

## **SYSTEMS AND METHODS FOR MONITORING AND DIAGNOSING INDUSTRIAL EQUIPMENT**

### **TECHNICAL FIELD**

5           This specification relates to monitoring and diagnosing the condition (e.g., the technical condition) of industrial equipment (e.g., pipelines, tanks, valves, seals, pipe connections, gland assemblies, gas separators, filters, pumps, compressors, fans and other units and machines and their combinations), mainly as part of complex technological units including installations and infrastructure facilities. Industrial equipment can be used in  
10 various settings including hazardous production facilities (HPF), oil and gas processing and chemical industries, power generation (e.g., wind turbines, hydropower stations, etc.), metallurgy, machinery, mechanical engineering, processing industry, shipbuilding, shipping, aircraft industry, mining, transport, printing machines, etc. Such equipment can include both dynamic equipment (e.g., gas separators, filters, pumps, compressors, fans, wind turbines, oil  
15 overflow systems, and other components) and static equipment (e.g., pipelines, tanks, valves, seals, pipeline connections, gland assemblies and their combinations). The monitoring and diagnosis techniques described in this specification can contribute to resource-saving management of the technical condition of industrial equipment as well as accident prevention processes for industrial equipment.

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### **BACKGROUND**

Many industries, including the oil and gas industry, require the use of systems comprising substantial industrial equipment. For example, oil and gas industrial equipment can include tens to hundreds (if not thousands) of kilometers of pipelines as well as tanks,  
25 valves, seals, pipe connections, gland assemblies, gas separators, filters, pumps, compressors, fans, etc. for the acquisition, processing, and transportation of oil and gas. Various processes and conditions such as metal corrosion, seal destruction due to vibration, aging of materials, weakening of nut and bolt threads, and exposure to temperature and pressure fluctuations can lead to the wearing down and deterioration of industrial equipment. This can compromise the  
30 integrity of industrial equipment and ultimately lead to defects, faults, and/or other undesirable conditions such as plastic deformation, fractures, cracks, fistulas, leaks, or

abnormal flow in the industrial equipment. Such defects, faults, and/or other undesirable conditions can in turn result in accidents, personnel poisoning, and significant financial losses. Timely identification and localization of weak points (or already existing defects, faults, and/or other undesirable conditions) in industrial equipment can prevent such outcomes. There are many settings where industrial equipment is used including hazardous production facilities (HPF), oil and gas processing and chemical industries, power generation (e.g., wind turbines, hydropower stations, etc.), metallurgy, machinery, mechanical engineering, processing industry, shipbuilding, shipping, aircraft industry, mining, transport, printing machines, etc.

## SUMMARY

This document describes systems and methods for monitoring and diagnosing industrial equipment, based on the registration and analysis of vibroacoustic oscillations in the equipment and acoustic noise emitted by the equipment. The system includes a set of software and hardware that solve the problems of constant monitoring of the technical condition of equipment and predicting malfunctions based on data received in real time. Through monitoring and predictive diagnostics of the equipment's condition, the risk of emergencies, unplanned equipment failures, and associated losses can be minimized.

Monitoring industrial equipment can include the control of certain equipment-associated parameters (e.g. rotation speed, vibration value, noise, temperature, pressure, etc.), the identification of trends in their changes, and the forecasting of the development of the monitored parameters. Diagnosing industrial equipment can include the identification of defects and the forecasting of their development. Predictive diagnostics of industrial equipment can enable prevention of emergencies and allow enterprises to switch from the practice of scheduled preventive and event-based repairs to maintenance based on the actual condition of the equipment. This can reduce operating costs and the amount of equipment downtimes. Monitoring and predictive diagnostics of equipment condition can benefit from accurate and continuous input data from a wide variety of sensors and parameters in real-time. For example, comparisons of real-time data with developed models of "normal" operation of equipment (e.g., a digital twin model of the "normal" or "good" technical condition of the equipment) make it possible to timely inform personnel about deviations in equipment parameters, and thereby prevent emergencies. The monitoring and diagnostic systems described herein based on the recording and analysis of vibroacoustic oscillations in equipment and the acoustic noise emitted by the equipment can be portable, mobile phone or

fixed, and can also be used to monitor and diagnose various kinds of dynamic and stationary equipment in a wide range of fields and conditions, (including dangerous fields and conditions).

Existing techniques for monitoring and diagnosing industrial equipment for weak points, defects, faults, and/or other undesirable conditions (e.g., plastic deformation, fractures, cracks, fistulas, leaks, etc.) can be complex to install or maintain, expensive to install or maintain, insufficiently sensitive for detecting certain conditions in real-time, etc. Various implementations of the systems and related methods described in this document, therefore, can have many advantages over existing techniques.

First, the technology disclosed herein can allow for early, fast-acting, and automated monitoring and diagnosis (including the detection of defects) of parts and components of industrial equipment during their manufacturing, operation, maintenance and/or repair processes. Specifically, the technology can be employed to assess the real-time, actual technical condition of parts, assemblies, and industrial equipment in general (e.g., rather than simply estimating when maintenance may be required). This can, in turn, result in decreased financial, technical, and time costs associated with repairing, overhauling, or replacing industrial equipment. The systems described herein can be portable, mobile, or stationary, and they can be used for the monitoring and diagnosis of various kinds of dynamic and stationary equipment in a wide range of fields and conditions, including hazardous ones.

