

Method, System and Computer Program for Fault Detection in a Machine

Field of the Invention

[0001] The present invention relates to condition monitoring of machinery. In particular, the invention provides methods, apparatuses and computer program products for detection of fault(s) or abnormal condition(s) in a machine, including without limitation rotating equipment such as centrifugal pumps.

Background

[0002] Condition monitoring refers to the process of monitoring one or more machine condition parameters to identify changes indicative of a developing or manifested fault condition or abnormality. It comprises a vital component of industrial safety and maintenance. Monitoring of machine condition parameters such as vibration characteristics, temperature, or input and output parameters may be used to determine fault conditions or developing fault conditions, and to trigger appropriate responses such as inspections, fault analysis, machine shutdowns, or repair and maintenance activity.

[0003] Plant maintenance and repair has been recognized as one of the major contributors of capital cost. It has been estimated that annual spending on maintenance of plant equipment and facilities in the U.S. alone is over USD 200 billion, and can vary between 15% and 60% of total cost of producing goods. Additionally, it has been estimated that over one third of maintenance costs are caused by unnecessary or improperly carried out maintenance. Timely and effective condition monitoring of industrial machinery and processes is therefore critical to operational and cost efficiencies – as it enables early detection and diagnosis of fault conditions or abnormalities in industrial assets. The present invention specifically addresses condition monitoring and fault detection in industrial machinery.

[0004] Rotating equipment including pumps and pumping equipment are an important class of industrial assets. Pumps are used to transfer or move fluids between or through machinery or equipment, and can operate as auxiliary equipment serving other industrial equipment such as boilers, chillers, cooling towers, and fluid processing units. Of the various types of pumps conventionally used (centrifugal, reciprocating and helical rotor), centrifugal pumps are among the most widely used. Simplicity of design, combined with cost and operating efficiencies, and robustness contribute to their popularity. The present invention particularly addresses condition monitoring and fault detection in rotating equipment such as centrifugal pumps.

[0005] **Figure 1** illustrates basic operating principles through a sectional view of a centrifugal pump **100** comprising a casing **102** and an impeller **104** housed within the casing **102** and having impeller blades **106**. The impeller **104** (and consequently impeller blades **106**) is capable of high speed rotations about a rotational axis within casing **102**. Fluid from a fluid inlet enters the casing axially through a casing eye **108**, is caught up in the impeller blades, and has a rotational motion imparted thereto. Upon rotation, centrifugal forces acting upon the fluid impart both velocity and pressure to the fluid, causing it to move tangentially and radially outwards until it leaves the casing through a fluid outlet **110**. The outgoing fluid lowers pressure within the casing **102**, causing fluid from the fluid inlet to be drawn into the casing **102** through the casing eye **108**.

[0006] **Figure 2** illustrates basic components of a centrifugal pump system **200**. The system **200** includes a casing **202** having an impeller **204** disposed therein. Impeller **204** is connected to motor **206** by drive shaft **208**. Current supplied to motor **206** from power source **224** causes the motor to rotate, which in turn rotates drive shaft **208** and drives impeller **204**. Impeller casing **202** is shown having a fluid inlet **210** connected to an inlet pipe **212**. Suction valve **214** disposed on inlet pipe **212** controls fluid flow into fluid inlet **210**. Impeller casing **202** is additionally shown having a fluid outlet **216** connected to an outlet pipe **218**. Discharge valve **220** is disposed on outlet pipe **218** and controls fluid discharge from fluid outlet **216**. Inlet pipe **212** may additionally have strainer **222** to filter sediment or particulate matter from fluid entering the pump casing.

[0007] Centrifugal pumps can suffer from process related faults as well as mechanical faults. Process faults include cavitation, discharge recirculation and strainer clogging, while mechanical faults include bad bearings, bent drive shafts, unbalanced rotors (the impeller together with the drive shaft), misalignments, broken impellers or broken or deformed impeller blades. Both process faults and mechanical faults fall within the broader category of fault conditions relating to a pump system. Presently methods for condition monitoring and fault diagnosis involving centrifugal pumps include monitoring design curve characteristics, manual inspection and offline analysis, and online vibration analysis.

[0008] Monitoring of design curve characteristics involves monitoring of a pump's performance characteristics during operation, for detecting deviations from a best efficiency point (BEP) prescribed by a manufacturer. **Figure 3** illustrates a sample design curve plotting the relationship between outlet fluid flow rate and one or more of total head, efficiency, shaft power and net pressure suction head (NPSH) in a pump. By comparing actual performance characteristics of a pump in operation against performance characteristics provided by a manufacturer / designer, detected underperformance may be treated as an indicator of a fault or abnormality. The design curve method has limitations in that the method allows identification of process faults but not of mechanical faults. Additionally, over time (and with wear), operating characteristics of a pump tend to deviate from the design characteristics provided at the time of manufacture. Moreover, operators may deliberately operate the pump away from the ideal design curve parameters to achieve operational efficiencies. In such cases, the design curve method is likely to fail, since it would indicate faults even in the absence of real faults.

[0009] Manual inspection and offline analysis involves periodic inspections of equipment by maintenance teams, including of lubrication oil levels, bearing temperatures and vibration characteristics within the pump system using portable devices such as vibration meters. While the method is useful for detecting both process and mechanical faults, the periodic or intermittent nature of the inspection is a disadvantage since it reduces the likelihood of detecting a problem immediately on occurrence.

[00010] Online vibration analysis involves continuous collection and analysis of high frequency vibration data from the centrifugal pump system – to identify process and mechanical faults as they occur. Defects including unbalanced components, bent shaft, eccentricity, misalignment, looseness and bearing defects can be detected using vibration measurement and analysis. However, commercial online vibration analysis systems are expensive and additionally require significant facilities and equipment for data storage and analysis. Since centrifugal pumps are considered auxiliary equipment, commercially available vibration analysis solutions typically provide on-demand analysis i.e. vibration characteristic data is collected and analysed periodically (e.g. once daily). As in

the case of manual inspections and offline analysis, this reduces the likelihood of detecting problems on occurrence or in real-time.

[00011] US 6,330,525 discloses a method of obtaining information on process or mechanical related faults in pumps by analysing current data (based on current supplied to the motor). Additionally, the reference contemplates use of process parameters (total head, NPSH, brake horse power, efficiency) and vibration data. The limitation of the reference is that it relies on suction pressure readings from the pump –where suction pressure readings are rarely available. Additionally, obtaining continuous vibration data typically involves a commercial vibration monitoring system – which is expensive.

[00012] US 6,757,665 contemplates use of current data for online pump diagnostics. However the prior art reference only contemplates diagnosis of cavitation, blockage and seal failures in pumps, and does not address diagnosis of other problems commonly encountered within centrifugal pump systems. The reference also does not contemplate any reliance on vibration data – which precludes root cause analysis for problems that have been detected by current signature analysis. Additionally, the reference implements an artificial neural network (ANN) to retain a knowledge model of fault signatures and to use it for future decision making. However, it has been found that knowledge models of fault signatures that have been developed by an ANN can lack consistency, since the model structure can vary with change in ANN parameters (e.g. number of layers), and hence such models do not respond to operating changes observed in pumps over time.

[00013] The existing state of art also includes use of current data for identifying motor related problems in a pump system (see for example, (i) Vinoth Kumar et al., A review of voltage and current signature diagnosis in industrial drives, International Journal of Power Electronics and Drive System, Vol. 1, No. 1, September 2011, pp. 75-82 and (ii) Kumar Pradhan et al., Fault detection in centrifugal pump using vibration and motor current signature analysis, International Journal of Automation and Control, Vol. 6, No. 3/4, 2012). While such solutions have been used for identifying motor related problems in pump systems, they do not address other process related faults (cavitation, discharge recirculation, strainer clogging) and mechanical related faults (bad bearings, bent shaft, unbalanced rotor, misalignment, broken impeller) in the pump system.

[00014] There is accordingly a need for a reliable and cost-effective solution for comprehensive, efficient and cost effective condition monitoring and fault detection in industrial machinery, including rotating equipment such as centrifugal pumps and centrifugal pump systems.

Summary

[00015] The invention provides methods, systems and computer program products for condition monitoring of a machine.

[00016] A method for condition monitoring of a machine in accordance with the present invention may comprise (i) obtaining a first set of data observations corresponding to a first pair of machine condition parameters, (ii) determining based on the first set of data observations, a first correlation coefficient corresponding to the first pair of machine condition parameters, (iii) determining based on the first correlation coefficient, a first p-value corresponding to the first pair of machine condition parameters, and (iv) selecting from among a plurality of available condition monitoring actions, at least one condition monitoring action for execution, wherein selection of the

condition monitoring action is based on at least the first p-value and one or more defined selection rules.

[00017] Selection rules in accordance with the present invention may be defined such that responsive to (i) the first pair of machine condition parameters comprising a correlated variable pair and (ii) the first p-value being greater than a first predefined p-value limit, the selected condition monitoring action is a condition monitoring action configured for execution in response to a detected fault condition.

[00018] In another embodiment, selection rules may be defined such that responsive to (i) the first pair of machine condition parameters comprising a non-correlated variable pair and (ii) the first p-value being less than or equal to a first predefined p-value limit, the selected condition monitoring action is a condition monitoring action configured for execution in response to a detected fault condition.

[00019] A condition monitoring action configured for execution in response to a detected fault condition may comprises any one or more of, signalling the detected fault condition, modifying an operating state of the machine, invoking a condition monitoring routine in response to the detected fault condition, triggering one or more of an alarm, alert, a manual inspection, or a sensor based test, triggering online vibration analysis, or executing at least one additional test regarding operating condition of the machine.

[00020] In an embodiment of the invention the first predefined p-value limit may have any value between 0.01 and 0.05.

[00021] The method of the present invention may additionally include (i) obtaining a second set of data observations corresponding to a second pair of machine condition parameters, (ii) determining based on the second set of data observations, a second correlation coefficient corresponding to the second pair of machine condition parameters, and (iii) determining based on the second correlation coefficient, a second p-value corresponding to the second pair of machine condition parameters, wherein selection of the condition monitoring action for execution is additionally based on at least the second p-value.

[00022] In an embodiment of the invention, (i) the machine may comprise a centrifugal pump system, (ii) the first pair of machine condition parameters may be a correlated variable pair comprising current and discharge pressure, (iii) the second pair of machine condition parameters may be a correlated variable pair comprising current and outflow rate and (iv) responsive to the first p-value being greater than a first predefined p-value limit or the second p-value being greater than a second predefined p-value limit, the selected condition monitoring action may comprise a condition monitoring action configured for execution in response to a detected fault condition.

[00023] In another embodiment of the method, (i) the machine may comprise a centrifugal pump system, (ii) the first pair of machine condition parameters may be a non-correlated variable pair comprising current and detected bearing temperature, (iii) the second pair of machine condition parameters may be a non-correlated variable pair comprising current and a detected vibration characteristic and (iv) responsive to the first p-value being less than or equal to a first predefined p-value limit, or the second p-value being less than or equal to a second predefined p-value limit, the

selected condition monitoring action may be a condition monitoring action configured for execution in response to a detected fault condition.

[00024] The method of the present invention may additionally comprise (i) obtaining a third set of data observations corresponding to a third pair of machine condition parameters and (ii) determining based on the third set of data observations, a third correlation coefficient corresponding to the third pair of machine condition parameters, wherein selection of the condition monitoring action for execution is additionally based on at least the third p-value.

[00025] In an embodiment of the invention (i) the machine may comprise a centrifugal pump system (ii) first pair of machine condition parameters may be a correlated variable pair comprising outflow rate and suction valve position, (iii) the second pair of machine condition parameters may be a correlated variable pair comprising outflow rate and discharge valve position, (iv) the third pair of machine condition parameters may be a correlated variable pair comprising outflow rate and inflow rate and (v) responsive to the first p-value being greater than a first predefined p-value limit, the second p-value being greater than a second predefined p-value limit and the third p-value being greater than a third predefined p-value limit, the method may select a condition monitoring action configured for execution in response to a detected fault condition.

