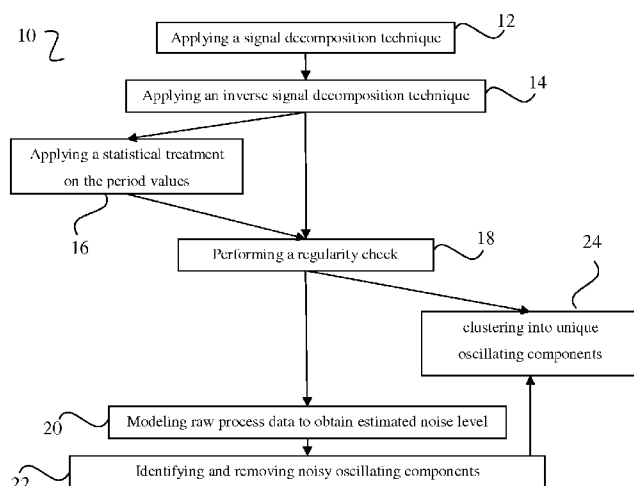


FIG. 1

(57) **Abstract:** The invention provides a method for ob-
taining valid oscillating components from raw process
data in a process plant. The method includes applying a
decomposition technique on the raw process data to ob-
tain oscillating components having period values. These
period values may be subjected to statistical treatment or
be used as such to obtain applicable period values. Then,
a regularity check is performed on the applicable period
values to obtain first level valid oscillating components.
Noise level in a process is estimated from the time series
data, which is used to remove noisy oscillating compo-
nents from the first level valid oscillating components to
obtain second level valid oscillating components. The in-
vention further includes clustering the second level valid
oscillating components into unique oscillating compo-
nents based on a mean period distance between given os-
cillating components.

METHOD AND SYSTEM FOR OBTAINING VALID OSCILLATING COMPONENTS

TECHNICAL FIELD

Embodiments of the present invention relate to processing of raw process data comprising multiple oscillations, and more specifically, the invention relates to a method for obtaining valid oscillating components in a raw process data.

BACKGROUND

A typical industrial process comprises a plurality of processes within it. Each of these processes is operated under nominal operating conditions to ensure high efficiency of operation of the process plants, wherein each of these processes are associated with its own set of unique process variables. Monitoring of these processes based on process variables using one or more sensors is necessary to identify any deviations from the nominal operating levels. Such deviations in a typical process plant are caused due to a variety of reasons, such as Proportional-Integral-Derivative (PID) controller tuning, valve problems like stiction, external process disturbances, and so on. These deviations from nominal operating conditions are generally identified based on examination of process data obtained over a period of time, which is termed in the art as time series data. The deviations may be viewed in many different ways, wherein one way of viewing them include oscillations in a standard visual depiction. When more than one cause exists for the deviations, then oscillation seen in the time series data is cumulative result of multiple oscillation components. Thus, detection of all unique oscillating components is one of the key steps in monitoring the performance and root cause analysis of industrial PID control loops. To be able to isolate the root causes of these oscillations using regular operating data, it is necessary that the oscillation detection method is capable of detecting the presence of multiple oscillations unambiguously and accurately from the given time series

data. Regular processing data is data collected under normal operating conditions wherein no explicit tests are done in the plant to generate data that would render it more suitable to assist any form of analysis.

For detection of multiple oscillations from time series of a single process variable, the existing methods include the modified empirical model decomposition (EMD) method [R. Srinivasan, R. Rengaswamy, R. Miller. A modified empirical model decomposition (EMD) process for oscillation characterization in control loops. *Control Eng. Practice*, 15(2007) 1135-1148], wavelet based method [T. Matsuo, H. Sasaoka, Y. Yamashita, Detection and diagnosis of oscillations in process plants', in *Proc of Seventh Int. Conf, Knowledge-Based Intelligent Information and Engineering Systems (KES 2003)*, UK 2003, pp. 1258-1264], regularity of zeros-crossings of Auto-Correlation Function (ACF) through detection of spectral peaks [N.F Thornhill, B Huang and H Zhang, Detection of multiple oscillations in control loops, *Journal of Process Control*, 13 (1), 2003, Pages 91–100] and Discrete Cosine Transform (DCT) based method [Xinong Li, Jiandong Wang, Biao Huang and Sien Lu, The DCT-based oscillation detection method for a single time series, *Journal of Process Control* 20 (2010) 609-617].