The technology disclosed herein also has the advantage of being a non-destructive testing (NDT) approach, allowing for monitoring and diagnosing industrial equipment without requiring disassembly of the equipment and without interfering with the functioning of the equipment. This can yield even further cost advantages. Compared to other NDT techniques (e.g., thermal, parametric, radiation, ultrasonic, magnetic, etc.), diagnosing industrial equipment only by noise can be particularly advantageous because it does not require the installation of contact emitters and receivers on the industrial equipment being monitored, which can substantially complicate, increase the cost of, and delay the diagnostic process. Instead, as described in this specification, the sensors described for noise-based diagnosis can be disposed remotely from the industrial equipment to capture characteristic noise signals produced by the industrial equipment as defects present themselves and potentially grow. For example, the process of gas flowing through holes in pipelines, vessels, and pneumatic systems in which gas is under pressure; the friction of moving parts during the operation of various mechanisms; the mechanical effects on the structure such as the impact of foreign or poorly fixed objects; and other electrical discharges at electric power facilities;

etc. are all accompanied by acoustic noises characterized by different parameters and can therefore be identified. High noise levels can also be generated due to non-optimal modes of operation of industrial equipment or deviation of operating parameters from their intended design. Under noise-based diagnostic approaches, the location of any defects can also be  
5   ascertained, for example, by analyzing the time it takes sound waves to reach the remotely positioned sensors. As used herein, “passive noise diagnostic” techniques such as those described in this specification refer to the process of determining the technical condition of an object (e.g., industrial equipment) based on the results of measuring the sound and/or ultrasonic pressure level it creates in a given frequency range at a certain control point. In  
10   general, the method of noise diagnostics is based on the registration and analysis of acoustic noise of the diagnostic object (e.g., a component of industrial equipment), which allows for judging the occurrence and development of defects, serviceability and malfunction, and even the nature and/or location of the malfunction of the object. Noise diagnostics can involve detection, location, tracking (monitoring), assessment of danger, and assessment of speed of  
15   fault development in order to stop operation or test in advance and prevent the destruction of industrial equipment. Thus, noise diagnostics can improve the reliability and service life of technical systems such as mechanisms and machinery (e.g., hydraulic drives, gearboxes, pumps, compressors, fans, and drive motors, etc.), pipelines, gas and liquid lines, pressure system housings, steam generators, gas and hydro supply systems, vessels, heat exchangers,  
20   automation and control system equipment, power supply equipment (e.g., transformers, switching equipment, etc.), and more.

Some implementations of the technology described herein can be more sensitive than existing techniques and can enable the monitoring and diagnosis of more industrial equipment (e.g., longer stretches of pipelines) with smaller amounts of sensing equipment.  
25   For example, by using highly sensitive fiber optic sensors (e.g., using interferometry techniques) to detect vibroacoustic signals and noise originating from the industrial equipment, it may be possible to detect minor leaks or weak points in a pipeline that alternative techniques (e.g., traditional microphones and piezoelectric detectors) would be unable to detect. Moreover, the high sensitivity of the fiber optics sensors may reduce or  
30   eliminate the need for using many sensors. For example, using the techniques disclosed herein, a single fiber optic sensor may be utilized to monitor and diagnose industrial equipment that is up to a few kilometers away from the sensor (e.g., less than 1 km away, 1 km away, 2 km away, 3 km away, 4 km away, etc.). This allows industrial equipment (e.g., long stretches of pipeline) to be monitored using less hardware compared to, e.g., (i)

distributed fiber-optic acoustic systems that involve using a fiber optic that extends along the length of the pipeline as the sensing element, or (ii) point-based acoustic detection systems that involve the use of multiple acoustic sensors spaced relatively close to one another (e.g., up to 50 meters apart from one another). The reduction in hardware can in turn yield  
5 advantages such as less expensive installation, reduced risk of failure, easier maintenance, etc.

Furthermore, the technology disclosed herein can be implemented using mechanical and optical components (e.g., optical sensors, fiber optic cables, etc.), which may be more robust for certain use cases (e.g., monitoring underwater pipelines) compared to existing  
10 technologies.

The non-destructive sensing and analysis of vibroacoustic signals and noise in the industrial equipment can save time, effort, and cost compared to alternative techniques that involve taking apart and examining the industrial equipment. In addition, the technology disclosed herein can be implemented using hardware that is external to and remote from the  
15 industrial equipment, which can make installation and maintenance easier compared to existing techniques that may require inserting a “pig” (e.g., an inspection gauge or alternative device) into the inside of the industrial equipment.

The technology disclosed herein can also have advantages in the way that it processes detected vibroacoustic signals within the industrial equipment and/or its noise to generate  
20 actionable information. For example, using the processing techniques disclosed herein, it may be possible not only to identify the existence of a particular condition (e.g., a leak or crack) in the industrial equipment, but also a location of the condition with increased accuracy compared to existing techniques. In some implementations, the processing techniques disclosed herein can also assist with distinguishing between different kinds of conditions to  
25 classify the condition as a particular type of condition (e.g., a leak, a plastic deformation, a fracture, etc.) or even a speed of fault development.

