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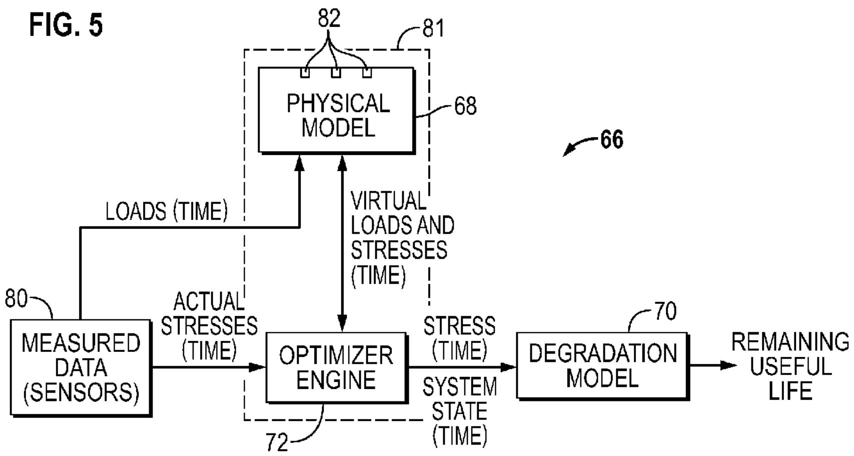
[Continued on next page]

(54) Title: STATE ESTIMATION AND RUN LIFE PREDICTION FOR PUMPING SYSTEM

FIG. 5



(57) **Abstract**: A technique facilitates formulation of predictions regarding the run life of a pumping system. Based on the predicted run life, and factors affecting that predicted run life, corrective actions may be selected and implemented. The corrective actions may involve adjustment of operational parameters regarding the pumping system so as to prolong the actual run life of the pumping system. The technique utilizes an algorithm which combines various models, e.g. physical models and degradation models, to provide various failure/run life predictions. The various models may utilize a variety of sensor data, such as actual sensor data and virtual sensor data, to both evaluate the state of the pumping system and the predicted run life of the pumping system.

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STATE ESTIMATION AND RUN LIFE PREDICTION FOR PUMPING SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present document is based on and claims priority to U.S. Provisional Application Serial No.: 61/974,786, filed April 3, 2014, which is incorporated herein by reference in its entirety.

BACKGROUND

[0002] Electric submersible pumping systems are used in a variety of pumping applications, including downhole well applications. For example, electric submersible pumping systems can be used to pump hydrocarbon production fluids to a surface location or to inject fluids into a formation surrounding a wellbore. Repair or replacement of an electric submersible pumping system located downhole in a wellbore is expensive and time-consuming. However, predicting run life and/or failure of the electric submersible pumping system is difficult and this limits an operator's ability to make corrective actions that could extend the run life of the pumping system.

SUMMARY

[0003] In general, a technique is provided to help predict the run life of a pumping system, e.g. an electric submersible pumping system. Knowledge regarding the predicted run life and factors affecting that predicted run life enables selection of corrective actions. The corrective actions may involve adjustment of operational parameters related to the pumping system so as to prolong the actual run life of the pumping system. The technique utilizes an algorithm which combines various models, e.g. physical models and degradation models, to provide various failure/run life predictions. The various models utilize a variety of sensor data which may include actual sensor data and virtual sensor data to both evaluate the state of the pumping system and the predicted run life of the pumping system.

[0004] However, many modifications are possible without materially departing from the teachings of this disclosure. Accordingly, such modifications are intended to be included within the scope of this disclosure as defined in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] Certain embodiments of the disclosure will hereafter be described with reference to the accompanying drawings, wherein like reference numerals denote like elements. It should be understood, however, that the accompanying figures illustrate the various implementations described herein and are not meant to limit the scope of various technologies described herein, and:

[0006] Figure 1 is a schematic illustration of a well system comprising an example of a pumping system, according to an embodiment of the disclosure;

[0007] Figure 2 is a schematic illustration of a processing system implementing an embodiment of an algorithm for predicting run life of a pumping system, according to an embodiment of the disclosure;

[0008] Figure 3 is an illustration of an example of an algorithm for predicting useful life of an overall pumping system or component of the pumping system prior to installation, according to an embodiment of the disclosure;

[0009] Figure 4 is an illustration of an example of an algorithm for predicting useful life of an overall pumping system or component of the pumping system in which the algorithm utilizes data from actual sensors, according to an embodiment of the disclosure;

[0010] Figure 5 is an illustration of an example of an algorithm for predicting useful life of an overall pumping system or component of the pumping system in which the algorithm utilizes data from actual sensors and virtual sensors, according to an embodiment of the disclosure; and

[0011] Figure 6 is an illustration of a method of controlling a pumping system to achieve a desired system state based on data regarding an actual system state as determined from actual sensor data and virtual sensor data, according to an embodiment of the disclosure.

DETAILED DESCRIPTION

[0012] In the following description, numerous details are set forth to provide an understanding of some embodiments of the present disclosure. However, it will be understood by those of ordinary skill in the art that the system and/or methodology may be practiced without these details and that numerous variations or modifications from the described embodiments may be possible.