However, the first three methods, viz. EMD method, wavelet based method and the regularity of zeros-crossings of ACF through detection of spectral peaks, cannot handle industrial noise well as such scenarios require careful manual determination of filter parameters and thresholds to handle the noise present ubiquitously in the industrial datasets. DCT based method requires only two user-defined thresholds (low and high sea-level parameters), for which good default parameter values are available. However, the existing version of DCT method has several shortcomings, which limits its usage in realistic scenario. For example, when the data is very noisy, DCT based method detects more oscillating components than that are actually present in the time series data. In such cases, the method returns large (more than 30 in some cases) number of oscillating components. This method is also not able to handle scenarios where frequencies of multiple oscillations are very close to each other. As before, in this case, the

method results in more oscillating components than that are actually present in the data.

Thus, in the operation of a typical process plant wherein the raw process data obtained over a period of time is generally very noisy, comprises multiple oscillating components, wherein the frequency of oscillations may be close to each other, and may also include highly irregular oscillations, there is a dire need for a method that can handle such data in a robust manner accurately so as to enable effective and efficient root cause analysis.

BRIEF DESCRIPTION

In one aspect, the invention provides a method for obtaining valid oscillating components from a raw process data in a process plant. The raw process data is a time series data. The method of the invention comprises obtaining the raw process data from at least one sensor. Then, the method includes applying a decomposition technique on the time series data to obtain at least one oscillating component. In one exemplary embodiment, the decomposition may involve the use of spectral decomposition methods followed by the application of inverse spectral decomposition technique on each of the at least one spectral component to obtain at least one oscillating component. Each of these oscillating components is associated with a period value. In some embodiments, the method involves performing a statistical treatment of the period values of the obtained oscillating component to get applicable period values. In other embodiments, the period values are used as applicable period values for further processing. The method further comprises performing a regularity check on the applicable period values of the at least one oscillating component using a predetermined cut-off value to determine if each oscillating component is a valid one. This process is repeated on all identified oscillating components to get first level valid oscillating components. In some instances, the method involves clustering the first level

valid oscillating components into unique oscillating components based on the mean period distance between given oscillating components.

In further embodiments, the method of the invention includes estimating a noise level in the time series data from the process, which is then used to identify and remove noisy oscillating components in the first level valid oscillating components to get second level valid oscillating components. Subsequently, the method involves clustering the second level valid oscillating components into unique oscillating components based on the mean period distance between given oscillating components.

In another aspect, the invention provides a tool used to implement the method of the invention.

In a further aspect, the invention provides a system for obtaining at least one of valid oscillating components, unique oscillating components, or combinations thereof, from raw process data in a process plant based on the method of the invention as described herein. The system comprises at least one sensor to provide the raw process data; and a processor module to process the raw process data to obtain the valid and/or unique oscillating components as described herein.

DRAWINGS

These and other features, aspects, and advantages of the present invention will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

FIG. 1 is a flowchart representation of exemplary steps in the method of the invention;

FIG. 2 is a block diagrammatic representation showing exemplary components of the system of the invention;

FIG. 3 shows multiple oscillation detection results from existing and proposed methods for simulated time series data set; and

FIG. 4 shows the multiple oscillation detection results from existing and proposed methods for industrial time series data set.

DETAILED DESCRIPTION

As used in this specification and the appended claims, the singular forms "a", "an", and "the" encompass embodiments having plural referents, unless the content clearly dictates otherwise.