In one aspect, a system for monitoring industrial equipment is featured. The system includes a sensor configured to capture a signal indicative of vibroacoustic vibrations and/or acoustic noise originating from the industrial equipment; and one or more computing devices  
30 including one or more processors. The one or more processors are configured to process an input signal derived from the signal captured by the sensor to identify a condition in the industrial equipment.

Implementations can include the examples described below and herein elsewhere. In some implementations, the one or more sensors can include a fiber optic sensor (FOS)

including a fiber optic light guide, a light source, and a photodetector. In some implementations, the light source can be a laser. In some implementations, the photodetector can be a photodiode. In some implementations, (i) the light source can be configured to output light that is received, at least in part, at the fiber optic light guide, and (ii) the photodetector can be configured to output an electrical signal corresponding to the light that is received at the fiber optic light guide. In some implementations, the electrical signal output by the photodetector can be indicative of the acoustic noise originating from the industrial equipment or vibroacoustic vibrations in the equipment. In some implementations, the fiber optic sensor can further include a pre-amplifier configured to amplify the electrical signal output by the photodetector. In some implementations, the sensor can be disposed at a distance from the industrial equipment. In some implementations, the system can include a converter configured to convert the signal captured by the sensor into a digital electrical signal. In some implementations, the one or more processors can be configured to (i) process the input signal derived from the signal captured by the sensor using a Fourier transform or a fast wavelet converter, and (ii) compare diagnostic indicators derived from the input signal with one or more reference values. In some implementations, the one or more processors can be further configured to identify the condition in the industrial equipment using a machine learning model. In some implementations, the identified condition in the industrial equipment can be a weak point, a plastic deformation, a fracture, a crack, a fistula, a leak, or an abnormal flow in the industrial equipment. In some implementations, the one or more processors can be further configured to estimate a location of the condition in the industrial equipment using a machine learning model. In some implementations, the one or more processors can be further configured to estimate a remaining service life of the industrial equipment using a machine learning model. In some implementations, the industrial equipment can include at least one of a pipeline, a tank, a valve, a seal, a pipe connection, a gland assembly, a gas separator, a filter, a pump, or a compressor. In some implementations, the industrial equipment can be composed, at least in part, from fiberglass and/or glass fiber. In some implementations, the system can include a display in communication with the one or more processors, the display configured to present information about the identified condition.

In another aspect, a method for monitoring industrial equipment is featured. The method includes capturing, by a sensor, a signal indicative of vibroacoustic vibrations in the equipment or acoustic noise originating from the industrial equipment. The method also includes processing an input signal derived from the signal captured by the sensor to identify a condition in the industrial equipment.

Implementations can include the examples described below and herein elsewhere. In some implementations, the sensor can include a fiber optic sensor comprising a fiber optic light guide, a light source, and a photodetector. In some implementations, capturing the signal indicative of the vibroacoustic vibrations or acoustic noise originating from the industrial equipment can include (i) outputting light from the light source; (ii) receiving, at the fiber optic light guide, at least a portion of the light outputted by the light source; and (iii) outputting, via the photodetector, an electrical signal corresponding to the light that is received at the fiber optic light guide. In some implementations, the electrical signal output by the photodetector can be indicative of the vibroacoustic vibrations in the equipment or acoustic noise originating from the industrial equipment. In some implementations, the method can include converting the signal captured by the sensor into a digital electrical signal. In some implementations, the method can include (i) processing the input signal derived from the signal captured by the sensor using a Fourier transform or a fast wavelet converter, and (ii) comparing diagnostic indicators derived from the input signal with one or more reference values. In some implementations, the method can include identifying the condition in the industrial equipment using a machine learning model. In some implementations, the method can include estimating a location of the condition in the industrial equipment using a machine learning model. In some implementations, the method can include estimating a remaining service life of the industrial equipment using a machine learning model.

Other features and advantages of the description will become apparent from the following description, and from the claims. Unless otherwise defined, the technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1, 2A, and 2B are diagrams showing example systems for monitoring industrial equipment.

FIG. 3 is a flowchart of an example process for monitoring industrial equipment.

FIG. 4 is a diagram illustrating an example of a computing environment.

FIGS. 5-13 are diagrams showing various applications of using fiber optic sensors for monitoring industrial equipment.

### DETAILED DESCRIPTION

To create monitoring and predictive diagnostic systems for industrial equipment, this specification describes solutions for designing and connecting sensors; setting up systems for collecting, transmitting and storing data; creating models of normal equipment operation; 5 developing algorithms for data analysis and forecasting; setting reference and threshold values of operational parameters and response rules; developing a system of reports; and displaying data. The general principles of operation of the monitoring and diagnostic systems described herein are as follows: First, data is collected by one or more sensors and transmitted via a communication channel (e.g., wired or wireless channels, Bluetooth, mobile 10 network, satellite, internet, communication lines, fiber optic communication channels, existing power grids, etc.) to a device (e.g., a server), where the data is recorded and stored. The data can also be transferred directly to one or more computing devices (e.g., a personal computer, phones, tablets, other hardware) on which software is installed to process the data. Next, the software processes the data according to predetermined algorithms and displays 15 results indicative of a state of the industrial equipment to an end-user (e.g., on a screen or display of a user device).