[00026] A more particular embodiment of the method for condition monitoring of a centrifugal pump comprises obtaining (i) a first p-value corresponding to a first correlated pair of machine condition parameters comprising current and discharge pressure, (ii) a second p-value corresponding to a second correlated pair of machine condition parameters comprising current and outflow rate, (iii) a third p-value corresponding to a third non-correlated pair of machine condition parameters comprising current and detected bearing temperature, (iv) a fourth p-value corresponding to a fourth non-correlated pair of machine condition parameters comprising current and a detected vibration characteristic, (v) a fifth p-value corresponding to a fifth correlated pair of machine condition parameters comprising outflow rate and suction valve position, (vi) a sixth p-value corresponding to a sixth correlated pair of machine condition parameters comprising outflow rate and discharge valve position, and (vii) a seventh p-value corresponding to a seventh correlated pair of machine condition parameters comprising outflow rate and inflow rate.

[00027] A first condition monitoring action may be selected from among a plurality of available condition monitoring actions, wherein responsive to (i) the first p-value being greater than a first predefined p-value limit, or the second p-value being greater than a second predefined p-value limit; and (ii) the third p-value being less than or equal to a third predefined p-value limit, or the fourth p-value being less than or equal to a fourth predefined p-value limit, the selected first condition monitoring action comprises a condition monitoring action configured for execution in response to a detected fault condition.

[00028] Alternately, a first condition monitoring action may be selected from among a plurality of available condition monitoring actions, wherein responsive to (i) the first p-value being greater than a first predefined p-value limit, or the second p-value being greater than a second predefined p-value limit; and (ii) the third p-value being greater than a third predefined p-value limit, and the fourth p-value being greater than a fourth predefined p-value limit, the selected first condition monitoring action comprises comparing a detected bearing temperature with a recommended operating temperature, comparing a detected vibration characteristic with a recommended vibration characteristic limit, and responsive to either the detected bearing temperature exceeding the

recommended operating temperature, or the detected vibration characteristic exceeding the recommended vibration characteristic limit, selecting from among the plurality of available condition monitoring actions, a second condition monitoring action for execution, wherein the second condition monitoring action comprises a condition monitoring action configured for execution in response to a detected fault condition.

[00029] Alternately, a first condition monitoring action may be selected from among a plurality of available condition monitoring actions, wherein responsive to the first p-value being less than or equal to a first predefined p-value limit and the second p-value being less than or equal to a second predefined p-value limit, the selected first condition monitoring action comprises (i) comparing an observed maximum outflow rate with an observed minimum outflow rate, and (ii) responsive to the maximum outflow rate exceeding the minimum outflow rate by more than a predefined first outflow variation limit, ascertaining whether (a) the fifth p-value is greater than a fifth predefined p-value limit, (b) the sixth p-value is greater than a sixth predefined p-value limit and (c) the seventh p-value is greater than a seventh predefined p-value limit.

[00030] In a method embodiment of the invention, any of the first to seventh predefined p-value limits may comprise any value between 0.01 and 0.05.

[00031] In a particular embodiment of the above method, responsive to the fifth p-value being greater than the fifth predefined p-value limit, the sixth p-value being greater than the sixth predefined p-value limit and the seventh p-value being greater than the seventh predefined p-value limit, the method may include (i) responding to a detected decrease in outflow rate exceeding a predefined second outflow variation limit, selecting from among the plurality of available condition monitoring actions, a third condition monitoring action for execution, wherein the third condition monitoring action comprises a condition monitoring action configured for execution in response to a detected discharge recirculation fault or a strainer clogging fault or (ii) responding to detecting oscillations in observed outflow rate and observed discharge pressure, selecting from among the plurality of available condition monitoring actions, a fourth condition monitoring action for execution, wherein the fourth condition monitoring action comprises a condition monitoring action configured for execution in response to a detected cavitation fault.

[00032] A system in accordance with the present invention may comprise a processor implemented data analysis and heuristics controller, configured for (i) obtaining a first set of data observations corresponding to a first pair of machine condition parameters, (ii) determining based on the first set of data observations, a first correlation coefficient corresponding to the first pair of machine condition parameter, (iii) determining based on the first correlation coefficient, a first p-value corresponding to the first pair of machine condition parameters, and (iv) selecting from among a plurality of available condition monitoring actions, at least one condition monitoring action for execution, wherein selection of the condition monitoring action is based on at least the first p-value, and one or more defined selection rules.

[00033] The system may further comprise at least one of (i) a pump diagnostics interface configured for receiving and communicating information regarding an operating state of the machine with a user or device, (ii) a pre-treatment engine configured for optimizing information from one or more sensors, for data analysis, or (iii) a trigger control configured for signalling or implementing a state change within the machine.

[00034] In a system embodiment, the selection rules may be retrieved from a database and may be defined such that responsive to (i) the first pair of machine condition parameters comprising a correlated variable pair and (ii) the first p-value being greater than a predefined p-value limit, the selected condition monitoring action is a condition monitoring action configured for execution in response to a detected fault condition.

[00035] In another system embodiment, selection rules may be retrieved from a database and defined such that responsive to (i) the first pair of machine condition parameters comprising a non-correlated variable pair and (ii) the first p-value being less than or equal to a predefined p-value limit, the selected condition monitoring action is a condition monitoring action configured for execution in response to a detected fault condition.

[00036] The system may be configured such that the condition monitoring action for execution in response to a detected fault condition, may comprise any one or more of signalling the detected fault condition, modifying an operating state of the machine, invoking a condition monitoring routine in response to the detected fault condition, triggering one or more of an alarm, alert, a manual inspection, or a sensor based test, triggering online vibration analysis, or executing at least one additional test regarding operating condition of the machine.

[00037] In an embodiment of the system, the first predefined p-value limit may have any value between 0.01 and 0.05.

[00038] The data analysis and heuristics controller may be further configured for (i) obtaining a second set of data observations corresponding to a second pair of machine condition parameters, (ii) determining based on the second set of data observations, a second correlation coefficient corresponding to the second pair of machine condition parameters and (iii) determining based on the second correlation coefficient, a second p-value corresponding to the second pair of machine condition parameters, wherein selection of the condition monitoring action for execution is additionally based on at least the second p-value.

[00039] The system may be configured for condition monitoring of a centrifugal pump system, wherein the first pair of machine condition parameters is a correlated variable pair comprising current and discharge pressure, and the second pair of machine condition parameters is a correlated variable pair comprising current and outflow rate. Responsive to the first p-value being greater than a first predefined p-value limit or the second p-value being greater than a second predefined p-value limit, the selected condition monitoring action may be a condition monitoring action configured for execution in response to a detected fault condition.

[00040] The system may alternately be configured for condition monitoring of a centrifugal pump system, wherein the first pair of machine condition parameters is a non-correlated variable pair comprising current and detected bearing temperature, and the second pair of machine condition parameters is a non-correlated variable pair comprising current and a detected vibration characteristic. In this embodiment, responsive to the first p-value being less than or equal to a first predefined p-value limit, or the second p-value being less than or equal to a second predefined p-value limit, the selected condition monitoring action may be a condition monitoring action configured for execution in response to a detected fault condition.

[00041] The data analysis and heuristics controller may be further configured for obtaining a third set of data observations corresponding to a third pair of machine condition parameters, and determining based on the third set of data observations, a third correlation coefficient corresponding to the third pair of machine condition parameters. In this embodiment, selection of the condition monitoring action for execution may additionally be based on at least the third p-value.

[00042] In a system embodiment configured for condition monitoring of a centrifugal pump system, the first pair of machine condition parameters may be a correlated variable pair comprising outflow rate and suction valve position, the second pair of machine condition parameters may be a correlated variable pair comprising outflow rate and discharge valve position and the third pair of machine condition parameters may be a correlated variable pair comprising outflow rate and inflow rate. Responsive to the first p-value being greater than a first predefined p-value limit, the second p-value being greater than a second predefined p-value limit and the third p-value being greater than a third predefined p-value limit, the selected condition monitoring action may be a condition monitoring action configured for execution in response to a detected fault condition.

[00043] In another system embodiment configured for condition monitoring of a centrifugal pump, the system may comprise a processor implemented data analysis and heuristics controller configured for obtaining, based on data observations received from one or more sensors, a first p-value corresponding to a first correlated pair of machine condition parameters comprising current and discharge pressure, a second p-value corresponding to a second correlated pair of machine condition parameters comprising current and outflow rate, a third p-value corresponding to a third non-correlated pair of machine condition parameters comprising current and detected bearing temperature, a fourth p-value corresponding to a fourth non-correlated pair of machine condition parameters comprising current and a detected vibration characteristic, a fifth p-value corresponding to a fifth correlated pair of machine condition parameters comprising outflow rate and suction valve position, a sixth p-value corresponding to a sixth correlated pair of machine condition parameters comprising outflow rate and discharge valve position, and a seventh p-value corresponding to a seventh correlated pair of machine condition parameters comprising outflow rate and inflow rate.

[00044] The data analysis and heuristics controller of the system is configured to select from among a plurality of available condition monitoring actions, a first condition monitoring action for execution.

[00045] In an embodiment of the system, responsive to (i) the first p-value being greater than a first predefined p-value limit, or the second p-value being greater than a second predefined p-value limit; and (ii) the third p-value being less than or equal to a third predefined p-value limit, or the fourth p-value being less than or equal to a fourth predefined p-value limit, the selected first condition monitoring action comprises a condition monitoring action configured for execution in response to a detected fault condition.

[00046] In another embodiment of the system, responsive to (i) the first p-value being greater than a first predefined p-value limit, or the second p-value being greater than a second predefined p-value limit; and (ii) the third p-value being greater than a third predefined p-value limit, and the fourth p-value being greater than a fourth predefined p-value limit, the selected first condition monitoring action comprises comparing a detected bearing temperature with a recommended maximum operating temperature, comparing a detected vibration characteristic with a recommended vibration characteristic limit, and responsive to either the detected bearing temperature exceeding

the recommended maximum operating temperature, or the detected vibration characteristic exceeding the recommended vibration characteristic limit, selecting from among the plurality of available condition monitoring actions, a second condition monitoring action for execution, wherein the second condition monitoring action comprises a condition monitoring action configured for execution in response to a detected fault condition.

[00047] In another embodiment, responsive to the first p-value being less than or equal to a first predefined p-value limit and the second p-value being less than or equal to a second predefined p-value limit, the selected first condition monitoring action comprises comparing an observed maximum outflow rate with an observed minimum outflow rate, and responsive to the maximum outflow rate exceeding the minimum outflow rate by more than a predefined first outflow variation limit, ascertaining whether (a) the fifth p-value is greater than a fifth predefined p-value limit, (b) the sixth p-value is greater than a sixth predefined p-value limit and (c) the seventh p-value is greater than a seventh predefined p-value limit.

[00048] In the system embodiments described above, any of the first to seventh predefined p-value limits may have any value between 0.01 and 0.05.

[00049] The system embodiments described above may additionally include at least one of (i) a pump diagnostics interface configured for receiving and communicating information regarding an operating state of the centrifugal pump system, with a user or device, (ii) a pre-treatment engine configured for optimizing information received from one or more sensors, for data analysis, and (iii) a trigger control configured for signalling or implementing a state change within the centrifugal pump system.

[00050] In a particular system embodiment, the data analysis and heuristics controller may be configured such that responsive to (a) the fifth p-value being greater than the fifth predefined p-value limit, (b) the sixth p-value being greater than the sixth predefined p-value limit and (c) the seventh p-value being greater than the seventh predefined p-value limit, the system (i) responds to a detected decrease in outflow rate exceeding a predefined second outflow variation limit, by selecting from among the plurality of available condition monitoring actions, a third condition monitoring action for execution, wherein the third condition monitoring action comprises a condition monitoring action configured for execution in response to a detected discharge recirculation fault or a strainer clogging fault, or (ii) responds to detected oscillations in observed outflow rate and observed discharge pressure, by selecting from among the plurality of available condition monitoring actions, a fourth condition monitoring action for execution, wherein the fourth condition monitoring action comprises a condition monitoring action configured for execution in response to a detected cavitation fault.