Unless otherwise indicated, all numbers expressing feature sizes, amounts, and physical properties used in the specification and claims are to be understood as being modified in all instances by the term "about." Accordingly, unless indicated to the contrary, the numerical parameters set forth in the foregoing specification and attached claims are approximations that can vary depending upon the desired properties sought by those skilled in the art utilizing the teachings disclosed herein.

As used in this specification and the appended claims, the term "or" is generally employed in its sense including "and/or" unless the content clearly dictates otherwise.

The phrase "process plant" is used to indicate any production plant that is being used for effecting an industrial process. This may involve several electrical, chemical and/or mechanical operations that result in the production of one or more products at the end. All process plants are associated with at least one desired product and possibly one or more byproducts. Exemplary process plants include pulp and paper industry, oil and gas plant, power generation plant, metal processing industry, oil production plant, and the like. Each process plant may include performance of one or more processes to achieve the final outcome, each process being done in specific process unit. For example, in a pulp and paper industry, the process plant may include process units such as debarking, chipping,

drying, digestion, bleaching, and so on. Further, any operational process involving monitoring of process parameters are included in the scope of the invention.

The use of the phrase "at least one" herein includes instances when there is an occurrence of the referred object once, more than once, and further includes instances when it does not occur at all. Thus, for example, the phrase "at least one parameter" includes situations when only one parameter is in use, or many parameters are in use, or when no parameters are in use. The exact number encompassing "at least one" as being one, none, or more than one, will become apparent to one skilled in the art, and all such instances are contemplated to be within the scope of the invention.

As noted herein already, the invention provides a method for obtaining valid oscillating components from raw process data in a process plant. Fig. 1 is a flowchart representation of exemplary steps in the method of the invention, wherein the method is depicted by numeral 10. The raw process data is obtained in the form of a time series data from at least one sensor situated in a suitable location in the process plant. The method includes applying a decomposition technique on the time series data to obtain at least one oscillating component. In some embodiments, the decomposition technique includes application of a signal decomposition technique, which step is depicted by numeral 12 in Fig. 1 followed by the application of an inverse decomposition technique, shown in Fig. 1 by numeral 14. Suitable signal decomposition techniques useful in the invention include DCT methods, wavelet based methods, EMD method, and the like. Other such useful techniques are known to those skilled in the art and are contemplated to be within the scope of the invention. In one specific embodiment, the signal decomposition technique is a DCT based method. One skilled in the art would understand that when there are no oscillating components occurring in the process, none will be obtained through the application of the signal decomposition technique, and the output will reflect the lack of presence of spectral components accordingly.

The choice of the inverse signal decomposition technique depends on the signal decomposition technique used in the previous step. Hence, if the time series data was subjected to a DCT based method, then the inverse signal decomposition technique used would typically be inverse DCT method. The choice of the inverse signal decomposition technique would become obvious to one skilled in the art without undue experimentation.

Then, the method involves applying a statistical treatment of period values to obtain applicable period values, shown in Fig. 1 by numeral 16. In one embodiment, statistical treatment includes removing extreme mean period values from the oscillating component. The extreme mean period values may be identified in a facile manner, such as those values deviating from the mean by a certain factor, or those values that are outside a given range, or some such known methods. Further, numerous statistical techniques are known to one skilled in the art to identify and discard extreme mean period values, and all such techniques are contemplated to be within the scope of the invention as described herein. In some instances, as described herein, the period values of the oscillating components are used in the method as the applicable period values.

Then, the method of the invention 10 comprises performing a regularity check on the applicable period values obtained by either ways described herein to know whether the oscillating component being examined is valid or not, shown in Fig. 1 by numeral 18. The regularity check involves computing the ratio (Standard deviation of period values)/(Mean of period values). If the ratio is less than a predetermined cut-off value for a given oscillating component, then it is considered to be valid oscillation. This regularity check is done on all the oscillating components to get first level valid oscillating components. In one exemplary embodiment, the cut-off value is 0.33, while in another exemplary embodiment, the cut-off value is 0.3, in yet another exemplary embodiment, the cut-off value is 0.25, and in a further exemplary embodiment, the cut-off value used for obtaining the first level valid oscillating component is 0.1.