In some implementations, vibration signals can have the greatest diagnostic information indicative of the state of industrial equipment, with many other types of signals substantially duplicating the information contained in the vibration signal. Another advantage 20 of using vibration signals is that they enable early detection of defects since defects can begin to develop long before emergencies occur while immediately beginning to affect vibration and acoustic noise. Thus, methods of vibration control and diagnostics are of great interest when building a basic monitoring and diagnostic system. The relevance of these methods is further due to the high sensitivity to changes in the oscillatory properties of industrial 25 equipment under the influence of malfunctions that commonly arise. A significant part of industrial equipment contains rotating parts such as rotors, turbine shafts, bearings and similar mechanisms and parts as main or auxiliary elements. All of them, to one degree or another, are subject to wear and tear, which during the operation of the equipment can cause unwanted vibrations or acoustic vibrations that spread throughout the equipment and into the 30 environment. Some types of vibrations indicate serious malfunctions in the operation of the equipment, for example, the imminent failure of some parts, especially bearings of various types. This can lead to premature failure of the equipment itself, thereby causing damage to a production process.

Vibration is a mechanical fluctuation transmitted through liquid or solid media. Acoustic noise is a closely related phenomenon resulting from vibrations transmitted through mediums such as air. From the point of view of physics, both noise and vibrations are complementary phenomena based on oscillatory processes and are similar in many respects.

5 However, vibrations of mechanical bodies with a frequency of less than 20 Hz are typically perceived by humans as vibration while vibrations with a frequency of more than 20 Hz are perceived as vibration and noise (e.g., sound). Therefore, unless otherwise stated herein, for the purposes of this document, vibroacoustic signals transmitted through industrial equipment are treated as distinct from “noise” signals, which can be perceived at a distance from the

10 industrial equipment. From the standpoint of a system for monitoring and diagnosing industrial equipment, the analysis of frequencies below and above 20Hz can be equally important depending on the application setting.

Industrial noise emitted from industrial equipment, can be considered as a set of many sounds or sound waves of different frequencies and intensity, randomly overlapping each other and chaotically transforming over time. Industrial noise typically results in a large

15 sound field or area of distribution of air oscillatory phenomena. A sound field is an air space in which sound waves propagate. Noise, like any phenomenon, has its own sources that determine its origin or nature. Noise sources should be understood as various phenomena, processes or actions that can cause vibrations of an elastic medium. According to the sources

20 of occurrence, mechanical, aerodynamic, hydrodynamic and electromagnetic noise can be distinguished. Noise of mechanical origin includes noise arising from vibration of the surfaces of machines and equipment, as well as single or periodic impacts in the joints of parts, assembly units or structures of the machines and equipment. Noise of aerodynamic origin includes noise arising because of stationary or non-stationary processes in gases (e.g.,

25 outflow of compressed air or gas from openings, pulsation of pressure during the movement of air or gas flows in pipes or during the movement of bodies in the air at high speeds, combustion of liquid and atomized fuel in nozzles, etc.). Noise of hydrodynamic origin includes noise arising because of stationary and non-stationary processes in liquids (e.g., hydraulic shocks, flow turbulence, cavitation, etc.) Noise of electromagnetic origin includes

30 noise arising from vibrations of elements of electromechanical devices under the influence of alternating magnetic forces (e.g., oscillations of the stator and rotor of electrical machines, the core of a transformer, etc.). Industrial noise is typically heterogeneous in composition due to various sources that form the noise regime in the working area. Therefore, it is referred to sometimes herein as “general noise.” General noise includes noise in a certain situation at a

certain time and in a certain place, usually consisting of noise from various sources, both far and close. At the same time, noise sources can be both external and/or internal. External noise sources are noise sources located outside a specified area (e.g., a building, a territory, etc.).

Usually, power plants, machines and mechanisms are simultaneously a source of  
5 noise of several types. Noise is transmitted to the environment in the form of vibrations of the external surfaces of the equipment. The most intense components of the noise spectrum are often in the low and medium frequencies and are multiples of a crankshaft speed and/or a number of cylinders of the industrial equipment. Oscillations of equipment parts often occur either with the frequency of the forcing force or with natural frequency (with a short-term  
10 effect of the force). Therefore, the mechanical noise spectrum often contains less intense components of natural oscillations in the range of medium and high frequencies. In contrast, due to the periodicity of processes (e.g., in pipelines and cylinders), gas-dynamic noise often has components of pressure fluctuations in the range of low and medium frequencies and high-frequency components of vortex origin (e.g., in gas distribution organs, in the flow parts  
15 of superchargers and turbines, etc.).

Dynamic loads in equipment components can cause the appearance and propagation of acoustic waves, both in the equipment itself and in the environment. Thus, the vibration parameters depend on the spectrum and intensity of the excitation forces and the properties of the vibroacoustic channel located between the vibration source and the point of information  
20 acquisition. The causes of malfunctions in industrial equipment are often initially associated with a change in the nature of the acting loads, which then lead to the appearance of a defect that changes the intrinsic properties of the system (e.g., the characteristics of the vibroacoustic channel). Consequently, in some cases, it can be possible to detect and prevent the development of defects earlier by vibroacoustic diagnostics methods in comparison with  
25 other methods. At the same time, the tasks of vibration diagnostics are complex, since the number of vibration sources in industrial equipment can be large, and vibrations can arrive at the point of vibroacoustic sensing in many ways.