[0013] The present disclosure generally relates to a technique which improves the ability to predict run life of a pumping system, e.g. an electric submersible pumping system. Depending on the application, the prediction of run life may be based on evaluation of the overall electric submersible pumping system, selected components of the electric submersible pumping system, or both the overall system and selected components. Knowledge regarding the predicted run life and factors affecting that predicted run life enables selection of corrective actions.

[0014] The corrective actions selected to prolong the run life of a pumping system, e.g. an electric submersible pumping system, can vary substantially depending on the specifics of, for example, an environmental change, an indication of component failure, goals of a production or injection operation, and/or other system or operational considerations. For example, corrective actions may involve adjustment of operational parameters regarding the electric submersible pumping system, including slowing the pumping rate, adjusting a choke, or temporarily stopping the pumping system.

[0015] The technique for predicting failure/run life of the pumping system utilizes an algorithm which combines various models, e.g. physical models and degradation models, to provide failure/run life predictions. The models may utilize a variety of sensor data including actual sensor data and virtual sensor data to both evaluate the state of the pumping system and the predicted run life of the pumping system. The overall algorithm may be adjusted to accommodate specific system considerations, environmental considerations, operational considerations, and/or other application-specific considerations.

[0016] Referring generally to Figure 1, an example of a well system 20 comprising a pumping system 22, such as an electric submersible pumping system or other downhole pumping system, is illustrated. In this embodiment, pumping system 22 is disposed in a wellbore 24 drilled or otherwise formed in a geological formation 26. The pumping system 22 is located below well equipment 28, e.g. a wellhead, which may be disposed at a seabed or a surface 30 of the earth. The pumping system 22 may be deployed in a variety of wellbores 24, including vertical wellbores or deviated, e.g. horizontal, wellbores. In the example illustrated, pumping system 22 is suspended by a deployment system 32, such as production tubing, coiled tubing, or other deployment system. In some applications, deployment system 32 comprises a tubing 34 through which well fluid is produced to wellhead 28.

[0017] As illustrated, wellbore 24 is lined with a wellbore casing 36 having perforations 38 through which fluid flows between formation 26 and wellbore 24. For example, a hydrocarbon-based fluid may flow from formation 26 through perforations 38 and into wellbore 24 adjacent pumping system 22. Upon entering wellbore 24, pumping system 22 is able to produce the fluid upwardly through tubing 34 to wellhead 28 and on to a desired collection point.

[0018] Although pumping system 22 may comprise a wide variety of components, the example in Figure 1 is illustrated as an electric submersible pumping system 22 having a submersible pump 40, a pump intake 42, and a submersible electric motor 44 that powers submersible pump 40. Submersible pump 40 may comprise a single pump or multiple pumps coupled directly together or disposed at separate locations along the submersible pumping system string. Depending on the application, various numbers of submersible pumps 40, submersible motors 44, other submersible components, or even additional pumping systems 22 may be combined for a given downhole pumping application.

[0019] In the embodiment illustrated, submersible electric motor 44 receives electrical power via a power cable 46 and is pressure balanced and protected from deleterious wellbore fluid by a motor protector 48. In addition, pumping system 22 may comprise other components including a connector 50 for connecting the components to deployment system 32. Another illustrated component is a sensor unit 52 utilized in sensing a variety of wellbore parameters. It should be noted, however, that sensor unit 52 may comprise a variety of sensors and sensor systems deployed along electric submersible pumping system 22, along casing 36, or along other regions of the wellbore

24 to obtain data for determining one or more desired parameters, as described more fully below. Furthermore, a variety of sensor systems 52 may comprise sensors located at surface 30 to obtain desired data helpful in the process of determining measured parameters related to prediction of failures/run life of electric submersible pumping system 22 or specific components of pumping system 22.

[0020] Data from the sensors of sensor system 52 may be transmitted to a processing system 54, e.g. a computer-based control system, which may be located at surface 30 or at other suitable locations proximate or away from wellbore 24. The processing system 54 may be used to process data from the sensors and/or other data according to a desired overall algorithm which facilitates prediction of system run life. In some applications, the processing system 54 is in the form of a computer based control system which may be used to control, for example, a surface power system 56 which is operated to supply electrical power to pumping system 22 via power cable 46. The surface power system 56 may be controlled in a manner which enables control over operation of submersible motor 44, e.g. control over motor speed, and thus control over the pumping rate or other aspects of pumping system operation.

[0021] Referring generally to Figure 2, an example of processing system 54 is illustrated schematically. In this embodiment, processing system 54 may be a computer-based system having a central processing unit (CPU) 58. CPU 58 is operatively coupled to a memory 60, as well as an input device 62 and an output device 64. Input device 62 may comprise a variety of devices, such as a keyboard, mouse, voice-recognition unit, touchscreen, other input devices, or combinations of such devices. Output device 64 may comprise a visual and/or audio output device, such as a monitor having a graphical user interface. Additionally, the processing may be done on a single device or multiple devices at the well location, away from the well location, or with some devices located at the well and other devices located remotely.

[0022] In the illustrated example, the CPU 58 may be used to process data according to an overall algorithm 66. As discussed in greater detail below, the algorithm

66 may utilize a variety of models, such as physical models 68, degradation models 70, and optimizer models 72, e.g. optimizer engines, to evaluate data and predict run life/failure with respect to electric submersible pumping system 22. Additionally, the processing system 54 may be used to process data received from actual sensors 74 forming part of sensor system 52. The processing system 54 also may be used to process virtual sensor data from virtual sensors 76. By way of example, the data from actual sensors 74 and virtual sensor 76 may be processed on CPU 58 according to desired models or other processing techniques embodied in the overall algorithm 66.