In the context of the method of the invention as described herein, robust regularity check is considered to have been performed when the regularity check is performed on applicable period values that have been obtained by performing a statistical treatment on the period values of the oscillating components. The robust regularity check ensures that even slightly irregular oscillations can be detected without being unduly influenced by extreme mean period values in the data. When the statistical treatment involves removal of extreme mean period values, it overcomes the shortcomings in the prior art methods which depend on comparison of an estimated quantity with predetermined values, which prior art methods fail when the two values are close to each other. Alternately, a relative difference approach wherein taking only those data points wherein the estimated quantity is less than the predetermined values multiplied by a factor that is obtained from empirical approaches may be suitably employed. However, such heuristic approaches do not allow for automation and not susceptible towards simplification as they are user dependent and error prone. The statistical treatment as described herein overcomes such disadvantages and provides for an improved method for obtaining valid oscillating components. Thus, the method of the invention encompasses getting first level valid oscillating components from applicable period values which were obtained from robust regularity check, as well as those from regularity check. One skilled in the art would immediately recognize that the applicable period values obtained from the robust regularity check would be more advantageous as compared to those obtained from regularity check.

In some instances, the method of the invention includes clustering the first level valid oscillating components into unique oscillating components based on a mean period distance between two given oscillations, depicted by numeral 24 in Fig. 1. Mathematically, the mean period distance between two oscillations is estimated as follows:

$$\text{Abs}(P1-P2)/\text{Max}(\text{std deviation1, std deviation2})$$

wherein $P1$ = Mean of period values present oscillating component 1;

$P2$ = Mean of period values present in oscillating component 2;

standard deviation 1 = standard deviation of period values present in oscillating component 1;

standard deviation 2 = standard deviation of period values present in oscillating component 1,

wherein if the estimated value of the mean period distance using the above mentioned formula is less than 1, then the two oscillations associated with the components 1 and 2 may be clustered together as single oscillation, else they are considered as being part of different oscillations. The method of the invention utilizes the mean period distance calculated from the oscillating components found in the given signal itself. In this manner unique oscillating components may be arrived at in a facile manner.

In other embodiments, the method of the invention 10 then involves estimating a noise level in the process based on the time series data obtained from the at least one sensor, depicted by numeral 20 in Fig. 1. This may be done in parallel to obtaining first level valid oscillating components, subsequent to it, or prior to it. One exemplary method for estimating noise level includes modeling the time series data using a parametric model. Several parametric models are known in the art, and the choice of the model to be used in a given situation depends on a variety of conditions and use case scenarios. All the models are contemplated to be within the scope of the invention. Some exemplary models useful here include, but not limited to, Auto Regressive (AR) Model, Auto Regressive with Exogenous input (ARX) Model, Auto Regressive Moving Average (ARMA) model, Auto Regressive Moving Average with Exogenous input (ARMAX) Model, Transfer function models (1st order, 1st order with delay, 2nd order etc), and the like, and combinations thereof.

The method 10 further comprises identifying and removing those oscillating components that would have arisen from noise, termed herein as noisy oscillating components, from the at least one first level valid oscillating components to give the second level valid oscillating components depicted by numeral 22 in Fig. 1. The first level valid oscillating components may be obtained from applicable period values that have undergone regularity check or the robust regularity check for the method of the invention as described herein. If the standard deviation of the first level valid oscillating component is less than standard deviation of estimated noise level, then this particular oscillating component is invalid and removed from further analysis. In instances when a parametric model is used to estimate noise in the process, residuals are estimated based on the amount of the data that cannot be explained by process model, which is considered to be a direct indication of level of noise. Thus, noise in the data is the detected residuals of the parametric model. In the techniques described in the prior art, many false oscillating components are generated that may actually be noise but are not recognized as such. The method described herein enables the identification of those false oscillating components using the standard deviation information from the detected noise level from the data. Further, instead of treating all process data in a standardized manner by applying a fixed value to validate oscillating components, the method described herein takes the uniqueness of each process data set, and accordingly treats the data set to identify noise and false oscillating components.