[00051] The invention may additionally include a computer program product for condition monitoring of a machine, comprising a non-transitory computer-readable storage medium having program code stored therein. The program code may comprise instructions for (i) obtaining a first set of data observations corresponding to a first pair of machine condition parameters, (ii) determining based on the first set of data observations, a first correlation coefficient corresponding to the first pair of machine condition parameters, (iii) determining based on the first correlation coefficient, a first p-value corresponding to the first pair of machine condition parameters, and (iv) selecting from among a plurality of available condition monitoring actions, at least one condition

monitoring action for execution, wherein selection of the condition monitoring action is based on at least the first p-value and one or more defined selection rules.

Brief Description of the Accompanying Drawings

[00052] **Figure 1** illustrates a sectional view of a centrifugal pump.

[00053] **Figure 2** illustrates basic components of a centrifugal pump system.

[00054] **Figure 3** illustrates a sample design curve for a pump.

[00055] **Figure 4** illustrates a method for condition monitoring and fault detection in a machine or system.

[00056] **Figures 5 to 8D** illustrate embodiments of a method for condition monitoring and fault detection in connection with a centrifugal pump system.

[00057] **Figure 9** illustrates a system for condition monitoring and fault detection in a machine or system.

[00058] **Figure 10** illustrates an exemplary computing system in which embodiments of the invention may be implemented.

Detailed Description

[00059] The present invention achieves reliable, real-time and cost-effective condition monitoring and fault detection in industrial machinery, including rotating equipment such as centrifugal pumps or centrifugal pump systems. The invention achieves this by implementing statistical analysis and pattern recognition to detect faults or abnormalities in machine condition parameters.

[00060] The invention provides a simple, robust and cost effective solution for identifying process and mechanical faults using various real time data observations in connection with one or more pairs of machine condition parameters. In an embodiment of the invention concerning condition monitoring of centrifugal pump systems, the invention monitors current data and one or more other machine condition parameters, and may optionally trigger a manual / offline inspection or an online vibration system for root cause analysis of any detected faults or abnormalities in machine condition parameters.

[00061] The invention is premised on the discovery that within a machine (i) specific pairs of machine condition parameters exhibit dependence (i.e. a correlation) when the machine is operating normally, and (ii) specific other pairs of machine condition parameters exhibit dependence when the machine is operating abnormally.

[00062] It has therefore been discovered that monitoring data observations corresponding to a variable pair that is known to exhibit dependence when a machine is operating normally, and detecting any deviations from an expected or prescribed correlation for the variable pair, can be used to detect manifested or developing fault(s) in the machine. Similarly, it has been discovered that monitoring data observations corresponding to a variable pair that does not exhibit dependence

when a machine is operating normally, and detecting any unexpected correlation for the variable pair, can be used to detect manifested or developing fault(s) in the machine.

[00063] In the specific instance of centrifugal pumps and centrifugal pump systems, it has been found that the following pairs of machine condition parameters exhibit dependence or correlation during normal operation:

- (a) current supply to the motor, and discharge pressure,
- (b) current supply to the motor, and volume of fluid outflow per unit time
- (c) volume of fluid outflow per unit time, and valve position of a suction valve controlling a fluid inlet
- (d) volume of fluid outflow per unit time, and valve position of a discharge valve controlling a fluid outlet
- (e) volume of fluid outflow per unit time, and volume of fluid inflow per unit time

[00064] Similarly, it has been discovered that the following pairs of machine condition parameters corresponding to centrifugal pumps and centrifugal pump systems do not exhibit dependence or correlation during normal operation:

- (a) current, and bearing temperature
- (b) current, and vibration characteristic data

[00065] By monitoring data observations corresponding to one of the above variable pair, and detecting (i) any deviations from an expected or prescribed correlation corresponding to a variable pair known to exhibit dependence in normal operations or (ii) any unexpected correlation corresponding to a variable pair that is known to not exhibit dependence in normal operations - manifested or developing fault(s) in a centrifugal pump or centrifugal pump system may be identified.

[00066] The invention may achieve this by employing sensors capable of obtaining machine condition parameter data. In the case of a centrifugal pump or centrifugal pump system, the obtained data may include data on one or more of source flow, discharge pressure, current, voltage, power, suction and discharge valve positions, bearing temperature and vibration characteristics. Sensor data may be subjected to statistical analysis for detecting and monitoring correlations between data corresponding to one or more of the above variable pairs, and deviations from expected or prescribed dependence behaviour for a particular variable pair is treated as an indication of a process fault or a mechanical fault condition or potential fault condition.

[00067] For the purposes of the invention, a “correlated variable pair” shall mean a pair of machine condition parameters known to exhibit dependence (correlation) with each other when the machine or system is operating in a normal or non-fault condition.

[00068] For the purposes of this invention the term “correlation” may be understood as quantifying the extent to which two quantitative variables are related. A positive correlation refers to a direct relationship between two quantitative variables wherein as the value of the first variable increases, the value of the second variable also increases, and correspondingly wherein as the value of the first variable decreases, the value of the second variable also decreases. A negative correlation refers to an inverse relationship between two quantitative variables wherein as the value of the first variable increases, the value of the second variable decreases, and correspondingly wherein as the value of the first variable decreases, the value of the second variable increases.

[00069] For the purposes of this invention, the term “correlation coefficient” may be understood as a number (ordinarily between -1 and 1) that determines whether a pair of data sets (corresponding to two quantitative variables) are related. A correlation coefficient approaching 1 is indicative of a positive linear correlation, while a correlation coefficient approaching -1 is indicative of a negative linear correlation. A correlation coefficient approaching 0 is indicative that no dependence exists between the two variables. Several different types of correlation coefficients are commonly used – including the Pearson product moment correlation coefficient and the Spearman rank correlation coefficient. Any type of correlation coefficient may be implemented in achieving the purposes of the present invention. A correlation coefficient for a variable pair may be determined using any number of statistical methods well known in the art. Additionally correlation coefficients may be determined by using software tools such as MS Excel (a product of Microsoft, Inc.) and MATLAB (a product of The MathWorks, Inc.). The present invention is capable of being implemented based on any statistical method or any software tool(s) for determining correlation coefficients.

[00070] For the purposes of the invention, the term “correlation coefficient matrix” shall mean a square symmetrical $M \times M$ matrix which describes correlation among M quantitative variables. The data value at an $(x,y)^{th}$ element of the matrix is the correlation coefficient between the $(x)^{th}$ and the $(y)^{th}$ variable. The data values at diagonal elements (correlation coefficients of each variable with itself) are always equal to 1.00. An $M \times M$ correlation coefficient matrix may be generated by using software tools such as MS Excel or MATLAB based on an input data matrix having M columns and N rows, where each row comprises a set of data observations (or readings) and each column corresponds to one of the M quantitative variables. The present invention is capable of being implemented based on any statistical method or any software tool(s) for generating a correlation coefficient matrix.

[00071] For the purposes of the invention, “current” (i_{motor}) shall mean current supplied by a power source to a motor.

[00072] For the purposes of the invention, “detected bearing temperature” ($BTemp_{Detected}$) shall mean a temperature reading corresponding to a bearing assembly (or part thereof) coupled with any of a motor, shaft, or impeller of a pump.

[00073] For the purposes of the invention, “detected vibration characteristic” ($VibData_{Detected}$) shall mean a vibration characteristic received from one or more vibration sensors (e.g. an accelerometer) disposed on or in the vicinity of any of a motor, shaft, or impeller of a pump.

[00074] For the purposes of the invention, “discharge pressure” ($Pressure_{Disch}$) shall mean fluid pressure generated at an outlet side of a pump.

[00075] For the purposes of the invention, “discharge valve position” ($DValve_{posn}$) shall mean valve position of a discharge valve controlling fluid outflow at an outlet side of a centrifugal pump.

[00076] For the purposes of the invention “fault condition” shall mean any abnormal condition or defect in a machine, system or process. Without limitation, fault condition may refer to any abnormal condition or defect observed in any (i) operating process (ii) component (iii) equipment, or (iv) sub-system. A fault condition may comprise a process fault, mechanical fault, electric fault, electronic fault, electro-mechanical fault, and any other fault that may cause a functional unit to perform sub-optimally, or to malfunction, or which may lead to failure of the functional unit.

[00077] For the purposes of the invention, “inflow rate” ($Inflow_{Rate}$) shall mean volumetric flow rate at an inlet side of a pump.

[00078] For the purposes of the invention, “machine” shall include any fully or partially mechanical, electro-mechanical, electrical, or electronic device or system.

[00079] For the purposes of the invention, a “non-correlated variable pair” shall mean a pair of machine condition parameters known to not exhibit dependence (correlation) with each other when the machine or system is operating in a normal or non-fault condition.

[00080] For the purposes of the invention, “outflow rate” ($Outflow_{Rate}$) shall mean volumetric flow rate at an outlet side of a pump.

[00081] For the purposes of the invention, “power” (P_{motor}) shall mean power transferred to a motor from the power supply.

[00082] For the purposes of the invention, the term “p-value” is understood as a probability of obtaining a correlation value corresponding to two variables, at least as extreme as the one that was actually observed, when the true correlation between the two variables is zero i.e. the two variables do not exhibit dependence on each other. The p-value may be a number between 0 and 1.

[00083] When calculated based on an observed correlation coefficient value between two variables that are known to be correlated (i.e. to exhibit dependence on each other):

- a small p-value (a p-value approaching 0) is indicative that the observed correlation coefficient value between the two variables is inconsistent with the assumption that the true correlation between the two variables is zero. In other words, a very small p-value is indicative that the observed correlation coefficient value between the two variables indicates that the two variables are correlated. Since the two variables for which the p-value has been calculated are already known to be correlated, a small p-value is indicative that data observations corresponding to the two variables are consistent with a known dependence relationship between said two variables.
- a large p-value (a p-value approaching 1) is indicative that the observed correlation coefficient value between the two variables is consistent with the

assumption that the true correlation between the two variables is zero. However, since the two variables for which the p-value has been calculated are already known to be correlated, a large p-value indicative that data observations corresponding to the two variables are inconsistent with a known dependence relationship between said two variables.

[00084] Conversely, when calculated based on an observed correlation coefficient value between two variables that are known to be not correlated (i.e. to not exhibit dependence on each other):

- a small p-value (a p-value approaching 0) is indicative that the observed correlation coefficient value between the two variables is inconsistent with the assumption that the true correlation between the two variables is zero. In other words, a very small p-value is indicative that the observed correlation coefficient value between the two variables indicates that the two variables are correlated. However, since the two variables for which the p-value has been calculated are known to be not correlated, a small p-value is indicative that data observations corresponding to the two variables are inconsistent with a known lack of dependence between said two variables.
- a large p-value (a p-value approaching 1) is indicative that the observed correlation coefficient value between the two variables is consistent with the assumption that the true correlation between the two variables is zero. Since the two variables for which the p-value has been calculated are known to be not correlated, a large p-value indicative that data observations corresponding to the two variables are consistent with a known lack of dependence between said two variables.

[00085] P-values may be calculated using statistical tables, or software tools such as MS Excel or MATLAB. The present invention is capable of being implemented based on any statistical method or any software tool(s) for generating a correlation coefficient matrix.

[00086] For the purposes of the invention, the term “p-value matrix” is understood as a square symmetrical $M \times M$ matrix, generated based on a corresponding $M \times M$ correlation coefficient matrix, where M is the total number of quantitative variables. The data value at an $(x,y)^{th}$ element of the p-value matrix is the p-value corresponding to the correlation coefficient between the $(x)^{th}$ and the $(y)^{th}$ variable in the correlation coefficient matrix. An $M \times M$ p-value matrix may be generated by using software tools such as MS Excel or MATLAB based on an input $M \times M$ correlation coefficient matrix. The present invention is capable of being implemented based on any statistical method or any software tool(s) for generating a correlation coefficient matrix.