[0023] As illustrated, the processing system 54 also may be used to control operation of the pumping system by, for example, controlling surface power system 56. This allows the processing system 54 to be used as a control system for adjusting operation of the electric submersible pumping system 22 in response to predictions of run life or component failure. In some applications, the control aspects of processing system 54 may be automated so that automatic adjustments to the operation of pumping system 22 may be implemented in response to run life/component failure predictions resulting from data processed according to algorithm 66.

[0024] Referring generally to Figure 3, an example of overall algorithm 66 is illustrated as one technique for evaluating data related to electric submersible pumping system 22 in a manner facilitating run life prediction. In this example, a mission profile 78 is used in cooperation with physical model 68 which, in turn, is used in cooperation with degradation model 70 to predict the useful life of at least one component of electric submersible pumping system 22. In this embodiment, the prediction is established before installation of electric submersible pumping system 22 into wellbore 24 and is based on the anticipated mission profile 78 to be employed during future operation of the electric submersible pumping system 22.

[0025] According to this method, the mission profile 78 provides inputs to processing system 54 as a function of run time. For example, the mission profile 78 may input “loads” such as pressure rise, vibration, stop/start of pumping system 22, and/or other inputs as a function of time. These loads are then input to the physical model 68 of the particular electric submersible pumping system 22 or of a specific component of the electric submersible pumping system 22. The physical model 68 is then used to predict "stresses" or system outputs as a function of run time. By way of example, such system outputs may comprise shaft cycle stress, pump front seal leakage velocity, motor winding temperature, and/or other system outputs. The system outputs are then input to the degradation model 70.

[0026] The degradation model 70 predicts the useful life of the overall electric submersible pumping system 22 or a component of the electric submersible pumping system 22. The degradation model 70 is configured to process the data from sensors 74 according to, for example, shaft fatigue analysis, stage front seal erosion models, motor insulation temperature degradation data analysis, and/or other suitable data analysis techniques selected to determine a predicted life of a given component or of the overall electric submersible pumping system 22.

[0027] Depending on the application, the physical model 68 may include, for example, data related to component mechanical stress, thermal stress, vibration, wear, and/or leakage. Various degradation models 70 may be selected to process the data from physical model 68 via processing system 54. For example, the degradation model or models 70 may further comprise wear models, empirical test data, and/or fatigue models to improve prediction of the component or system life based on data from physical model 68.

[0028] Referring generally to Figure 4, another example of an overall algorithm 66 is illustrated as one technique for evaluating data related to electric submersible pumping system 22 in a manner facilitating run life prediction. The example illustrated in Figure 4 may be used independently or combined with other prediction techniques, such as the prediction technique described with reference to Figure 3. In the example illustrated in Figure 4, measured data 80 is obtained and provided to degradation model 70. The measured data 80 is obtained from sensors, such as sensors 74, which monitor at least one component of electric submersible pumping system 22 during operation. This data is provided to the component/system degradation model 70 so that the data may be appropriately processed via processing system 54 to predict a remaining useful life of the component (or overall pumping system 22) during operation of the electric submersible pumping system 22.

[0029] In this example, "stresses" are measured in real-time by actual sensors 74 which may be disposed along the electric submersible pumping system 22 and/or at other suitable locations. For example, the actual sensors 74 may be located along pumping system 22 to monitor parameters related to an individual component or to combinations of components. In some applications, actual sensors 74 may be located to monitor the motor winding temperature of submersible motor 44. The measured motor winding temperatures are then used in the corresponding degradation model 70 to predict in real-time the remaining useful life of the pumping string component, e.g. submersible motor 44. In this specific example, the degradation model 70 may be programmed or otherwise configured to predict the remaining useful life of the motor magnet wire based on the motor winding temperatures according to predetermined relationships between useful life and temperatures.

[0030] However, the use of actual sensor data in combination with degradation model 70 may be applied to a variety of components according to this embodiment of overall algorithm 66. For example, sensors 74 may be used to monitor specific motor temperatures and this data may be provided to the degradation model 70 to predict the aging of a motor lead wire, a magnet wire, and/or a coil retention system. According to another example, sensors 74 may be positioned to monitor water ingress into, for example, motor protector 48 and submersible motor 44. This data is then used by degradation model 70 to predict when the water front will reach the submersible motor 44 in a manner which corrupts operation of the submersible motor 44.

[0031] In another example, the actual sensors 74 are used to monitor temperatures along the well system 20, e.g. along electric submersible pumping system 22. This temperature data is then used by degradation model 70 to predict aging and stress relaxation (sealability) of elastomeric seals along the electric submersible pumping system 22. The actual sensors 74 also may be positioned at appropriate locations along the electric submersible pumping system 22 to measure vibration. The vibration data is then analyzed according to degradation model 70 to predict failure of bearings within the electric submersible pumping system 22.

[0032] A variety of sensors may be used to collect data related to various aspects of pumping system operation, and selected degradation models 70 may be used for analysis of that data on processing system 54. In many applications, the output from the degradation model 70 regarding remaining useful life of a given component can be used to make appropriate adjustments to operation of the electric submersible pumping system 22. In some applications, the appropriate adjustments may be performed automatically via processing/control system 54.