The method of the invention further includes clustering second level oscillating components into unique oscillating components based on a mean period distance between two given oscillations as already described herein, depicted in Fig. 1 by numeral 24.

In one specific embodiment, the first level valid oscillating components are obtained from a robust regularity check that includes a statistical treatment of period values, such as elimination of extreme mean period values. In this specific embodiment, noise levels for the process in the time series data are estimated in parallel or subsequently or earlier, wherein in one specific instance, the estimation

is achieved using a parametric model. Further, the noise levels are used to eliminate noisy oscillating components in the first level valid oscillating components to obtain second level valid oscillating components. Then, the specific embodiment of the method of the invention includes the clustering of the second level valid oscillating components as described herein to obtain unique oscillating components. The specific embodiment described herein involves following all the exemplary steps for the method of the invention shown in Fig. 1.

The method of the invention may further comprise one or more pre-processing steps to obtain the raw process data (not shown in Fig. 1). The pre-processing steps may be conducted to remove linear trend, spurious data from unforeseen situations, obvious outliers, data stationarity, etc. In some embodiments, the time series data obtained from at least one sensor is subjected to a transformation step to obtain the raw process data. Such linear and non-linear data transformation techniques are known to one skilled in the art, and are contemplated to be within the scope of the invention.

The invention provides a robust method for the detection of multiple oscillations and so it finds tremendous use in any industrial scenario. The robustness of the method arises from the fact that the detected oscillations are true oscillations in the process. Spurious oscillating components that arise from noise present in the data is handled by estimating the noise level of each time series through methods such as AR model identification procedure, which is then used to eliminate the DCT components that are not distinguishable from noise part of the signal. Further, the use of the mean period distance based clustering method ensures that multiple oscillating components are not identified when the oscillation frequencies are close to each other, and instead only actual numbers of oscillating components present in the process are identified. Also, by eliminating the extreme mean period values before applying the regularity check, the number of missed detections is reduced. The method of the invention is also applicable in a wide variety of situations, and is uniquely adaptable for any process data. Further, the method takes into account the uniqueness of each process data, and the

identification of oscillating components is done based on the data obtained instead of on the basis of predefined, and sometimes arbitrary, threshold values.

The identification of oscillating components in a process allows for more accurate and timely root cause analysis for the oscillations. Based on the ability to detect multiple oscillations accurately and the improved root cause analysis of oscillations, control loop performance monitoring and diagnosis can be improved greatly, thus providing great advantages to the process industry implementing the method of the invention. Such advantages may include, for example, increased productivity, lesser downtime, energy efficiency, and the like, and combinations thereof.

One skilled in the art will also immediately recognize that the method of the invention may be effected through a suitable software tool. Thus, in other aspects, the invention provides a tool for implementing the method of the invention for identifying at least one unique oscillating component from a raw process data obtained from at least one sensor in a process plant as an independent tool. The software tool may be made available through any known formats, such as a downloadable file from a suitable location, or in a storage medium such as CD or DVD or a flash drive, or alternately in an EPROM that is integrated into the existing control system of the process plant.

In yet another aspect, the invention provides a system for obtaining the unique oscillating components from the raw process data in the process plant based on the method of the invention. Fig. 2 is a block diagrammatic representation showing exemplary components of the system of the invention, wherein the system is depicted by numeral 26. The system comprises at least one sensor 28 in a process plant to provide the raw process data. The system 26 then comprises a processor module 30 to process the raw process data to obtain the unique oscillating components as described herein. The system may also further comprise an analytics module 32 that is configured for root cause analysis of each oscillating components. The system 26 may further include a reporting module (not shown

in Fig. 2) to provide visual depiction of the processed data and analyses reports to support any decision making processes and enable corrective measures if required.