[00087] For the purposes of the invention “ $P_v [p,q]$ ” shall mean a p-value corresponding to a variable pair comprising variables p and q .

[00088] For the purposes of the invention, “recommended bearing temperature limit” ($BTemp_{Rec}$) shall mean a recommended maximum operating temperature for a bearing assembly (or part thereof) coupled with a motor, shaft, or impeller of a pump.

[00089] For the purposes of the invention, “recommended vibration characteristic limit” ($\text{VibData}_{\text{rec}}$) shall mean a recommended maximum permissible limit for a vibration characteristic at or in the vicinity of a motor, shaft or impeller of a pump.

[00090] For the purposes of the invention “R [p,q]” shall mean a correlation coefficient corresponding to a variable pair comprising variables p and q.

[00091] For the purposes of the invention, “resistance” (R_{motor}) shall mean resistance of a motor.

[00092] For the purposes of the invention, “suction valve position” ($\text{SValve}_{\text{posn}}$) shall mean valve position of a suction valve controlling fluid inflow at the inlet side of a pump.

[00093] For the purposes of the invention, “voltage” (V_{motor}) shall mean supply voltage provided to a motor.

[00094] **Figure 4** illustrates a method for condition monitoring and fault detection in a machine or system, in accordance with the present invention.

[00095] Step 402 comprises obtaining at least a prescribed number of data observations corresponding to at least a pair of machine condition parameters related to the machine or system. The pair of machine condition parameters may comprise any first machine condition parameter and second machine condition parameter, which first and second machine condition parameters are either (i) a correlated variable pair or (ii) a non-correlated variable pair.

[00096] The prescribed number of data observations may comprise any number greater than one. In a particular embodiment, the prescribed number of data observations is any number of data observations greater than or equal to thirty, and in a preferred embodiment the prescribed number of data observations is greater than or equal to sixty. In another embodiment, the prescribed number of data observations may be configurable by a user, system operator or system administrator. In an embodiment of the invention, each data observation may include a first data observation corresponding to the first machine condition parameter and a second data observation corresponding to the second machine condition parameter.

[00097] Step 404 comprises determining a correlation coefficient corresponding to the first and second machine condition parameters – which correlation coefficient may be determined based on the data observations related to the first and second machine condition parameters. Thereafter, at step 406, a p-value corresponding to first and second machine condition parameters is determined – which determination may be based on the determined correlation coefficient.

[00098] At step 408, the method selects, from among a plurality of available condition monitoring actions, one or more condition monitoring actions for execution - wherein selection of the one or more condition monitoring actions for execution is based on (i) at least the determined p-value corresponding to the first and second machine condition parameters, and (ii) one or more selection rules.

[00099] The one or more selection rules comprise predefined rules which determine selection of one or more condition monitoring actions for execution, from among the plurality of condition monitoring actions. Each of the one or more selection rules is mapped to or associated with a p-

value or a range of p-values. Accordingly, subsequent to determination of a p-value corresponding to the first and second machine condition parameters at step 406, step 408 may invoke the one or more selection rules mapped to or associated with the determined p-value (or with a range of p-values within which the determined p-value falls). The invoked one or more selection rules results in selection of one or more condition monitoring actions for execution, from among the available plurality of condition monitoring actions.

[000100] It would be understood that the selection rules may be configurable, thereby enabling the method to be customized for a specific machine, system, or pair of machine condition parameters.

[000101] In an embodiment of the invention, the selection rules may be defined such that:

- in case of a correlated variable pair, responsive to determining that a p-value is less than or equal to a predefined p-value limit, at least one of the selected one or more condition monitoring actions is a condition monitoring action configured for execution in response to a normal or non-fault operating condition of the machine or system, or
- in case of a correlated variable pair, responsive to obtaining a p-value value greater than a predefined p-value limit, at least one of the selected one or more condition monitoring actions is a condition monitoring action configured for execution in response to an abnormal or fault- condition of the machine or system, or
- in case of a non-correlated variable pair, responsive to obtaining a p-value value greater than a predefined p-value limit, at least one of the selected one or more condition monitoring actions is a condition monitoring action configured for execution in response to a normal or non-fault operating condition of the machine or system, or
- in case of a non-correlated variable pair, responsive to obtaining a p-value value less than or equal to a predefined p-value limit, at least one of the selected one or more condition monitoring actions is a condition monitoring action configured for execution in response to an abnormal or fault- condition of the machine or system.

[000102] The predefined value limit in any of the above embodiments may comprise any numerical value between 0 and 1. In any embodiment of the invention, the predefined p-value limit may be any numerical value between 0.01 and 0.05.

[000103] In an embodiment of the invention, a condition monitoring action configured for execution in response to detection of a normal or non-fault condition of the machine or system may comprise any one or more of (i) signalling or communicating to a user or a device, the normal or non-fault condition of the machine or system (ii) continuing operation of the machine or system without any changes to operating parameters (iii) continuing condition monitoring of the machine or system without invoking any condition monitoring routines or sub-routines specific to a detected abnormality or fault condition or (iv) executing a confirmatory check regarding operating condition of the machine or machine system.

[000104] A condition monitoring action configured for execution in response to detection of an abnormal or fault condition of the machine or system may comprise any one or more of (i) signalling or communicating to a user or a device, the abnormal or fault condition of the machine or system (ii) changing operating parameters of the machine or system (iii) invoking a condition monitoring routine or sub-routine specific to a detected abnormality or fault condition (iv) triggering one or more of an alarm or alert, a manual inspection, or a sensor based testing methodology or (v) executing a confirmatory check regarding operating condition of the machine or machine system.

[000105] It would be understood that the method illustrated and discussed above in connection with the present invention may be implemented in connection with more than one pair of machine condition parameters. In such cases, correlation coefficients corresponding to each pair of machine condition parameters may be determined separately, or may be determined all together using a correlation coefficient matrix. Likewise p-values corresponding to each pair of machine condition parameters may be determined separately, or alternatively may be determined all together using a p-value matrix.

[000106] Although not specifically illustrated, it would be understood that in the case of any method described (in connection with **Figure 4** or otherwise) within the present disclosure, the method may include any one or more of: (i) monitoring and ensuring that at least a prescribed number of data observations are obtained (ii) monitoring status and connectivity of sensors or devices responsible for obtaining data observations (iii) executing periodic checks on operational status of sensors or devices responsible for obtaining data observations (iv) alerting an operator to inconsistencies or errors in incoming data observations (v) filtering noise from data signals received from sensors or devices responsible for obtaining data observations and (vi) wherever possible, responsive to unavailability of direct data observations corresponding to any required machine condition parameter, deriving such data observations from observations corresponding to any related machine condition parameter.

[000107] **Figure 5** illustrates an embodiment of the method of **Figure 4** – implemented in connection with a centrifugal pump system.

[000108] Step 502 comprises obtaining from an operating centrifugal pump system, at least a prescribed number of data observations corresponding to (i) current (ii) discharge pressure and (iii) outflow rate. It has been found that in centrifugal pump systems, current and discharge pressure comprise a first correlated variable pair, while current and outflow rate comprise a second correlated variable pair. Accordingly, when a centrifugal pump system is operating in a normal or non-fault condition, data observations corresponding to current and discharge pressure would exhibit correlation, and likewise data observations corresponding to current and outflow rate would also exhibit correlation.

[000109] At step 504, a first correlation coefficient ($R[i_{\text{motor}}, \text{Pressure}_{\text{Disch}}]$) corresponding to current (i_{motor}) and discharge pressure ($\text{Pressure}_{\text{Disch}}$) is determined based on the obtained data observations corresponding to current and discharge pressure. A first p-value ($P_v[i_{\text{motor}}, \text{Pressure}_{\text{Disch}}]$) corresponding to current (i_{motor}) and discharge pressure ($\text{Pressure}_{\text{Disch}}$) is thereafter determined based on the first correlation coefficient ($R[i_{\text{motor}}, \text{Pressure}_{\text{Disch}}]$).

[000110] At step 506, a second correlation coefficient ($R[i_{\text{motor}}, \text{Outflow}_{\text{Rate}}]$) corresponding to current (i_{motor}) and outflow rate ($\text{Outflow}_{\text{Rate}}$) is determined based on the obtained data observations

corresponding to current and outflow rate. A second p-value ($P_v[i_{\text{motor}}, \text{Outflow}_{\text{Rate}}]$) corresponding to current (i_{motor}) and discharge pressure ($\text{Outflow}_{\text{Rate}}$) is thereafter determined based on the second correlation coefficient ($R[i_{\text{motor}}, \text{Outflow}_{\text{Rate}}]$).

[000111] Step **508** determines whether (i) the first p-value $P_v[i_{\text{motor}}, \text{Pressure}_{\text{Disch}}]$ is less than or equal to a predefined first p-value limit, and (ii) the second p-value $P_v[i_{\text{motor}}, \text{Outflow}_{\text{Rate}}]$ is less than or equal to a predefined second p-value limit.

[000112] If (i) the first p-value $P_v[i_{\text{motor}}, \text{Pressure}_{\text{Disch}}]$ is less than or equal to a predefined first p-value limit, and (ii) the second p-value $P_v[i_{\text{motor}}, \text{Outflow}_{\text{Rate}}]$ is less than or equal to a predefined second p-value limit, step **510** selects for execution, from among a plurality of condition monitoring actions, a first condition monitoring action for execution.

[000113] If on the other hand either (i) the first p-value $P_v[i_{\text{motor}}, \text{Pressure}_{\text{Disch}}]$ is greater than a predefined first p-value limit, or (ii) the second p-value $P_v[i_{\text{motor}}, \text{Outflow}_{\text{Rate}}]$ is greater than a predefined second p-value limit, step **512** selects for execution, from among a plurality of condition monitoring actions, a second condition monitoring action for execution.

[000114] The first and second predefined p-value limits of **Figure 5** may comprise any numerical value between 0 and 1. In any embodiment of the invention, either or both of the predefined first and second p-value limits may be any numerical value between 0.01 and 0.05.

[000115] Since each of the first variable pair (current and discharge pressure) and the second variable pair (current and outflow rate) are known to be respectively correlated variable pairs, in normal or non-fault operating conditions, each of the two variable pairs may be expected to have a p-value respectively equal to or below the predefined first and second p-value limits (and preferably approaching 0). In the event the determined first and second p-values are consistent with such behaviour, it may be deduced that the centrifugal pump system is operating in a normal or non-fault condition. Accordingly, in an embodiment of the invention, the first condition monitoring action selected for execution at step **510** may comprise an action configured for execution in response to a normal or non-fault operating condition of the centrifugal pump system. In another embodiment of the invention, the first condition monitoring action may comprise an action configured for executing a confirmatory check regarding operating condition of the centrifugal pump system.

[000116] Conversely, since each of the first variable pair (current and discharge pressure) and the second variable pair (current and outflow rate) are known to be a correlated variable pair, in abnormal or fault conditions, at least one of the two variable pairs may be expected to have a p-value respectively greater than the predefined first and second p-value limits. In the event either of the determined first and second p-values is consistent with such behaviour, it may be deduced that the centrifugal pump system is operating in an abnormal or fault condition. Accordingly, in an embodiment of the invention, the second condition monitoring action selected for execution at step **512** may comprise an action configured for execution in response to an abnormal or fault operating condition of the centrifugal pump system. In another embodiment of the invention, the second condition monitoring action may comprise an action configured for executing a confirmatory check regarding operating condition of the centrifugal pump system.

[000117] **Figure 6** illustrates another embodiment of the method of **Figure 4**, implemented in connection with a centrifugal pump system.