One scheme of diagnostics is based on the measurement of acoustic noise emitted by equipment, as well as pulsations of velocity and pressure in the flow of liquid and gas,  
30 vibration of the equipment body, oscillations of impeller blades and other critical elements of rotors of turbine machines. One method is the acoustic emission method and is based on the registration of stress waves that occur when defects such as cracks or plastic deformation appear in the structure of the equipment. The relevant frequencies for this method typically

lie in the range of more than 100 kHz. The method is highly sensitive and is used to detect cracks and deformations at the initial/early stages of their development.

As noted above, the complexity of vibroacoustic control is primarily due to the vibration parameters and depends on the spectrum and intensity of the excitatory forces and properties of the vibroacoustic channel located between the vibration source and the point of information acquisition. At the same time, the number of vibration sources in the equipment can be large, and vibrations can arrive at the point of sensing vibroacoustic information in many ways. In this regard, there is doubt about the effectiveness of using point sensors for vibration diagnostics.

Also noted above, industrial equipment is subject to wear and tear, which during the operation of the equipment can cause unwanted vibrations or acoustic vibrations that spread throughout the equipment and into the environment. Some types of vibrations indicate serious malfunctions in the operation of the equipment, for example, the imminent failure of some parts, especially bearings of various types. This can lead to premature failure of the equipment itself, thereby causing damage to the production process. Vibroacoustic and noise analyses make it possible to detect a malfunction at an early stage of its development. In addition, the parameters of other processes can be controlled and monitored, but to diagnose units with sufficient accuracy to predict their condition, it can be helpful to carry out an in-depth analysis of their vibroacoustic signals and acoustic noise emitted by the equipment.

Technical means of vibroacoustic diagnostics can be portable, mobile or stationary means of monitoring/diagnosing of equipment condition, and the techniques described herein can include advanced capabilities for analyzing vibration and noise signals occurring in the industrial equipment of interest. In general, the software of a vibroacoustic diagnostic system can include three main systems: (1) a vibroacoustic analysis program, which is an accessory of a basic vibroacoustic analyzer, (2) a condition monitoring program, which is part of a condition monitoring system, and (3) a diagnostics program. The basis of the diagnostic program can be a set of diagnostic modules for each type of monitored equipment.

In some implementations, the systems for measuring vibroacoustic signals and/or noise can be portable or portative. Such systems can include one measuring channel and collect short durations of diagnostic measurements with large intervals between measurements of the vibroacoustic signal and/or noise of the industrial equipment of interest. Such systems can then use those measurements to (1) detect typical defects at the stage of nucleation according to the characteristic parameters of the vibroacoustic signal and noise, (2) forecast the fault-free operation of the monitored equipment, and/or (3) observe the

defect's development (e.g., "defect monitoring") up until a state is reached that warrants repair or maintenance.

One advantage of a portable system is the ability to use several independent features of multiple incipient defects in parallel. For example, the portable system can enable analysis of the spectral composition of the periodic components of the vibroacoustic signal and noise as well as the analysis of the shape of its random components of impact origin. Such an analysis makes it possible to detect defects already at the stage of nucleation by high-frequency vibration, which manifests itself on the body of the defective equipment unit, and in this way, carry out node-by-node diagnostics. Using group statistical models, it is possible to determine thresholds for the initiation of defects and use these thresholds to predict the initiation of defects for a group of similar aggregates from single measurements of the vibroacoustic signal and noise. In some cases, portable monitoring/diagnostic systems can be used both in an automated version (e.g., based on established thresholds) and in a manual version (e.g., when initially setting up the equipment).

In some cases, portable monitoring/diagnostic systems can be implemented in the form of multi-channel systems for parallel monitoring of vibroacoustic signal and/or noise. A multi-channel system can be organized through the parallel operation of several devices with individual analog-to-digital converters (ADCs), or with the parallel operation of fiber optic sensors (FOSs) with a multi-channel ADC. It is possible to multiplex just the sensitive elements of a FOS or the FOS as a whole (e.g., the sensitive element of the FOS and the electronic unit of the FOS—described in further detail below). The accumulation of periodic measurements of the vibroacoustic signal and/or noise allows for both frequency and time domain analysis as well as analysis of monotonous and/or spasmodic changes to predict the behavior of controlled vibration parameters of the equipment of interest.

In one implementation of the diagnostics system, a broadband signal with a small number of frequency bands is recorded, the analysis of which does not require complex diagnostic algorithms. Thus, the digitized broadband signal is able to be analyzed on site, including, e.g., determining a mean square, PIR, PEAK, high-frequency vibration factor, and other characteristics that do not require complex calculation and analysis algorithms. The original digitized broadband signal and on-site analysis results are then sent via a communication channel or wirelessly to a computing device (e.g., a central server in the cloud) for deeper diagnosis. Further, the broadband signal is divided into narrow bands by sliding window or defect masking (defect signatures) techniques in the controlled frequency range and analyzed by a diagnostics module of the system.