EXAMPLE 1: Simulation Scenario

A simulated time series data set is obtained using the equation given herein:

$$Y = 4\sin(2\pi 0.5t) + 2\sin(3\pi 0.05t) + \eta(0, 2.8)$$

where $\eta(0, 2.8)$ is Gaussian noise with zero mean and variance of 2.8

Fig. 3a shows the raw process data as obtained from the simulation. The simulated raw process data has one high frequency oscillating component and another low frequency component, whose power is lower than the noise level. Only the high frequency oscillating component from this signal needs to be detected as the other component even though oscillating is not of interest as it is shadowed by the noise. It is important as industrial data is always corrupted with noise, and identification of oscillating components with low power often leads to false alarms.

The simulated time series data is subjected to the steps as described in the method of the invention, as well as to a DCT method described in the prior art. Fig. 3b shows the multiple oscillation detection results obtained when the raw process data is subjected to the existing DCT method. Fig. 3c shows the multiple oscillation detection results obtained when the raw process data is subjected to the steps involved in the method of the invention.

As seen in Fig. 3, the method of the invention successfully detects the high frequency oscillation component alone, while the DCT method of the prior art detects additional oscillation component which is due to noise.

EXAMPLE 2: An Industrial Scenario

An industrial time series data set was used to compare the method of the invention with the DCT method of the prior art. Fig. 4 shows the multiple oscillation detection results from existing and proposed methods for the industrial time series

data set. Fig. 4a shows the industrial time series data, wherein there is only one oscillation present with some noise. Fig. 4b shows the industrial time series data that was subjected to the DCT method of the prior art, wherein an extra oscillation component is detected as a result of noise in the input data. Fig. 4c shows the industrial time series data that is subjected to the steps involved in the method of the invention, wherein only a single oscillating component is detected correctly.

While only certain features of the invention have been illustrated and described herein, many modifications and changes will occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

We Claim:

1. A method for obtaining valid oscillating components from a raw process data that is obtained in the form of a time series data from at least one sensor in a process plant, wherein the method comprises:

applying a decomposition technique on the time series data to obtain at least one oscillating component, wherein each oscillating component is associated with period values that is used to obtain applicable period values;

performing a regularity check on the applicable period values using the period for each data point based on a predetermined cut-off value to obtain first level valid oscillating component;

estimating a noise level for the raw process data; and

identifying and removing noisy oscillating components in the first level valid oscillating component based on the estimated noise level to obtain second level valid oscillating components.
2. The method of claim 1 wherein decomposition involves use of a spectral method followed by application of an inverse signal decomposition technique on each of the at least one spectral component to obtain at least one oscillating component.
3. The method of claim 1 further comprising applying a statistical treatment on the period values to obtain the applicable period values.
4. The method of claim 2 wherein the applying the statistical treatment comprises identifying and eliminating extreme mean period values from the oscillating components.

5. The method of claim 1 further comprising clustering at least one of the first level valid oscillating components or the second level valid oscillating components into unique oscillating components based on a mean period distance between given oscillating components.
6. The method of claim 1 wherein the estimating the noise level comprises modeling the raw process data using a parametric model.
7. The method of claim 1 wherein the raw process data is subjected to at least one pre-processing step.
8. The method of claim 2 wherein the signal decomposition technique is a DCT based method.
9. The method of claim 6 wherein the parametric model is an auto regressive model.
10. A method for obtaining valid oscillating components from a raw process data that is obtained in the form of a time series data from at least one sensor in a process plant, wherein the method comprises:

applying a decomposition technique on the time series data to obtain at least one oscillating component, wherein each oscillating component is associated with period values;

applying a statistical treatment on the period values to obtain applicable period values; and

performing a regularity check on the applicable period values using the period for each data point based on a predetermined cut-off value to obtain first level valid oscillating components.