[000118] Step 602 comprises obtaining from an operating centrifugal pump system, at least a prescribed number of data observations corresponding to (i) current (ii) detected bearing temperature and (iii) a detected vibration characteristic. It has been found that in centrifugal pump systems, current and detected bearing temperature comprise a first non-correlated variable pair (i.e. changing motor current should not, in a normal or non-fault condition, affect bearing temperature), while current and a detected vibration characteristic comprise a second non-correlated variable pair (i.e. changing motor current should not, in a normal or non-fault condition, affect detected vibration characteristics). Accordingly, when a centrifugal pump system is operating in a normal or non-fault condition, data observations corresponding to current and detected bearing temperature would not exhibit correlation, and likewise data observations corresponding to current and a detected vibration characteristic would also not exhibit correlation.

[000119] At step 604, a first correlation coefficient ($R[i_{\text{motor}}, BTemp_{\text{Detected}}]$) corresponding to current (i_{motor}) and detected bearing temperature ($BTemp_{\text{Detected}}$) is determined based on the obtained data observations corresponding to current and detected bearing temperature. A first p-value ($P_v[i_{\text{motor}}, BTemp_{\text{Detected}}]$) corresponding to current (i_{motor}) and detected bearing temperature ($BTemp_{\text{Detected}}$) is thereafter determined based on the first correlation coefficient ($R[i_{\text{motor}}, BTemp_{\text{Detected}}]$).

[000120] At step 606, a second correlation coefficient ($R[i_{\text{motor}}, VibData_{\text{Detected}}]$) corresponding to current (i_{motor}) and a detected vibration characteristic ($VibData_{\text{Detected}}$) is determined based on the obtained data observations corresponding to current and $VibData_{\text{Detected}}$. A second p-value ($P_v[i_{\text{motor}}, VibData_{\text{Detected}}]$) corresponding to current (i_{motor}) and the detected vibration characteristic ($VibData_{\text{Detected}}$) is thereafter determined based on the second correlation coefficient ($R[i_{\text{motor}}, VibData_{\text{Detected}}]$).

[000121] Step 608 determines whether (i) the first p-value $P_v[i_{\text{motor}}, BTemp_{\text{Detected}}]$ is less than or equal to a predefined first p-value limit, or (ii) the second p-value $P_v[i_{\text{motor}}, VibData_{\text{Detected}}]$ is less than or equal to a predefined second p-value limit.

[000122] If (i) the first p-value $P_v[i_{\text{motor}}, BTemp_{\text{Detected}}]$ is greater than a predefined first p-value limit, and (ii) the second p-value $P_v[i_{\text{motor}}, VibData_{\text{Detected}}]$ is greater than a predefined second p-value limit, step 610 selects for execution, from among a plurality of condition monitoring actions, a first condition monitoring action for execution.

[000123] If on the other hand either (i) the first p-value $P_v[i_{\text{motor}}, BTemp_{\text{Detected}}]$ is less than or equal to a predefined first p-value limit, or (ii) the second p-value $P_v[i_{\text{motor}}, VibData_{\text{Detected}}]$ is less than or equal to a predefined second p-value limit, step 612 selects for execution, from among a plurality of condition monitoring actions, a second condition monitoring action for execution.

[000124] The first and second predefined p-value limits of **Figure 6** may comprise any numerical value between 0 and 1. In any embodiment of the invention, either or both of the predefined first and second p-value limits may be any numerical value between 0.01 and 0.05.

[000125] Since each of the first variable pair (current and detected bearing temperature) and the second variable pair (current and a detected vibration characteristic) are known to be respectively non-correlated variable pairs, in normal or non-fault operating conditions, each of the two variable

pairs may be expected to have a p-value respectively greater than the predefined first and second p-value limits. In the event the determined first and second p-values are consistent with such behaviour, it may be deduced that the centrifugal pump system is operating in a normal or non-fault condition. Accordingly, in an embodiment of the invention, the first condition monitoring action selected for execution at step 610 may comprise an action configured for execution in response to a normal or non-fault operating condition of the centrifugal pump system. In another embodiment of the invention, the first condition monitoring action may comprise an action configured for executing a further check or a confirmatory check regarding operating condition of the centrifugal pump system.

[000126] Conversely, since each of the first variable pair (current and discharge pressure) and the second variable pair (current and outflow rate) are known to be respectively correlated variable pairs, in abnormal or fault conditions, at least one of the two variable pairs may be expected to have a p-value respectively greater than the predefined first and second p-value limits. In the event either of the determined first and second p-values is consistent with such behaviour, it may be deduced that the centrifugal pump system is operating in an abnormal or fault condition. Accordingly, in an embodiment of the invention, the second condition monitoring action selected for execution at step 612 may comprise an action configured for execution in response to an abnormal or fault operating condition of the centrifugal pump system. In another embodiment of the invention, the second condition monitoring action may comprise an action configured for executing a further check or a confirmatory check regarding operating condition of the centrifugal pump system.

[000127] Figure 7 illustrates yet another embodiment of the method of Figure 4, also implemented in connection with a centrifugal pump system.

[000128] Step 702 comprises obtaining from an operating centrifugal pump system, at least a prescribed number of data observations corresponding to (i) suction valve position (ii) discharge valve position (iii) outflow rate and (iv) inflow rate. It has been found that in centrifugal pump systems, outflow rate and suction valve position comprise a first correlated variable pair, outflow rate and discharge valve position comprise a second correlated variable pair, and outflow rate and inflow rate comprise a third correlated variable pair. Accordingly, when a centrifugal pump system is operating in a normal or non-fault condition, data observations corresponding respectively to outflow rate and suction valve position, outflow rate and discharge valve position, and outflow rate and inflow rate would exhibit correlation.

[000129] At step 704, a first correlation coefficient ($R[\text{Outflow}_{\text{Rate}}, \text{SValve}_{\text{posn}}]$) corresponding to outflow rate ($\text{Outflow}_{\text{Rate}}$) and suction valve position ($\text{SValve}_{\text{posn}}$) is determined based on the obtained data observations corresponding to outflow rate and suction valve position. A first p-value ($P_v[\text{Outflow}_{\text{Rate}}, \text{SValve}_{\text{posn}}]$) corresponding to outflow rate ($\text{Outflow}_{\text{Rate}}$) and suction valve position ($\text{SValve}_{\text{posn}}$) is thereafter determined based on the first correlation coefficient ($R[\text{Outflow}_{\text{Rate}}, \text{SValve}_{\text{posn}}]$).

[000130] At step 706, a second correlation coefficient ($R[\text{Outflow}_{\text{Rate}}, \text{DValve}_{\text{posn}}]$) corresponding to outflow rate ($\text{Outflow}_{\text{Rate}}$) and discharge valve position ($\text{DValve}_{\text{posn}}$) is determined based on the obtained data observations corresponding to outflow rate and discharge valve position. A second p-value ($P_v[\text{Outflow}_{\text{Rate}}, \text{DValve}_{\text{posn}}]$) corresponding to outflow rate ($\text{Outflow}_{\text{Rate}}$) and discharge valve position ($\text{DValve}_{\text{posn}}$) is thereafter determined based on the second correlation coefficient ($R[\text{Outflow}_{\text{Rate}}, \text{DValve}_{\text{posn}}]$).

[000131] At step 708, a third correlation coefficient ($R[\text{Outflow}_{\text{Rate}}, \text{Inflow}_{\text{Rate}}]$) corresponding to outflow rate ($\text{Outflow}_{\text{Rate}}$) and inflow rate ($\text{Inflow}_{\text{Rate}}$) is determined based on the obtained data observations corresponding to outflow rate and inflow rate. A third p-value ($P_v[\text{Outflow}_{\text{Rate}}, \text{Inflow}_{\text{Rate}}]$) corresponding to outflow rate ($\text{Outflow}_{\text{Rate}}$) and discharge valve position ($\text{Inflow}_{\text{Rate}}$) is thereafter determined based on the third correlation coefficient ($R[\text{Outflow}_{\text{Rate}}, \text{Inflow}_{\text{Rate}}]$).

[000132] Step 710 determines whether (i) the first p-value $P_v[\text{Outflow}_{\text{Rate}}, \text{SValve}_{\text{posn}}]$ is less than or equal to a predefined first p-value limit, (ii) the second p-value $P_v[\text{Outflow}_{\text{Rate}}, \text{DValve}_{\text{posn}}]$ is less than or equal to a predefined second p-value limit or (iii) the third p-value $P_v[\text{Outflow}_{\text{Rate}}, \text{Inflow}_{\text{Rate}}]$ is less than or equal to a predefined third p-value limit.

[000133] In an embodiment, if (i) the first p-value $P_v[\text{Outflow}_{\text{Rate}}, \text{SValve}_{\text{posn}}]$ is less than or equal to a predefined first p-value limit, or (ii) the second p-value $P_v[\text{Outflow}_{\text{Rate}}, \text{DValve}_{\text{posn}}]$ is less than or equal to a predefined second p-value limit, or (iii) the third p-value $P_v[\text{Outflow}_{\text{Rate}}, \text{Inflow}_{\text{Rate}}]$ is less than or equal to a predefined third p-value limit, step 712 selects for execution, from among a plurality of condition monitoring actions, a first condition monitoring action for execution.

[000134] If on the other hand (i) the first p-value $P_v[\text{Outflow}_{\text{Rate}}, \text{SValve}_{\text{posn}}]$ is greater than a predefined first p-value limit, and (ii) the second p-value $P_v[\text{Outflow}_{\text{Rate}}, \text{DValve}_{\text{posn}}]$ is greater than a predefined second p-value limit, and (iii) the third p-value $P_v[\text{Outflow}_{\text{Rate}}, \text{Inflow}_{\text{Rate}}]$ is greater than a predefined third p-value limit, step 714 selects for execution, from among a plurality of condition monitoring actions, a second condition monitoring action for execution.

[000135] The first, second and third predefined p-value limits of **Figure 7** may comprise any numerical value between 0 and 1. In any embodiment of the invention, one or more of the predefined first, second and third p-value limits may be any numerical value between 0.01 and 0.05.

[000136] Since each of the first variable pair (outflow rate and suction valve position), second variable pair (outflow rate and discharge valve position) and third variable pair (outflow rate and inflow rate) are known to be respectively correlated variable pairs, in normal or non-fault operating conditions, at least one of the three variable pairs may be expected to have a p-value respectively equal to or below the predefined first, second and third p-value limits (and preferably approaching 0). In the event any of the determined first, second and third p-values are consistent with such behaviour, it may be deduced that the centrifugal pump system is operating in a normal or non-fault condition. Accordingly, in an embodiment of the invention, the first condition monitoring action selected for execution at step 712 may comprise an action configured for execution in response to a normal or non-fault operating condition of the centrifugal pump system. In another embodiment of the invention, the first condition monitoring action may comprise an action configured for executing a further check or a confirmatory check regarding operating condition of the centrifugal pump system.

[000137] Conversely, since each of the first variable pair (outflow rate and suction valve position), second variable pair (outflow rate and discharge valve position) and third variable pair (outflow rate and inflow rate) are known to be respectively correlated variable pairs, in abnormal or fault conditions, all three of the variable pairs may be expected to have a p-value respectively greater than the predefined first, second and third p-value limits. In the event the determined first, second and third p-values are consistent with such behaviour, it may be deduced that the centrifugal pump

system is operating in an abnormal or fault condition. Accordingly, in an embodiment of the invention, the second condition monitoring action selected for execution at step 714 may comprise an action configured for execution in response to an abnormal or fault condition of the centrifugal pump system. In another embodiment of the invention, the second condition monitoring action may comprise an action configured for executing a further check or a confirmatory check regarding operating condition of the centrifugal pump system.

[000138] Figures 8A to 8D illustrate another embodiment of the invention implemented in connection with a centrifugal pump system.