The portable systems described herein enable the tracking of changes in the power of individual components of the vibroacoustic signal and/or noise over time. The output data of the portable system (e.g., in the form of an assessment of the condition, a rate of change and, in the presence of dangerous changes, an assessment of the residual life of the units) can be transmitted to users online via the Internet. The control signals of various devices generated by the monitoring program can be transmitted through the same network or via a different communication channel. The system can be operated in a completely autonomous version and can be used to monitor the status of remote and unattended units. Monitoring of the state of equipment units by vibroacoustic signal and/or noise can be primarily focused on tracking the power of individual components over time (e.g., periodic, random and impulse components), a noticeable change in which is a sign of the appearance of a developed defect. In some cases, diagnosis of developed defects can be based solely on the measurement history of a particular equipment unit. However, for early detection of defects, more sophisticated analysis of vibration signals can be performed such as diagnosing defects based on thresholds obtained during statistical processing of the results of similar measurements of a large group of similar equipment units. Such “group diagnostic” techniques for diagnosing incipient defects in equipment can be carried out either once or periodically. Diagnosis of incipient defects can be advantageously carried out by portable system implementations that enable simultaneous analysis of a large group of similar (or identical) equipment units.

The portable system implementations described herein can divide vibration signals into periodic (or “batch”), random, and impulse components, as well as subsequent analysis of their fine structure. Wideband-narrowband signal analysis can be used to divide a vibration signal into components, narrowband spectral analysis can be used to analyze the periodic components of the signal, narrowband spectral analysis of the envelope can be used to analyze the selected modulated random components, and shape analysis (as a function of time) of the signal’s power (envelope) can be used to analyze pulse components. Diagnostic software provides automation of the main processes of defect detection, including the processing of spectra containing a large number of narrow-band components, the search for diagnostic signs of defects, the determination of the type of defect and the formation of thresholds for determining the degree of danger of each defect. The diagnostic software also provides “group diagnostics” capabilities, making it possible, for example, to combine equipment units and their components into groups of similar (or identical) diagnostic objects. The output data of the diagnostic software includes the type and magnitude of the most

probable defects detected in a monitored equipment unit compared to typical units of that type.

In some implementations, to reduce cost, a monitoring and diagnostic system can be implemented with permanently standing sensing elements on the equipment unit of interest and with other portable elements configured to take diagnostic information. This can allow the use of multi-channel means of parallel signal acquisition. The system can enable diagnosis of both individual components and the unit, and, if necessary, for a group of units, to detect faults.

In some implementations, the systems for measuring vibroacoustic signals and/or noise can be stationary. Stationary systems can provide continuous condition monitoring and on-line diagnostics of equipment. For example, for critical equipment units, it may be desirable to install stationary monitoring systems for continuous condition monitoring and/or for online diagnostics of these units. Monitoring equipment condition with stationary systems can involve continuous real-time measurements of vibroacoustic signals and/or noise, and diagnostics are performed upon recording changes in the condition periodically, at short intervals. Algorithms and thresholds for monitoring and diagnostics in such a system change when the operating mode of the monitored object changes. All measurements and analysis of measurement results can be carried out in parallel such that the number of measuring channels of the stationary system is equal to the number of control points used for process diagnostics. The stationary systems described in this document can provide solutions to a range of diagnostic tasks including: (1) controlling a current state of equipment in all modes of operation, (2) providing an emergency alarm indicating the cause of a dangerous condition related to the equipment, (3) detecting and monitoring of a dangerous defects' development, (4) forecasting a residual life of a monitored object, and (5) assessing the overloading consequences of equipment during operation. These stationary systems can operate completely autonomously, without human intervention, including providing automatic adaptation of equipment state thresholds as measurement data accumulates. With a large number of periodic measurement results, the stationary monitoring and diagnostics systems described in this document can analyze the trends of monitored parameters. The software of the condition monitoring and operational diagnostic system can include a data exchange module with a vibroacoustic signal analyzer and/or a noise analyzer, a condition monitoring module optimized for different defect rates, diagnostic modules, a database, as well as various applications, working in the information network.

Stationary systems for monitoring and diagnosing equipment can have various advantages. For example, they can provide the ability to predict the residual life of the unit after the appearance of dangerous defects. They can also provide parallel diagnostics of defects having different rates of development with optimization of thresholds for the speed of development of different defect types. Furthermore, stationary systems for monitoring and diagnosing equipment can detect control errors leading to an equipment's overloading and can assess the consequences of running overloaded equipment (e.g., by analyzing trends in parameters that changed during overloading).

In some implementations, the systems for measuring vibroacoustic signals and/or noise can be mobile. Mobile systems occupy an intermediate niche between portable and stationary systems for monitoring/diagnosis of equipment condition. Mobile systems can be equipped with diagnostic programs depending on the application setting, and they can be used to perform tasks including (1) monitoring and analysis of vibroacoustic signals and/or noise during equipment start-up; (2) monitoring of vibroacoustic signals and/or noise on stands and/or at the site of operation after manufacture, repair, installation or routine maintenance of equipment; (3) monitoring the condition and diagnostic of equipment units during testing and running-in; and (4) inspecting an equipment unit to identify the causes of increased vibration. Mobile systems for monitoring/diagnosing equipment can advantageously be used to continuously analyze vibrations online over a long period of time.