11. The method of claim 10 wherein decomposition involves use of a spectral method followed by application of an inverse signal decomposition technique on each of the at least one spectral component to obtain at least one oscillating component.
12. The method of claim 10 wherein the applying a statistical treatment comprises identifying and eliminating extreme mean period values from the oscillating components.
13. The method of claim 10 further comprising:

estimating a noise level for the raw process data; and

identifying and removing noisy oscillating components in the first level valid oscillating component based on the estimated noise level to obtain second level valid oscillating components.
14. The method of claim 13 wherein the estimating the noise level comprises modeling the raw process data using a parametric model.
15. The method of claim 13 further comprising clustering at least one of the first level valid oscillating components or the second level valid oscillating components into unique oscillating components based on a mean period distance between given oscillating components.
16. The method of claim 14 wherein the parametric model is an auto regressive model.
17. The method of claim 11 wherein the spectral method is a DCT based method.

18. A method for obtaining unique oscillating components from a raw process data that is obtained in the form of a time series data from at least one sensor in a process plant, wherein the method comprises:

applying a decomposition technique on the time series data to obtain at least one oscillating component, wherein each oscillating component is associated with period values that is used to obtain applicable period values;

performing a regularity check on the applicable period values using the period for each data point based on a predetermined cut-off value to obtain at least one first level valid oscillating component; and

clustering the first level valid oscillating components into unique oscillating components based on a mean period distance between given oscillating components.

19. The method of claim 18 wherein decomposition involves use of a spectral method followed by application of an inverse signal decomposition technique on each of the at least one spectral component to obtain at least one oscillating component.
20. The method of claim 18 further comprising applying a statistical treatment on the period values to obtain the applicable period values.
21. The method of claim 20 wherein the applying a statistical treatment comprises identifying and eliminating extreme mean period values from the oscillating components.

22. The method of claim 18 further comprising:
- estimating a noise level for the raw process data;
 - identifying and removing noisy oscillating components in the first level valid oscillating components based on the estimated noise level to obtain second level valid oscillating components; and
 - clustering the second level valid oscillating components into unique oscillating components based on a mean period distance between given oscillating components.
23. The method of claim 22 wherein the estimating the noise level comprises modeling the raw process data using a parametric model.
24. The method of claim 23 wherein the parametric model is an auto regressive model.
25. The method of claim 19 wherein the spectral method is a DCT based method.