[000139] Step 802 comprises obtaining from an operating centrifugal pump system, at least a prescribed number of data observations corresponding to (i) at least one of current (i_{motor}), voltage (V_{motor}) or power (P_{motor}) (ii) discharge pressure ($\text{Pressure}_{\text{Disch}}$) (iii) Outflow rate ($\text{Outflow}_{\text{Rate}}$) (iv) Inflow rate ($\text{Inflow}_{\text{Rate}}$) (v) Suction valve position ($\text{SValve}_{\text{posn}}$) (vi) Discharge valve position ($\text{DValve}_{\text{posn}}$) (vii) Detected bearing temperature ($\text{BTmp}_{\text{Detected}}$) and (viii) a detected vibration characteristic ($\text{VibData}_{\text{Detected}}$).

[000140] In the event of unavailability of direct data observations corresponding to current (i_{motor}), step 804 obtains data observations corresponding to current based on (i) data observations corresponding to voltage (V_{motor}) or power (P_{motor}) and (ii) resistance (R_{motor}) of the centrifugal pump motor.

[000141] As discussed above, in centrifugal pump systems, each of (i) current and discharge pressure (ii) current and outflow rate (iii) outflow rate and suction valve position (iv) outflow rate and discharge valve position and (v) outflow rate and inflow rate, are correlated variable pairs. Accordingly, when a centrifugal pump system is operating in a normal or non-fault condition, data observations corresponding to each of the above variable pairs should exhibit correlation.

[000142] Additionally, each of (i) current and detected bearing temperature, and (ii) current and a detected vibration characteristic, are non-correlated variable pairs. Accordingly, when a centrifugal pump system is operating in a normal or non-fault condition, data observations corresponding to each of these variable pairs should not exhibit correlation.

[000143] Step 806 determines:

- a first correlation coefficient $R[i_{\text{motor}}, \text{Pressure}_{\text{Disch}}]$ and a first p-value $P_v[i_{\text{motor}}, \text{Pressure}_{\text{Disch}}]$ corresponding to a first pair of machine condition parameters comprising current and discharge pressure,
- a second correlation coefficient $R[i_{\text{motor}}, \text{Outflow}_{\text{Rate}}]$ and a second p-value $P_v[i_{\text{motor}}, \text{Outflow}_{\text{Rate}}]$ corresponding to a second pair of machine condition parameters comprising current and outflow rate,
- a third correlation coefficient $R[i_{\text{motor}}, \text{BTmp}_{\text{Detected}}]$ and a third p-value $P_v[i_{\text{motor}}, \text{BTmp}_{\text{Detected}}]$ corresponding to a third pair of machine condition parameters comprising current and detected bearing temperature,

- a fourth correlation coefficient $R[i_{\text{motor}}, \text{VibData}_{\text{Detected}}]$ and a fourth p-value $P_v[i_{\text{motor}}, \text{VibData}_{\text{Detected}}]$ corresponding to a fourth pair of machine condition parameters comprising current and a detected vibration characteristic,
- a fifth correlation coefficient $R[\text{Outflow}_{\text{Rate}}, \text{SValve}_{\text{posn}}]$ and a fifth p-value $P_v[\text{Outflow}_{\text{Rate}}, \text{SValve}_{\text{posn}}]$ corresponding to a fifth pair of machine condition parameters comprising outflow rate and suction valve position,
- a sixth correlation coefficient $R[\text{Outflow}_{\text{Rate}}, \text{DValve}_{\text{posn}}]$ and a sixth p-value $P_v[\text{Outflow}_{\text{Rate}}, \text{DValve}_{\text{posn}}]$ corresponding to a sixth pair of machine condition parameters comprising outflow rate and discharge valve position, and
- a seventh correlation coefficient $R[\text{Outflow}_{\text{Rate}}, \text{Inflow}_{\text{Rate}}]$ and a seventh p-value $P_v[\text{Outflow}_{\text{Rate}}, \text{Inflow}_{\text{Rate}}]$ corresponding to a seventh pair of machine condition parameters comprising outflow rate and inflow rate

[000144] Step 808 checks to ascertain whether (i) the first p-value $P_v[i_{\text{motor}}, \text{Pressure}_{\text{Disch}}]$ is less than or equal to a predefined first p-value limit, and (ii) the second p-value $P_v[i_{\text{motor}}, \text{Outflow}_{\text{Rate}}]$ is less than or equal to a predefined second p-value limit. If both conditions are satisfied, the method proceeds to step 820. If at least one of the two conditions is not satisfied, the method instead proceeds to step 810.

[000145] Step 810 checks to ascertain whether either (i) the third p-value $P_v[i_{\text{motor}}, \text{BTemp}_{\text{Detected}}]$ is less than or equal to a predefined third p-value limit, or (ii) the fourth p-value $P_v[i_{\text{motor}}, \text{VibData}_{\text{Detected}}]$ is less than or equal to a predefined fourth p-value limit. If at least one of the two conditions is satisfied, the method proceeds to step 814. If neither of the two conditions is satisfied, the method proceeds to step 812.

[000146] Step 812 checks to ascertain whether either (i) a detected bearing temperature is greater than a recommended bearing temperature limit, or (ii) a detected vibration characteristic greater than a recommended vibration characteristic limit. If either of the two conditions is satisfied, the method proceeds to step 816. If neither condition is satisfied, the method instead proceeds to step 818.

[000147] Step 814 comprises selecting for execution, a first condition monitoring action from among a plurality of condition monitoring actions. Step 816 comprises selecting for execution, a second condition monitoring action from among a plurality of condition monitoring actions. In an embodiment of the invention, either or both of the first condition monitoring action and the second condition monitoring action may be respectively configured for execution in response to detection of an abnormal or fault condition of the machine or system, and may comprise any one or more of (i) signalling or communicating to a user or a device, the abnormal or fault condition of the machine or system (ii) changing operating parameters of the machine or system (iii) invoking a condition monitoring routine or sub-routine specific to a detected abnormality or fault condition (iv) triggering one or more of an alarm or alert, a manual inspection, or a sensor based testing methodology or (v) executing a confirmatory check regarding operating condition of the machine or machine system. In a specific embodiment, either or both of the first condition monitoring action and the second condition monitoring action may be configured for triggering data collection or analysis by an online vibration monitoring and analysis system.

[000148] Step 818 comprises selecting for execution, a third condition monitoring action from among a plurality of condition monitoring actions. In an embodiment of the invention, the third condition monitoring action may be configured for execution in response to detection of a normal or non-fault condition of the machine or system may comprise any one or more of (i) signalling or communicating to a user or a device, the normal or non-fault condition of the machine or system (ii) continuing operation of the machine or system without any changes to operating parameters (iii) continuing condition monitoring of the machine or system without invoking any condition monitoring routines or sub-routines specific to a detected abnormality or fault condition or (iv) executing a confirmatory check regarding operating condition of the machine or machine system.

[000149] Step 820 checks from among the obtained data observations corresponding to outflow rate ($\text{Outflow}_{\text{rate}}$), whether the maximum outflow rate exceeds the minimum outflow rate by more than a predefined first outflow variation limit. In an embodiment of the invention, the predefined first outflow variation limit may comprise any value between 0% and 20%. If the maximum outflow rate exceeds the minimum outflow rate by more than the predefined first outflow variation limit, the method proceeds to step 822. If the maximum outflow rate does not exceed the minimum outflow rate by more than the predefined first outflow variation limit, the method deduces that the centrifugal pump system is operating in a normal or non-fault condition and proceeds to step 828.

[000150] Step 822 comprises checking whether (i) the fifth p-value $P_v [\text{Outflow}_{\text{Rate}}, \text{SValve}_{\text{posn}}]$ is less than or equal to a predefined fifth p-value limit, or (ii) the sixth p-value $P_v [\text{Outflow}_{\text{Rate}}, \text{DValve}_{\text{posn}}]$ is less than or equal to a predefined sixth p-value limit, or (iii) the seventh p-value $P_v [\text{Outflow}_{\text{Rate}}, \text{Inflow}_{\text{Rate}}]$ is less than or equal to a predefined seventh p-value limit. If any of the above conditions are satisfied, the method deduces that the obtained data observations are consistent with operator or system controlled load changes, and that the centrifugal pump system is operating in a normal or non-fault condition, and thereafter proceeds to step 830. If on the other hand, none of the above conditions are satisfied, the method instead proceeds to step 824.

[000151] Step 824 checks from among the obtained data observations corresponding to outflow rate ($\text{Outflow}_{\text{rate}}$), for whether there has been a decrease in outflow rate beyond a predefined second outflow variation limit. In an embodiment of the invention, the predefined second outflow variation limit may comprise any value less than or equal to 20%. If an observed decrease in outflow rate does not exceed the predefined second outflow variation limit, the method proceeds to step 826. Alternately, if the observed decrease in outflow rate exceeds the predefined second outflow variation limit, the method deduces that the centrifugal pump system may be subject to a discharge recirculation fault or a strainer clogging fault, and proceeds to step 832.

[000152] Step 826 checks for periodic oscillation in (i) observed data values corresponding to outflow rate and (ii) observed data values corresponding to discharge pressure. If oscillation is detected in connection with both machine condition parameters, the method deduces that the centrifugal pump system may be subject to a cavitation problem and proceeds to step 834. If oscillation is not detected in connection with at least one of the two machine condition parameters, the method may terminate.

[000153] Step 828 comprises selecting for execution, a fourth condition monitoring action from among a plurality of condition monitoring actions. Step 830 comprises selecting for execution, a fifth condition monitoring action from among a plurality of condition monitoring actions. Step 832

comprises selecting for execution, a sixth condition monitoring action from among a plurality of condition monitoring actions. Step 834 comprises selecting for execution, a seventh condition monitoring action from among a plurality of condition monitoring actions.

[000154] In an embodiment of the invention, either or both of the fourth condition monitoring action and the fifth condition monitoring action may be respectively configured for execution in response to detection of a normal or non-fault condition of the machine or system may comprise any one or more of (i) signalling or communicating to a user or a device, the normal or non-fault condition of the machine or system (ii) continuing operation of the machine or system without any changes to operating parameters (iii) continuing condition monitoring of the machine or system without invoking any condition monitoring routines or sub-routines specific to a detected abnormality or fault condition or (iv) executing a confirmatory check regarding operating condition of the machine or machine system. In a particular embodiment, the fifth condition monitoring action may comprise signalling, communicating or displaying to a user or on a device, detection of operator or system controlled load changes, and that the centrifugal pump system is operating in a normal or non-fault condition.

[000155] In an embodiment of the invention, either or both of the sixth condition monitoring action and the seventh condition monitoring action may be respectively configured for execution in response to detection of an abnormal or fault condition of the machine or system, and may comprise any one or more of (i) signalling or communicating to a user or a device, the abnormal or fault condition of the machine or system (ii) changing operating parameters of the machine or system (iii) invoking a condition monitoring routine or sub-routine specific to a detected abnormality or fault condition (iv) triggering one or more of an alarm or alert, a manual inspection, or a sensor based testing methodology or (v) executing a confirmatory check regarding operating condition of the machine or machine system.

[000156] In an embodiment, the sixth condition monitoring action may comprise one or both of (i) signalling, communicating or displaying to a user or on a device, detection of a discharge recirculation fault or a strainer clogging fault and (ii) triggering data collection or analysis by an online vibration monitoring and analysis system.

[000157] In an embodiment, the seventh condition monitoring action may comprise one or both of (i) signalling, communicating or displaying to a user or on a device, detection of a cavitation fault and (ii) triggering data collection or analysis by an online vibration monitoring and analysis system.

[000158] **Figure 9** illustrates a system 902 in accordance the present invention, which may be configured to implement one or more of the methods for machine condition monitoring described in connection with **Figures 4 to 8D**. The system 902 comprises pre-treatment engine 908, pump diagnostics interface 910, Data analysis and heuristics controller 912 and trigger control 916.