[0033] Referring generally to Figure 5, another example of an overall algorithm 66 is illustrated as one technique for evaluating data related to electric submersible pumping system 22 in a manner facilitating run life prediction. The example illustrated in Figure 5 may be used independently or combined with other prediction techniques, such as the prediction techniques described above. In the example illustrated in Figure 5, measured data 80 is obtained from actual sensors 74 employed to monitor the electric submersible pumping system 22 during operation. In combination with the measured data 80, a physical model 68 of the electric submersible pumping system 22 and a component degradation model 70 are used to predict remaining run life of pumping system components or the overall pumping system 22.

[0034] According to this method, “loads” measured in real-time by actual sensors 74 positioned along electric submersible pumping system 22 are used by the physical model or models 68 to predict “virtual stresses” on the electric submersible pumping system 22 or components of the pumping system 22 in real-time. Furthermore, actual stresses measured by sensors 74 may be used together with the physical model(s) 68 and optimizer engine 72 to determine a set of measured system loads and virtual system loads. The virtual system loads are system loads not measured by actual sensors 74 but which provide a desired correlation between actual stresses measured by actual sensors 74 and the same virtual stresses predicted by the physical model(s) 68. The set of virtual loads and measured loads as well as the set of virtual stresses and measured stresses determined according to this method provide an improved description of the “system state” of the pumping system 22 as a function of operating time. The set of actual measured stresses and virtual stresses are then used by degradation model 70 to predict a remaining useful life of the pumping system components or the overall electric submersible pumping string 22.

[0035] In various applications, a “system identification” process may be employed for determining the virtual loads, as represented by module 81 in Figure 5. The system identification process/module 81 may encompass, for example, physical models 68 and optimizer engine 72. System identification refers to a process utilizing physical models which may range from “black box” processes in which no physical model is employed to “white box” processes in which a complete physical model is known and employed. In system identification processes, the terminology “grey box” also is sometimes used to represent semi-physical modeling. The black, grey, and white box aspects of the system identification process are represented by reference numeral 82 in Figure 5.

[0036] Generally, the system identification process employs statistical methods for constructing mathematical models of dynamic systems from measured data, e.g. the data obtained from actual sensors 74. The system identification process also may comprise generating informative data used to fit such models and to facilitate model reduction. By way of example, such a system identification process may utilize measurements of electric submersible pumping system behavior and/or external influences on the pumping system 22 based on data obtained from actual sensors 74.

[0037] The data is then used to determine a mathematical relationship between the data and a state or occurrence, e.g. a virtual load or even a run life or component failure. This type of "system identification" approach enables determination of such mathematical relationships without necessarily obtaining details on what actually occurs within the system of interest, e.g. within the electric submersible pumping system 22. White box methodologies may be used when activities within the pumping system 22 and their relationship to run life are known, while grey box methodologies may be used when the activities and/or relationships are partially understood. Black box methodologies may comprise system identification algorithms and may be employed when no prior model for understanding the activities/relationships is known. A variety of system identification techniques are available and may be used to establish virtual loads and/or to develop failure/run life predictions.

[0038] The use of such virtual stresses may be helpful in a variety of applications to predict remaining useful life. For example, the use of virtual motor temperature data from locations other than locations at which temperature data is measured by actual sensors 74 can be useful in predicting the aging of, for example, motor lead wire, magnet wire, and coil retention systems. Similarly, virtual motor temperature data from locations other than locations monitored by actual sensors 74 can be useful in predicting aging and stress relaxation (sealability) of elastomeric seals in the electric submersible pumping string 22. Additionally, the use of virtual water front data can be used to effectively predict when a water front will reach the submersible motor 44.

[0039] In various applications, virtual bearing data, e.g. bearing contact stress, lubricant film thickness, vibration, can be used to predict the remaining life of pumping system bearings. Similarly, virtual pump thrust washer loads may be used to predict washer life. Virtual wear data, such as virtual pump erosive and abrasive wear data, can be used to predict pump stage bearing life and pump stage performance degradation. Additionally, virtual torque shaft data may be used to predict torsional fatigue life damage and remaining fatigue life of various shafts in submersible pumping system 22. Virtual shaft seal data, e.g contact stress, misalignment, vibration, may be used to predict the remaining life of various seals. Virtual data may be combined with actual data in many ways to improve the ability to predict run life of a given component or system. As described above, the virtual data may be in the form of virtual stresses predicted by physical model(s) 68 and actual data may be in the form of actual stresses measured by sensors 74.

[0040] Referring generally to Figure 6, another example of an overall algorithm 66 is illustrated as one technique for evaluating data related to electric submersible pumping system 22 in a manner facilitating run life prediction. The example illustrated in Figure 6 may be used independently or combined with other prediction techniques, such as the prediction technique described above. In the example illustrated in Figure 6, the “system state” of measured parameters and virtual parameters determined in real-time may be obtained by a suitable method, such as the method described above with reference to Figure 5.

[0041] The system state of measured parameters and virtual parameters is then used to identify events such as undesirable or non-optimum operating conditions. Examples of such conditions include gas-lock or other conditions which limit or prevent operation of the electric submersible pumping system 22. The system state of measured parameters and virtual parameters may be further used to control the electric submersible pumping string 22 by, for example, processor/control system 54. For example, the processor/control system 54 may utilize overall algorithm 66 to correct for conditions in the actual system state to achieve a new desired system state 84, as illustrated in Figure 6.