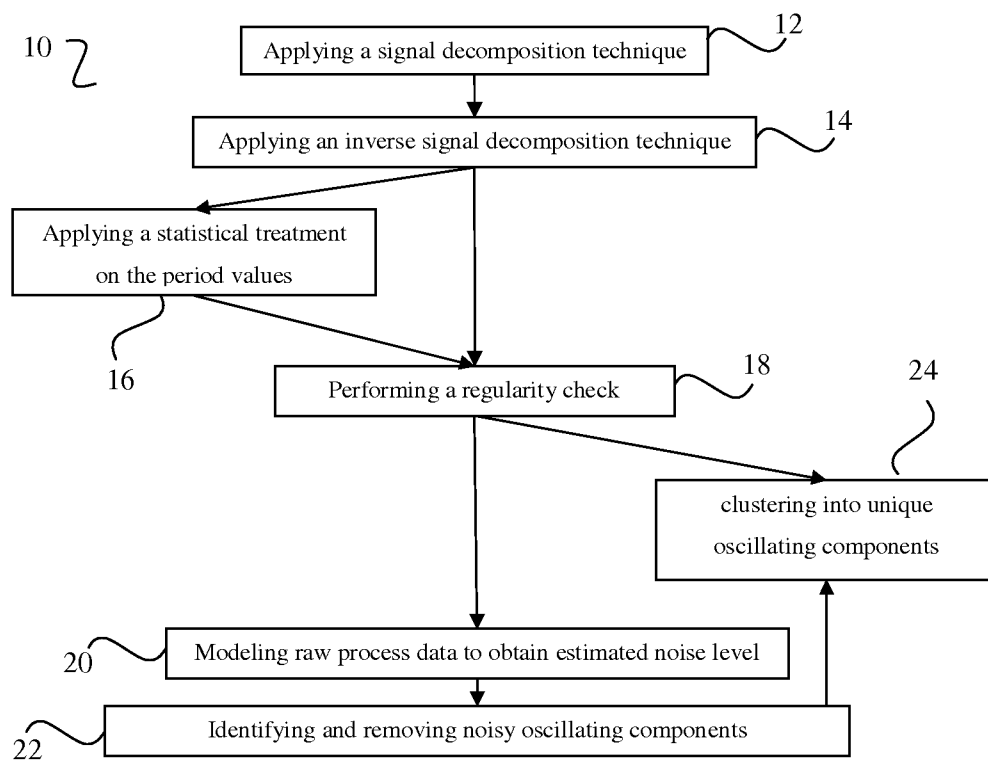


FIG. 1

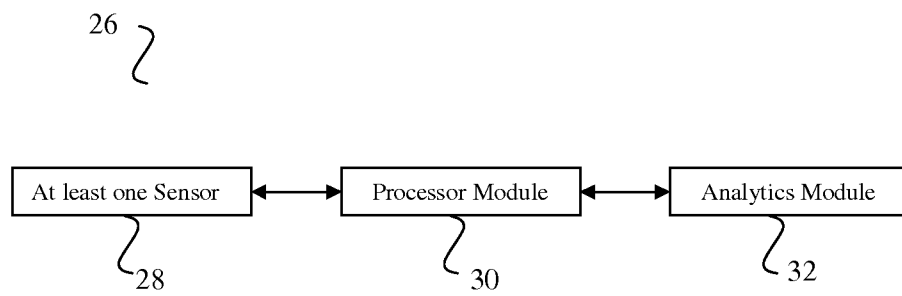


FIG. 2

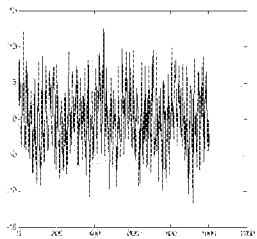


Fig. 3a

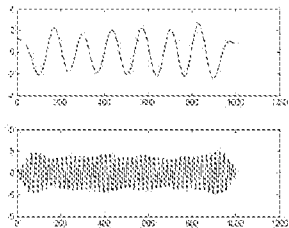


Fig. 3b

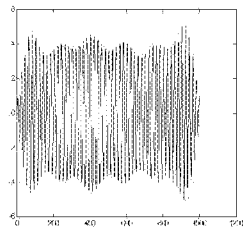


Fig. 3c

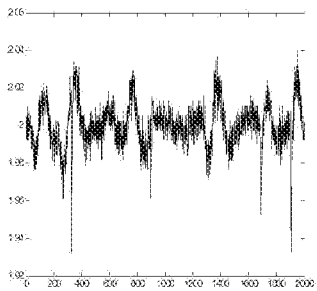


Fig. 4a

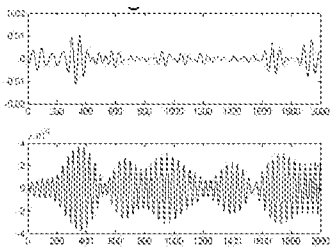


Fig. 4b

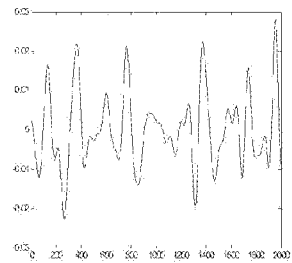


Fig. 4c