[000159] Data observations corresponding to machine condition parameters may be obtained using sensors 904. In an embodiment of the invention sensors 904 may comprise at least one or more individual sensors 904a, 904b, 904c and 904d, each of which may be configured to obtain data observations corresponding to a specific machine condition parameter. In an embodiment of the invention configured for condition monitoring of a centrifugal pump system, sensors 904 may be configured to obtain data observations in connection with any one or more of current (i_{motor}), voltage (V_{motor}) or power (P_{motor}) (ii) discharge pressure ($\text{Pressure}_{\text{Disch}}$) (iii) Outflow rate ($\text{Outflow}_{\text{Rate}}$) (iv)

Inflow rate ($\text{Inflow}_{\text{Rate}}$) (v) Suction valve position ($\text{SValve}_{\text{posn}}$) (vi) Discharge valve position ($\text{DValve}_{\text{posn}}$) (vii) Detected bearing temperature ($\text{BTemp}_{\text{Detected}}$) and (viii) Detected vibration characteristic ($\text{VibData}_{\text{Detected}}$).

[000160] Data observations obtained from sensors **904** may be stored in process data database **906**. Data observations obtained directly from sensors **904** or retrieved from process data database **906** may be communicated to pre-treatment engine **908** within system **902**.

[000161] Pre-treatment engine **908** may be configured to optimize information received from sensors **904** for data analysis, wherein optimizing the received information may include one or more of: (i) monitoring and ensuring that at least a prescribed number of data observations are received from sensors **904** or process data database **906** (ii) monitoring status and connectivity of sensors **904** (iii) executing periodic checks on operational status of sensors **904** (iv) alerting an operator to inconsistencies or errors in incoming sensor readings (v) filtering noise from data signals received from sensors **904** and (vi) responsive to unavailability of direct data observations corresponding to current, obtaining data observations corresponding to current based on (i) measured voltage or power and (ii) a known resistance.

[000162] Pump diagnostics interface **910** provides a user or device interface configured for one or more of signalling, communicating, receiving or displaying, information or instructions related to one or more of (i) an operating state of the machine or system, (ii) one or more machine condition parameters (iii) an ongoing machine condition monitoring routine or sub-routine or (iv) diagnostic data or results related to the machine or system.

[000163] Data analysis and heuristics controller **912** may be communicably coupled with pre-treatment engine **908** or pump diagnostics interface **910**, and comprises a processor implemented controller configured for executing any of the one or more of methods steps described in connection with **Figures 4 to 8D**, including without limitation (i) determining correlation coefficients corresponding to one or more pairs of machine condition parameters (ii) determining p-values corresponding to one or more pairs of machine condition parameters (iii) selecting, from among a plurality of condition monitoring actions, one or more condition monitoring actions for execution – which selection may be based on a determined p-value and one or more selection rules. The one or more selection rules may be stored in and retrieved from rules database **914**.

[000164] Trigger control **916** may be coupled to one or both of pump diagnostics interface **910** and data analysis and heuristics controller **912**, and in an embodiment of the invention may be configured for signalling or implementing a state change within the machine or device being monitored – including without limitation by (i) raising an alarm responsive to detection of a fault or abnormal operating condition, (ii) raising an alert for commencing a manual inspection of the machine or machine system (iii) commencing online vibration testing of the machine or system or (iv) any other action including collecting more data observations for further analysis, or prioritization of tasks assigned to a field operator based on the trigger control output.

[000165] **Figure 10** illustrates an exemplary computing system in which various embodiments of the invention may be implemented.

[000166] The system **1002** comprises at-least one processor **1004** and at-least one memory **1006**. The processor **1004** executes program instructions and may be a real processor. The

processor **1004** may also be a virtual processor. The computer system **1002** is not intended to suggest any limitation as to scope of use or functionality of described embodiments. For example, the computer system **1002** may include, but not be limited to, one or more of a general-purpose computer, a programmed microprocessor, a micro-controller, an integrated circuit, and other devices or arrangements of devices that are capable of implementing the steps that constitute the method of the present invention. Exemplary embodiments of a system **1002** in accordance with the present invention may include one or more servers, desktops, laptops, tablets, smart phones, mobile phones, mobile communication devices, tablets, phablets and personal digital assistants. In an embodiment of the present invention, the memory **1006** may store software for implementing various embodiments of the present invention. The computer system **1002** may have additional components. For example, the computer system **1002** includes one or more communication channels **1008**, one or more input devices **1010**, one or more output devices **1012**, and storage **1014**. An interconnection mechanism (not shown) such as a bus, controller, or network, interconnects the components of the computer system **1002**. In various embodiments of the present invention, operating system software (not shown) provides an operating environment for various softwares executing in the computer system **1002** using a processor **1004**, and manages different functionalities of the components of the computer system **1002**.

[000167] The communication channel(s) **1008** allow communication over a communication medium to various other computing entities. The communication medium provides information such as program instructions, or other data in a communication media. The communication media includes, but not limited to, wired or wireless methodologies implemented with an electrical, optical, RF, infrared, acoustic, microwave, Bluetooth or other transmission media.

[000168] The input device(s) **1010** may include, but not limited to, a touch screen, a keyboard, mouse, pen, joystick, trackball, a voice device, a scanning device, or any another device that is capable of providing input to the computer system **1002**. In an embodiment of the present invention, the input device(s) **1010** may be a sound card or similar device that accepts audio input in analog or digital form. The output device(s) **1012** may include, but not limited to, a user interface on CRT, LCD, LED display, or any other display associated with any of servers, desktops, laptops, tablets, smart phones, mobile phones, mobile communication devices, tablets, phablets and personal digital assistants, printer, speaker, CD/DVD writer, or any other device that provides output from the computer system **1002**.

[000169] The storage **1014** may include, but not limited to, magnetic disks, magnetic tapes, CD-ROMs, CD-RWs, DVDs, any types of computer memory, magnetic stripes, smart cards, printed barcodes or any other transitory or non-transitory medium which can be used to store information and can be accessed by the computer system **1002**. In various embodiments of the present invention, the storage **1014** contains program instructions for implementing the described embodiments.

[000170] In an embodiment of the present invention, the computer system **1002** is part of a distributed network where various embodiments of the present invention are implemented for rapidly developing end-to-end software applications.

[000171] The present invention may be implemented in numerous ways including as a system, a method, or a computer program product such as a computer readable storage medium or a computer network wherein programming instructions are communicated from a remote location.

[000172] The present invention may suitably be embodied as a computer program product for use with the computer system **1002**. The method described herein is typically implemented as a computer program product, comprising a set of program instructions which is executed by the computer system **1002** or any other similar device. The set of program instructions may be a series of computer readable codes stored on a tangible medium, such as a computer readable storage medium (storage **1004**), for example, diskette, CD-ROM, ROM, flash drives or hard disk, or transmittable to the computer system **1002**, via a modem or other interface device, over either a tangible medium, including but not limited to optical or analogue communications channel(s) **1008**. The implementation of the invention as a computer program product may be in an intangible form using wireless techniques, including but not limited to microwave, infrared, bluetooth or other transmission techniques. These instructions can be preloaded into a system or recorded on a storage medium such as a CD-ROM, or made available for downloading over a network such as the Internet or a mobile telephone network. The series of computer readable instructions may embody all or part of the functionality previously described herein.

[000173] It will be understood that methods, systems and computer program products in accordance with the present invention provide a reliable and cost effective solution for condition monitoring of machinery in real time, which remains effective despite changes in performance characteristics of a machine over time. Additionally, the invention is capable of detecting and diagnosing a variety of mechanical as well as process related faults or abnormalities, using ordinary and routinely implemented sensor technologies. The simplicity of the sensors used and the machine condition parameters relied on, provides for a simple, robust and cost effective solution for identifying process and mechanical faults using real time data observations.

[000174] While the exemplary embodiments of the present invention are described and illustrated herein, it will be appreciated that they are merely illustrative. It will be understood by those skilled in the art that various modifications in form and detail may be made therein without departing from or offending the spirit and scope of the invention as defined by the appended claims.

Claims:

1. A method for condition monitoring of a machine, comprising:
 - obtaining a first set of data observations corresponding to a first pair of machine condition parameters;
 - determining based on the first set of data observations, a first correlation coefficient corresponding to the first pair of machine condition parameters;
 - determining based on the first correlation coefficient, a first p-value corresponding to the first pair of machine condition parameters; and
 - selecting from among a plurality of available condition monitoring actions, at least one condition monitoring action for execution, wherein selection of the condition monitoring action is based on:
 - at least the first p-value; and
 - one or more defined selection rules.
2. The method as claimed in claim 1, wherein the selection rules are defined such that:
 - responsive to (i) the first pair of machine condition parameters comprising a correlated variable pair and (ii) the first p-value being greater than a first predefined p-value limit, or
 - responsive to (iii) the first pair of machine condition parameters comprising a non-correlated variable pair and (iv) the first p-value being less than or equal to a first predefined p-value limit,

the selected condition monitoring action is a condition monitoring action configured for execution in response to a detected fault condition.
3. The method as claimed in claim 2, wherein the condition monitoring action configured for execution in response to a detected fault condition comprises any one or more of:
 - signaling the detected fault condition;
 - modifying an operating state of the machine;
 - invoking a condition monitoring routine in response to the detected fault condition;
 - triggering one or more of an alarm, alert, a manual inspection, or a sensor based test;
 - triggering online vibration analysis; or
 - executing at least one additional test regarding operating condition of the machine.
4. The method as claimed in claim 2, wherein the first predefined p-value limit is any value between 0.01 and 0.05.

5. The method as claimed in claim 1, further comprising:

obtaining a second set of data observations corresponding to a second pair of machine condition parameters;

determining based on the second set of data observations, a second correlation coefficient corresponding to the second pair of machine condition parameters; and

determining based on the second correlation coefficient, a second p-value corresponding to the second pair of machine condition parameters;

wherein selection of the condition monitoring action for execution is additionally based on at least the second p-value.

6. The method as claimed in claim 5, wherein the machine comprises a centrifugal pump system and wherein:

the first pair of machine condition parameters is a correlated variable pair comprising current and discharge pressure;

the second pair of machine condition parameters is a correlated variable pair comprising current and outflow rate; and

responsive to the first p-value being greater than a first predefined p-value limit or the second p-value being greater than a second predefined p-value limit, the selected condition monitoring action is a condition monitoring action configured for execution in response to a detected fault condition.

7. The method as claimed in claim 5, wherein the machine comprises a centrifugal pump system and wherein:

the first pair of machine condition parameters is a non-correlated variable pair comprising current and detected bearing temperature;

the second pair of machine condition parameters is a non-correlated variable pair comprising current and a detected vibration characteristic; and

responsive to the first p-value being less than or equal to a first predefined p-value limit, or the second p-value being less than or equal to a second predefined p-value limit, the selected condition monitoring action is a condition monitoring action configured for execution in response to a detected fault condition.

8. The method as claimed in claim 5, further comprising:

obtaining a third set of data observations corresponding to a third pair of machine condition parameters; and

determining based on the third set of data observations, a third correlation coefficient corresponding to the third pair of machine condition parameters;

wherein selection of the condition monitoring action for execution is additionally based on at least the third p-value.

9. The method as claimed in claim 8, wherein the machine comprises a centrifugal pump system and wherein:

the first pair of machine condition parameters is a correlated variable pair comprising outflow rate and suction valve position;

the second pair of machine condition parameters is a correlated variable pair comprising outflow rate and discharge valve position;

the third pair of machine condition parameters is a correlated variable pair comprising outflow rate and inflow rate; and

responsive to the first p-value being greater than a first predefined p-value limit, the second p-value being greater than a second predefined p-value limit and the third p-value being greater than a third predefined p-value limit, the selected condition monitoring action is a condition monitoring action configured for execution in response to a detected fault condition.