[0042] In this method, the processor/control system 54 may be programmed according to a variety of models, algorithms or other techniques to automatically adjust operation of the electric submersible pumping system 22 from a detected actual system state to a desired system state. Depending on the application, the actual system state may be determined by actual sensor data, virtual sensor data, or a combination of actual and virtual sensor data. In some applications, both actual measured data and virtual data may be used as described above with respect to the embodiment illustrated in Figure 5 to determine the actual system state of operation with respect to electric submersible pumping system 22. The processor/control system 54 then automatically adjusts operation of the electric submersible pumping system 22 according to the programmed algorithm, model, or other technique to move operation of the pumping system 22 to the desired system state. By way of example, the processor/control system 54 may implement a change in motor speed and/or a change in a surface choke setting to adjust operation to the desired system state.

[0043] Depending on the application, the electric submersible pumping system 22 may have a variety of configurations and/or components. Additionally, the overall algorithm 66 may be configured to sense and track a variety of actual data and virtual data to monitor actual states of specific components or of the overall pumping system 22. The actual data and virtual data also may be related to various combinations of components and/or operational parameters. Additionally, the actual data and virtual data may be processed by various techniques selected according to the type of data and the types of conditions being monitored. Based on predictions of run life determined from the actual data and/or virtual data, various operational adjustments may be made manually or automatically to achieve desired system states so as to enhance longevity and/or other operational aspects related to the run life of the electric submersible pumping system.

[0044] Depending on the application, the methodologies described herein may be used to predict a run life of a pumping string, e.g. electric submersible pumping system, prior to installation based on an anticipated mission profile. The methodologies also may be used to predict remaining run life during operation of the pumping system. For example, the methodologies may be used to predict not simply imminent potential failure but also the time to failure throughout the life of the pumping system. In electric submersible pumping system applications, for example, the methodologies provide an operator or an automated control system with a substantial warning period prior to failure of the pumping system.

[0045] The methodologies described herein further facilitate improved responses to dynamic changes in, for example, an electric submersible pumping system string due to variable operating conditions. The improved responses enhance production and/or extend the run life of the electric submersible pumping system prior to failure. In various applications, virtual data is calculated according to a physical model for parameters other than those for which actual measured data is available. The virtual data may be used alone or in combination with actual measured data to enable a more comprehensive evaluation of potential pumping system failure modes. The more comprehensive evaluation enables improved control responses to mitigate those failure modes.

[0046] Although a few embodiments of the disclosure have been described in detail above, those of ordinary skill in the art will readily appreciate that many modifications are possible without materially departing from the teachings of this disclosure. Accordingly, such modifications are intended to be included within the scope of this disclosure as defined in the claims.

CLAIMS

What is claimed is:

1. A method for evaluating operation of a pumping system, comprising:

obtaining actual sensor data from sensors monitoring operation of an electric submersible pumping system;

using a physical model of the electric submersible pumping system to determine virtual sensor data;

processing the actual sensor data and the virtual sensor data to determine an actual system state as a function of operating time; and

applying a degradation model to the actual sensor data and the virtual sensor data to provide a predictor of remaining useful life of at least a component of the electric submersible pumping system.

2. The method as recited in claim 1, further comprising adjusting operation of the electric submersible pumping system to a desired system state.

3. The method as recited in claim 1, further comprising adjusting operation of the electric submersible pumping system to a desired system state which enhances the longevity of the electric submersible pumping system.

4. The method as recited in claim 1, further comprising automatically adjusting operation of the electric submersible pumping system to a desired system state via a control system.

5. The method as recited in claim 1, wherein using comprises using an optimizer engine to help determine the virtual sensor data.

6. The method as recited in claim 1, wherein processing comprises using both actual sensor data and virtual sensor data on temperature to predict aging of at least a portion of a submersible motor.

7. The method as recited in claim 1, wherein processing comprises using both actual sensor data and virtual sensor data on water ingress to predict when a water front will detrimentally reach a submersible motor of the electric submersible pumping system.

8. The method as recited in claim 1, wherein processing comprises using both actual sensor data and virtual sensor data on temperature to predict aging and stress relaxation of elastomeric seals of the electric submersible pumping system.

9. The method as recited in claim 1, wherein processing comprises using both actual sensor data and virtual sensor data on bearings to predict bearing failure within the electric submersible pumping system.

10. A method, comprising:

obtaining actual sensor data from actual sensors monitoring parameters of a pumping system in real-time;

processing the actual sensor data via a degradation model; and

using an output of the degradation model to predict in real-time a remaining useful life of at least one component of the pumping system.

11. The method as recited in claim 10, wherein obtaining comprises obtaining actual sensor data regarding an electric submersible pumping system.

12. The method as recited in claim 11, wherein obtaining further comprises obtaining virtual sensor data from virtual sensors regarding parameters of the electric submersible pumping system.

13. The method as recited in claim 12, wherein processing comprises processing both the actual sensor data and the virtual sensor data.

14. The method as recited in claim 13, further comprising adjusting operation of the electric submersible pumping system to extend the remaining useful life.