In general, a challenge of implementing systems for monitoring/diagnosing equipment is the construction of threshold values for defect detection. In the initial period of equipment observation, before the detection of incipient defects, thresholds can be determined by measuring the vibroacoustic signal and/or noise of a group of similar (or identical) equipment units in ideal operating modes. After detecting a defect, thresholds are determined according to the history of measurements on this type of equipment. Usually, the first signs of an incipient change in the state of an operating object are manifested in high-frequency noise and vibration. For this reason, broadband noise measurement can be particularly useful for condition monitoring. Since a large number of components from different objects are mixed in high-frequency noise, it can also be advantageous to conduct a narrowband analysis of the broadband spectrum using modern methods of analysis to separate them. Furthermore, it can be beneficial to measure not only the power (level) of noise, but also fluctuations, including modulation, jumps, and monotonous changes. The analysis of the vibration/noise signals can include time domain analysis, frequency domain analysis, and/or spatial analysis, as well as both deterministic and statistical methods.

The energy of the vibroacoustic signal and the energy of the emitted structural noise transmitted from it to the external environment depend not on the vibration displacement at the control point, but on the rate of its change (e.g., the “vibration velocity”). Important parameters determined when measuring vibration velocity include mean square and reduced peak, and vibration displacement mean square and reduced span. Using these parameters (among other parameters described in this document), the equipment monitoring and diagnosis systems described herein can detect defects in a controlled machine or equipment, identify the type of each defect, determine a degree of development of each defect, provide a list of diagnostic signs of each defect, determine the date of the next measurement of the vibroacoustic signal/noise, and/or provide recommendations on any subsequent actions to be taken (e.g., repair or maintenance actions).

In general, the various systems described herein can use special analysis methods and software for predictive diagnostics of equipment such as predicting malfunctions based on collected data (e.g., vibration/noise data). The software can also be designed for cloud implementations, allowing the connection of multiple physical devices and sensors to the digital information space. In some implementations, the systems described herein can include a cloud platform/hardware with highly efficient data storage, various applications, and infrastructure for connecting sensors and collecting and analyzing data. The cloud platform/hardware can thus bring together multiple services and interfaces needed to run infrastructure and applications. For example, the system based on the cloud platform/hardware can include all the necessary tools for building predictive diagnostic systems such as a service package with a set of algorithms and libraries for creating predictive models using deep machine learning methods, neural networks, mathematical models, etc. Ready-to-use analytical modules within the cloud platform/hardware can be quickly configured and connected to industrial data sources storing data about the operation of industrial equipment. Applications within the cloud platform/hardware can provide the necessary tools for data analysis, such as signal analysis, trend prediction, anomaly detection, etc., and provide a variety of algorithms and application libraries with open programming interfaces. Some or all of the applications and interfaces within the cloud platform/hardware can be separate software modules that process data and scale independently of the rest of the system.

For the systems described herein, the infrastructure for data collection can contain software and hardware solutions that connect various sources of information to the cloud platform/hardware using different types of protocols based on the specifics of use. For

example, sensors associated with industrial equipment being monitored/diagnosed can create large data streams and signals. Analysis of these signals can enable one to control and predict the operation of the equipment, e.g., by comparing the real-time data of the equipment with models of normal operation of the equipment to identify anomalies and deviations.

5           In some implementations, transferring all raw data to the cloud platform/hardware can be inefficient in terms of bandwidth and central server load. Thus, to solve the problems of signal processing and streaming data, the systems described herein can include additional tools for monitoring and analyzing the equipment state at the production site where the sensors are installed. These tools can include subsystems with libraries and signal analysis  
10   tools having the capabilities of spectral and vibration analysis of signals, dynamic correlation of data streams, anomaly search, trend detection, etc. The pre-processed and compressed data can then be transferred to the cloud platform/hardware for subsequent detailed analysis, considering the diagnostics of the entire equipment and its operating history. Various tools can help identify anomalous system behavior or damage to mechanisms at an early stage  
15   through in-depth analysis and real-time monitoring of equipment performance. This enables optimization of production processes and can reduce maintenance costs through condition forecasts and planned shutdowns.

          The technical condition of the equipment being monitored/diagnosed (and the individual elements of such equipment) can be determined by recording certain operational  
20   parameters including rotation speed, vibration value, noise, temperature, pressure, etc. However, it is to be understood that the most relevant parameters to record may vary for different types of equipment. For automated diagnostics, it is often desirable to know and constantly record these indicators in real-time using one or more sensors to identify potential problems and inform subsequent maintenance of the equipment. For example, monitoring the  
25   technical condition parameters of rotating equipment (e.g., fans or turbines) can be desirable at all stages of the equipment's life cycle, from the early stages of design and manufacture to the later stages of operation and repair.

          At present, there are many different types of measuring systems and complex processing methods without any single universal monitoring or diagnostic system for  
30   different types of equipment and/or defects. More and more complex automation technologies are being developed that do not consider the optimization of physical control procedures. At the same time, specific systems are being created for various tasks, designs and control and measurement systems. To address these problems, the present document describes widely applicable monitoring and diagnostics systems that can measure and analyze

the main parameters responsible for the most common equipment defects and causes of accidents. Moreover, the systems described herein are easily able to be expanded and improved upon with the appearance and/or discovery of new equipment, new controlled parameters, new tasks, and new methods of controlling and measuring equipment based on other physical principles. For example, as innovative parameter processing methods continue to be developed, the space of informative features for the operation of classifiers (e.g., support vector machines, neural networks, etc.) will continue to grow such that the monitoring and diagnostic capabilities of the systems described herein will continue to improve.