10. A method for condition monitoring of a centrifugal pump system, comprising:

obtaining based on data observations:

a first p-value corresponding to a first correlated pair of machine condition parameters comprising current and discharge pressure;

a second p-value corresponding to a second correlated pair of machine condition parameters comprising current and outflow rate,

a third p-value corresponding to a third non-correlated pair of machine condition parameters comprising current and detected bearing temperature,

a fourth p-value corresponding to a fourth non-correlated pair of machine condition parameters comprising current and a detected vibration characteristic,

a fifth p-value corresponding to a fifth correlated pair of machine condition parameters comprising outflow rate and suction valve position,

a sixth p-value corresponding to a sixth correlated pair of machine condition parameters comprising outflow rate and discharge valve position, and

a seventh p-value corresponding to a seventh correlated pair of machine condition parameters comprising outflow rate and inflow rate;

selecting from among a plurality of available condition monitoring actions, a first condition monitoring action for execution, wherein:

responsive to (i) the first p-value being greater than a first predefined p-value limit, or the second p-value being greater than a second predefined p-value limit; and (ii) the third p-value being less than or equal to a third predefined p-value limit, or the fourth p-value being less than or equal to a fourth predefined p-value limit, the selected first condition monitoring action comprises a condition monitoring action configured for execution in response to a detected fault condition; or

responsive to (iii) the first p-value being greater than a first predefined p-value limit, or the second p-value being greater than a second predefined p-value limit; and (iv) the third p-value being greater than a third predefined p-value limit, and the fourth p-value being greater than a fourth predefined p-value limit, the selected first condition monitoring action comprises:

comparing a detected bearing temperature with a recommended operating temperature;

comparing a detected vibration characteristic with a recommended vibration characteristic limit; and

responsive to either the detected bearing temperature exceeding the recommended operating temperature, or the detected vibration characteristic exceeding the recommended vibration characteristic limit, selecting from among the plurality of available condition monitoring actions, a second condition monitoring action for execution, wherein the second condition monitoring action comprises a condition monitoring action configured for execution in response to a detected fault condition;

or

responsive to the first p-value being less than or equal to a first predefined p-value limit and the second p-value being less than or equal to a second predefined p-value limit, the selected first condition monitoring action comprises:

comparing an observed maximum outflow rate with an observed minimum outflow rate; and

responsive to the maximum outflow rate exceeding the minimum outflow rate by more than a predefined first outflow variation limit, ascertaining whether (a) the fifth p-value is greater than a fifth predefined p-value limit, (b) the sixth p-value is greater than a sixth predefined p-value limit and (c) the seventh p-value is greater than a seventh predefined p-value limit.

11. The method as claimed in claim 10, wherein any of the first to seventh predefined p-value limits comprises any value between 0.01 and 0.05.

12. The method as claimed in claim 10, wherein responsive to (a) the fifth p-value being greater than the fifth predefined p-value limit, (b) the sixth p-value being greater than the sixth predefined p-value limit and (c) the seventh p-value being greater than the seventh predefined p-value limit, the method further comprises:

responding to a detected decrease in outflow rate exceeding a predefined second outflow variation limit, selecting from among the plurality of available condition monitoring actions, a third condition monitoring action for execution, wherein the third condition monitoring action comprises a condition monitoring action configured for execution in response to a detected discharge recirculation fault or a strainer clogging fault; or

responding to detecting oscillations in observed outflow rate and observed discharge pressure, selecting from among the plurality of available condition monitoring actions, a fourth condition monitoring action for execution, wherein the fourth condition monitoring action comprises a condition monitoring action configured for execution in response to a detected cavitation fault.

13. A system for condition monitoring of a machine, comprising:

a processor implemented data analysis and heuristics controller configured for:

obtaining a first set of data observations corresponding to a first pair of machine condition parameters;

determining based on the first set of data observations, a first correlation coefficient corresponding to the first pair of machine condition parameters;

determining based on the first correlation coefficient, a first p-value corresponding to the first pair of machine condition parameters; and

selecting from among a plurality of available condition monitoring actions, at least one condition monitoring action for execution, wherein selection of the condition monitoring action is based on:

at least the first p-value; and

one or more defined selection rules.

14. The system as claimed in claim 13, comprising at least one of:

a pump diagnostics interface configured for receiving and communicating information regarding an operating state of the machine with a user or device;

a pre-treatment engine configured for optimizing information from one or more sensors, for data analysis; or

a trigger control configured for signaling or implementing a state change within the machine.

15. The system as claimed in claim 13, wherein the selection rules are retrieved from a database and are defined such that:

responsive to (i) the first pair of machine condition parameters comprising a correlated variable pair and (ii) the first p-value being greater than a predefined p-value limit, or

responsive to (iii) the first pair of machine condition parameters comprising a non-correlated variable pair and (iv) the first p-value being less than or equal to a predefined p-value limit,

the selected condition monitoring action is a condition monitoring action configured for execution in response to a detected fault condition.

16. The system as claimed in claim 15, wherein the condition monitoring action configured for execution in response to a detected fault condition, comprises any one or more of:

signaling the detected fault condition;

modifying an operating state of the machine;

invoking a condition monitoring routine in response to the detected fault condition;

triggering one or more of an alarm, alert, a manual inspection, or a sensor based test;

triggering online vibration analysis; or

executing at least one additional test regarding operating condition of the machine.

17. The method as claimed in claim 15, wherein the first predefined p-value limit is any value between 0.01 and 0.05.

18. The system as claimed in claim 13, wherein the data analysis and heuristics controller is further configured for:

obtaining a second set of data observations corresponding to a second pair of machine condition parameters;

determining based on the second set of data observations, a second correlation coefficient corresponding to the second pair of machine condition parameters; and

determining based on the second correlation coefficient, a second p-value corresponding to the second pair of machine condition parameters;

wherein selection of the condition monitoring action for execution is additionally based on at least the second p-value.

19. The system as claimed in claim 18, wherein the machine comprises a centrifugal pump system and wherein:

the first pair of machine condition parameters is a correlated variable pair comprising current and discharge pressure;

the second pair of machine condition parameters is a correlated variable pair comprising current and outflow rate; and

responsive to the first p-value being greater than a first predefined p-value limit or the second p-value being greater than a second predefined p-value limit, the selected condition monitoring action is a condition monitoring action configured for execution in response to a detected fault condition.

20. The system as claimed in claim 18, wherein the machine comprises a centrifugal pump system and wherein:

the first pair of machine condition parameters is a non-correlated variable pair comprising current and detected bearing temperature;

the second pair of machine condition parameters is a non-correlated variable pair comprising current and a detected vibration characteristic; and

responsive to the first p-value being less than or equal to a first predefined p-value limit, or the second p-value being less than or equal to a second predefined p-value limit, the selected condition monitoring action is a condition monitoring action configured for execution in response to a detected fault condition.

21. The system as claimed in claim 18, wherein the data analysis and heuristics controller is further configured for:

obtaining a third set of data observations corresponding to a third pair of machine condition parameters; and

determining based on the third set of data observations, a third correlation coefficient corresponding to the third pair of machine condition parameters;

wherein selection of the condition monitoring action for execution is additionally based on at least the third p-value.

22. The system as claimed in claim 21, wherein the machine comprises a centrifugal pump system and wherein:

the first pair of machine condition parameters is a correlated variable pair comprising outflow rate and suction valve position;

the second pair of machine condition parameters is a correlated variable pair comprising outflow rate and discharge valve position;

the third pair of machine condition parameters is a correlated variable pair comprising outflow rate and inflow rate; and

responsive to the first p-value being greater than a first predefined p-value limit, the second p-value being greater than a second predefined p-value limit and the third p-value being greater than a third predefined p-value limit, the selected condition monitoring action is a condition monitoring action configured for execution in response to a detected fault condition.

23. A system for condition monitoring of a centrifugal pump system, comprising:

a processor implemented data analysis and heuristics controller configured for:

obtaining, based on data observations received from one or more sensors:

a first p-value corresponding to a first correlated pair of machine condition parameters comprising current and discharge pressure;

a second p-value corresponding to a second correlated pair of machine condition parameters comprising current and outflow rate;

a third p-value corresponding to a third non-correlated pair of machine condition parameters comprising current and detected bearing temperature;

a fourth p-value corresponding to a fourth non-correlated pair of machine condition parameters comprising current and a detected vibration characteristic;

a fifth p-value corresponding to a fifth correlated pair of machine condition parameters comprising outflow rate and suction valve position;

a sixth p-value corresponding to a sixth correlated pair of machine condition parameters comprising outflow rate and discharge valve position; and

a seventh p-value corresponding to a seventh correlated pair of machine condition parameters comprising outflow rate and inflow rate;

selecting from among a plurality of available condition monitoring actions, a first condition monitoring action for execution, wherein:

responsive to (i) the first p-value being greater than a first predefined p-value limit, or the second p-value being greater than a second predefined p-value limit; and (ii) the third p-value being less than or equal to a third predefined p-value limit, or the fourth p-value being less than or equal to a fourth predefined p-value limit, the selected first condition monitoring action comprises a condition monitoring action configured for execution in response to a detected fault condition; or

responsive to (iii) the first p-value being greater than a first predefined p-value limit, or the second p-value being greater than a second predefined p-value limit; and (iv) the third p-value being greater than a third predefined p-value limit,

and the fourth p-value being greater than a fourth predefined p-value limit, the selected first condition monitoring action comprises:

comparing a detected bearing temperature with a recommended operating temperature;

comparing a detected vibration characteristic with a recommended vibration characteristic limit; and

responsive to either the detected bearing temperature exceeding the recommended operating temperature, or the detected vibration characteristic exceeding the recommended vibration characteristic limit, selecting from among the plurality of available condition monitoring actions, a second condition monitoring action for execution, wherein the second condition monitoring action comprises a condition monitoring action configured for execution in response to a detected fault condition;

or

responsive to the first p-value being less than or equal to a first predefined p-value limit and the second p-value being less than or equal to a second predefined p-value limit the selected first condition monitoring action comprises:

comparing an observed maximum outflow rate with an observed minimum outflow rate; and

responsive to the maximum outflow rate exceeding the minimum outflow rate by more than a predefined first outflow variation limit, ascertaining whether (a) the fifth p-value is greater than a fifth predefined p-value limit, (b) the sixth p-value is greater than a sixth predefined p-value limit and (c) the seventh p-value is greater than a seventh predefined p-value limit.

24. The system as claimed in claim 23, comprising at least one of:

a pump diagnostics interface configured for receiving and communicating information regarding an operating state of the centrifugal pump system, with a user or device;

a pre-treatment engine configured for optimizing information received from one or more sensors, for data analysis; and

a trigger control configured for signaling or implementing a state change within the centrifugal pump system.

25. The system as claimed in claim 23, wherein any of the first to seventh predefined p-value limits comprises any value between 0.01 and 0.05.

26. The system as claimed in claim 23, wherein the data analysis and heuristics controller is configured such that responsive to (a) the fifth p-value being greater than the fifth predefined p-value limit, (b) the sixth p-value being greater than the sixth predefined p-value limit and (c) the seventh p-value being greater than the seventh predefined p-value limit, the system:

responds to a detected decrease in outflow rate exceeding a predefined second outflow variation limit, by selecting from among the plurality of available condition monitoring actions, a third condition monitoring action for execution, wherein the third condition monitoring action comprises a condition monitoring action configured for execution in response to a detected discharge recirculation fault or a strainer clogging fault; or

responds to detected oscillations in observed outflow rate and observed discharge pressure, by selecting from among the plurality of available condition monitoring actions, a fourth condition monitoring action for execution, wherein the fourth condition monitoring action comprises a condition monitoring action configured for execution in response to a detected cavitation fault.

27. A computer program product for condition monitoring of a machine, comprising a non-transitory computer-readable storage medium having program code stored therein, the program code comprising computer readable instructions for:

obtaining a first set of data observations corresponding to a first pair of machine condition parameters;

determining based on the first set of data observations, a first correlation coefficient corresponding to the first pair of machine condition parameters;

determining based on the first correlation coefficient, a first p-value corresponding to the first pair of machine condition parameters; and

selecting from among a plurality of available condition monitoring actions, at least one condition monitoring action for execution, wherein selection of the condition monitoring action is based on:

at least the first p-value; and

one or more defined selection rules.

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