15. The method as recited in claim 14, wherein adjusting comprises automatically adjusting via a control system.

16. A method for improving a life expectancy of a pumping system, comprising:

obtaining actual sensor data from sensors monitoring operation of a pumping system;

using a physical model of the pumping system to determine virtual sensor data;

processing the actual sensor data and the virtual sensor data to determine an actual system state of the pumping system as a function of operating time; and

adjusting operation of the pumping system from the actual system state to a desired system state which increases the run life of the pumping system.

17. The method as recited in claim 16, further comprising applying a degradation model to the actual sensor data and the virtual sensor data to provide a predictor of remaining useful life of at least a component of the pumping system.

18. The method as recited in claim 16, wherein adjusting comprises automatically adjusting via a control system.

19. The method as recited in claim 18, wherein automatically adjusting comprises changing a motor speed of a submersible motor of the pumping system.

20. The method as recited in claim 18, wherein automatically adjusting comprises changing a surface choke setting.

FIG. 1

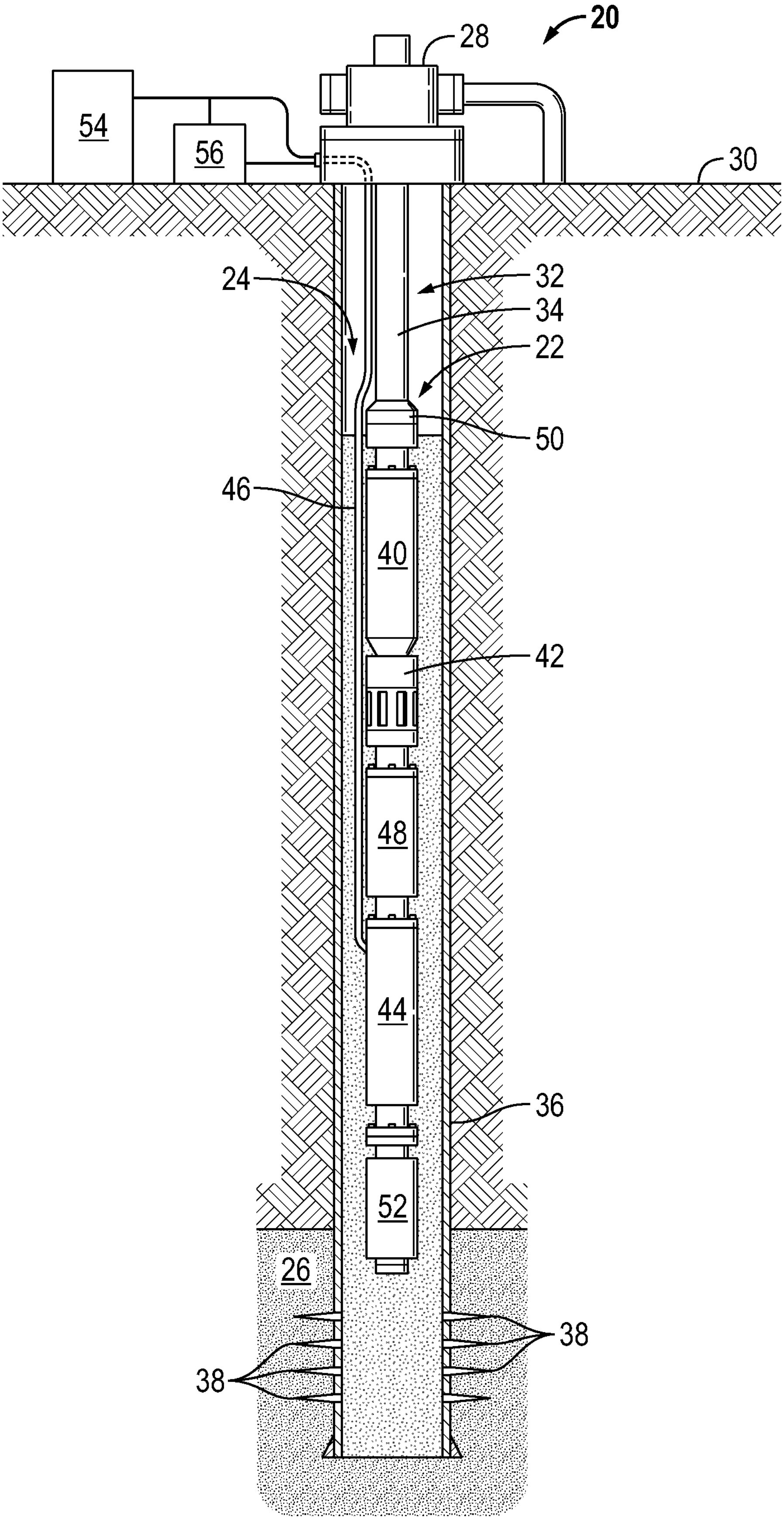


FIG. 2

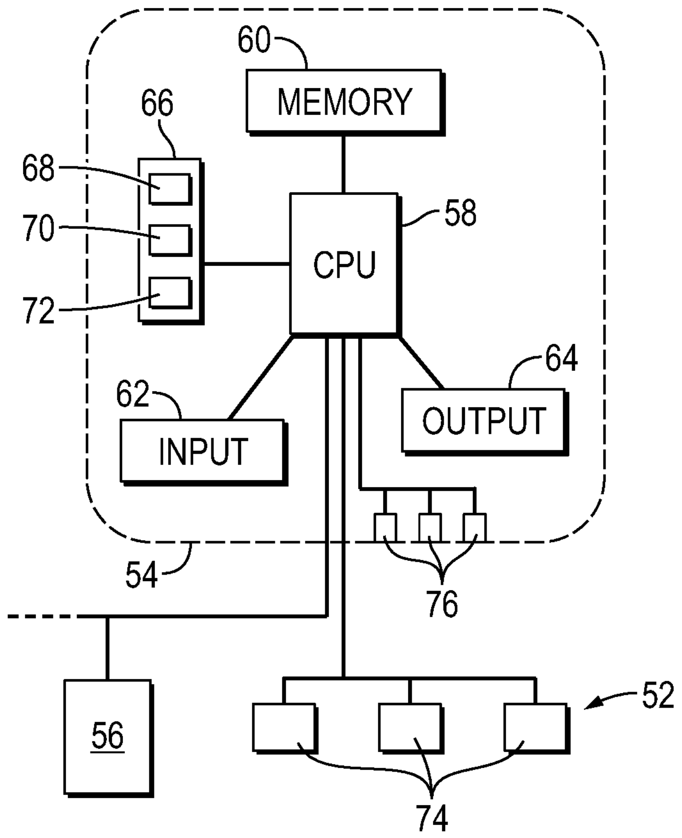


FIG. 3

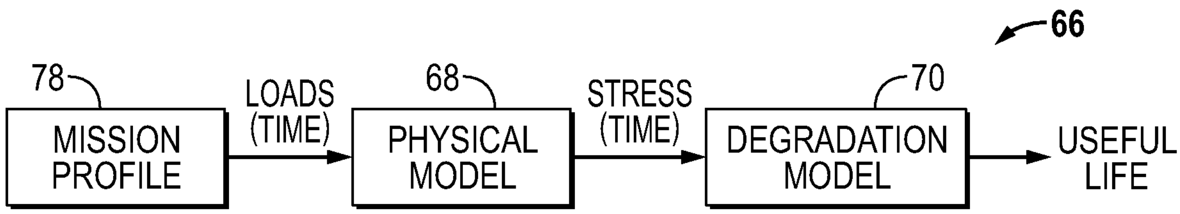


FIG. 4

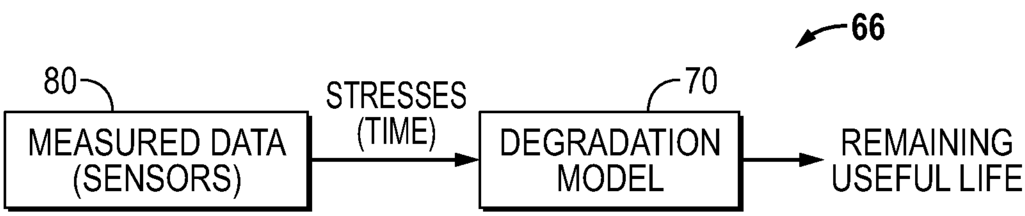


FIG. 5

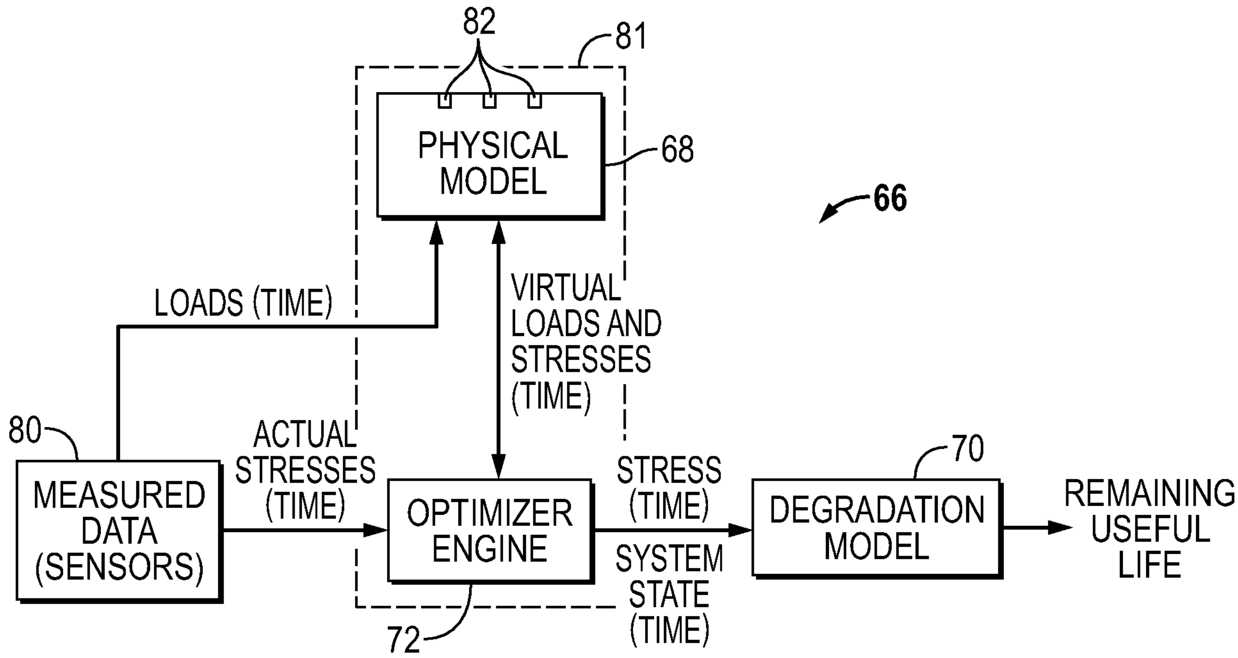
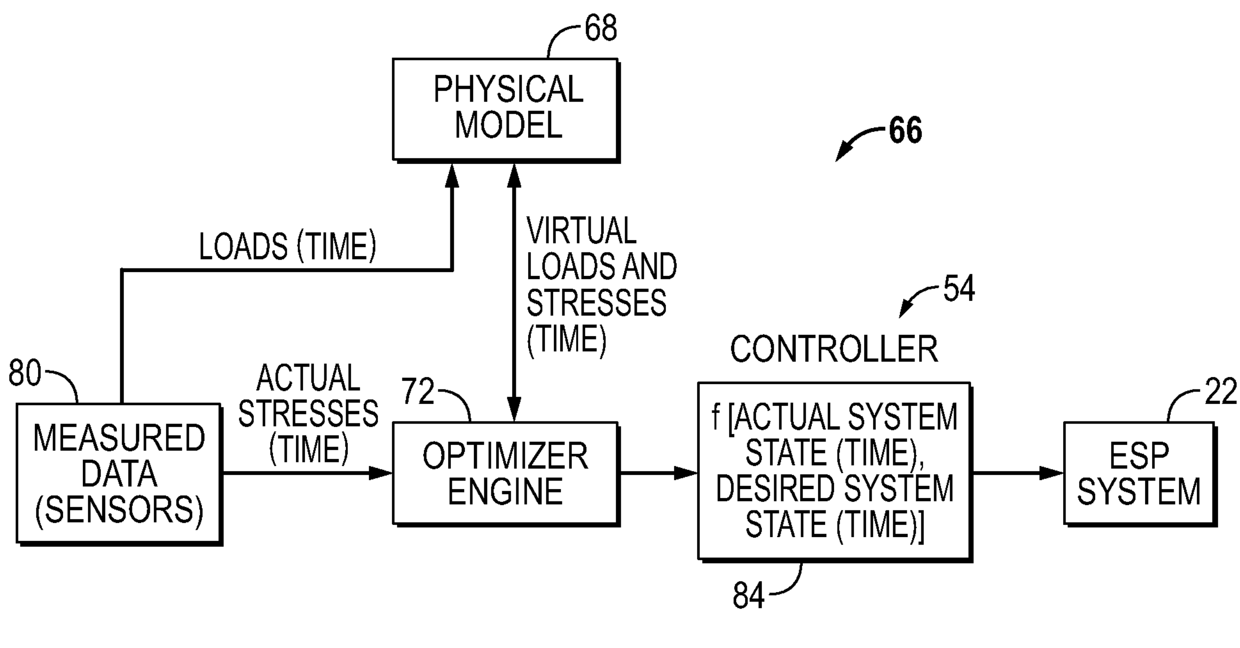

82
81
PHYSICAL MODEL
68
66
LOADS (TIME)
VIRTUAL LOADS AND STRESSES (TIME)
80
ACTUAL STRESSES (TIME)
MEASURED DATA (SENSORS)
OPTIMIZER ENGINE
STRESS (TIME)
SYSTEM STATE (TIME)
70
DEGRADATION MODEL
REMAINING USEFUL LIFE
72

FIG. 6


68
PHYSICAL MODEL
66
LOADS (TIME)
VIRTUAL LOADS AND STRESSES (TIME)
54
CONTROLLER
80
ACTUAL STRESSES (TIME)
72
22
MEASURED DATA (SENSORS)
OPTIMIZER ENGINE
f [ACTUAL SYSTEM STATE (TIME), DESIRED SYSTEM STATE (TIME)]
ESP SYSTEM
84

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/023606

A. CLASSIFICATION OF SUBJECT MATTER

E21B 43/12(2006.01)i, F04D 13/10(2006.01)i, E21B 21/08(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
E21B 43/12; G05D 7/00; E21B 47/00; G08B 21/00; E21B 44/00; G06F 15/18; G06N 5/02; F04D 13/10; E21B 21/08

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: wellbore, submersible pump, physical model, degradation model, control, life, automatically and sensor

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2011-0071966 A1 (HOLLEY et al.) 24 March 2011 See paragraphs [0026]-[0065], [0087], [0147].	1,10-13
Y		2-9,14-20
Y	US 2013-0175030 A1 (IGE et al.) 11 July 2013 See paragraphs [0082]-[0146], claim 15 and figure 7.	2-9,14-20
A	US 2007-0252717 A1 (FIELDER, LANCE I.) 01 November 2007 See claims 1-11 and figures 1-2.	1-20
A	US 2003-0015320 A1 (CROSSLEY, ALEXANDER) 23 January 2003 See paragraphs [0013]-[0032] and figures 1-3.	1-20
A	US 4854164 A (RHOADS, BENJAMIN J.) 08 August 1989 See abstract, claims 1-11 and figures 5, 7.	1-20

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 July 2015 (10.07.2015)	**13 July 2015 (13.07.2015)**

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2015/023606

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