In general, the systems of monitoring and diagnosing the condition of industrial equipment that are described in this document can be designed to satisfy certain technical specifications. These specifications include the ability to measure vibroacoustic signals and/or noise; determine vibration velocity and vibration acceleration in standard frequency bands (e.g., 2-1000 Hz, 10-1000 Hz, 10-2000 Hz, etc.), and detect/forecast an equipment's state using trends characterizing the equipment's change over time. The technical specifications can also include measuring the third-octave vibration spectrum in the bands of 2-10,000 Hz or 10-10,000 Hz for monitoring the condition and partial identification of malfunctions of mechanical and electromechanical units. The technical specifications can also include measuring the mean square and peak values of ultrasonic vibration in the frequency band of 15-25 kHz for lubrication control in friction elements (or in the frequency band of 6-10 kHz for low-speed equipment). The technical specifications can also include determining a rotational speed of the equipment and mechanisms for the selection of appropriate thresholds of warning or hazard conditions; comparing measurement results with determined thresholds; and carrying out measurements that are stored in an external database. In some implementations, the systems described herein can be implemented to work with or without an external monitoring program that enables preparation of equipment configuration, reception of measurement data, automated construction of thresholds, storage of measurement data and their output for graphical analysis, graphical data analysis with automatic trend generation, automatic indication of missed and erroneous measurements, and preparation of reports.

Referring to FIG. 1, an example monitoring and diagnostic system 100 for industrial equipment is shown. In particular, industrial equipment 102 (sometimes referred to as "controlled equipment" or simply "equipment") is depicted and can be monitored using the system 100. In oil and gas settings, the industrial equipment 102 can include valves and seals

of gas pipelines, pipe connections (e.g., flanged pipe connections), gland assemblies, blowdown pipes, shut off valves, purging lines, pumps, compressors, filters, fans, and pressure vessels (e.g., gas separators, filters, etc.). However, in other settings, the industrial equipment 102 can include mechanisms and machinery (e.g., hydraulic drives, gearboxes, pumps, compressors, fans, and drive motors, etc.), gas and liquid pipelines, pressure system housings, steam generators, gas and hydro supply systems, vessels, heat exchangers, automation and control system equipment, power supply equipment (e.g., transformers, switching equipment, etc.), and more. The techniques described herein are not limited to industrial equipment of any particular material and can be applied to industrial equipment composed of materials including metal, plastic, glass, fiberglass, glass fiber, etc.

The industrial equipment 102 can be monitored using an acoustic sensor 104 that is configured to capture acoustic signals originating from the industrial equipment 102. The acoustic sensor 104 can be disposed remotely from the industrial equipment 102 such that it is not in contact with the industrial equipment 102 and captures noise originating from the industrial equipment 102. However, in some implementations, the acoustic sensor can be positioned in proximity to the industrial equipment 102 and can be strategically positioned at selected measurement points that are of particular interest for monitoring (e.g., near a component that is known to be prone to failure). The positioning of the acoustic sensor 104 (and other acoustic sensors) can be determined and optimized experimentally depending on the characteristics of the acoustic sensor 104 and the noise level of acoustic noise emanating from various units and/or portions of the industrial equipment 102 (e.g., to avoid saturation of the captured signal and to maximize sensitivity of the acoustic sensor 104). Importantly, the acoustic sensor 104 should be installed such that acoustic signals originating from the industrial equipment 102 can be measured. In some implementations, the acoustic sensor 104 can have high enough sensitivity to detect noises in the industrial equipment originating from up to a few kilometers away from the sensor 104 (e.g., less than 1 km away, 1 km away, 2 km away, 3 km away, 4 km away, etc.). This high sensitivity can mitigate the need for utilizing multiple acoustic sensors depending on the use case.

It is important to note that while FIG. 1 depicts the sensor 104 at distance from the industrial equipment 102, in some implementations, the sensor 104 (or a sensitive element of the sensor 104) can be in physical contact (e.g., disposed on, wound around, etc.) the industrial equipment 102. Such implementations can be particularly useful for capturing vibroacoustic signals or acoustic emission pulses transmitted through the industrial equipment 102 that may not emit any audible noise signals into the environment for remote

sensing. Example applications where such implementations can be advantageous are described below in relation to FIGS. 5-13.

If a defect 106 (or alternatively, a fault, a deviation from normal operating conditions, an undesirable condition, etc.) becomes present in the industrial equipment 102, then noise signals emitted by the defect 106 (or from the location of abnormal operating conditions) are transmitted to the equipment's housing structures and radiated into the control zone 180 (e.g., through air, water, through the ground, etc.). Examples of defects, faults, and/or other undesirable conditions include plastic deformation, fractures, cracks, fistulas, leaks, or abnormal flows in the industrial equipment 102 as well as other defects described in this document.

The acoustic sensor 104 is configured to capture a signal indicative of acoustic noise originating from the industrial equipment 102 (and in particular, from the defect 106). The acoustic sensor is connected (e.g., via a cable connection) to a converter 108 that converts the acoustic energy captured by the acoustic sensor 104 into electrical energy. In some cases, the converter 108 can be considered part of the acoustic sensor 104 itself. The electrical energy output by the converter 108 is still indicative of the acoustic noise originating from the industrial equipment 102 and is typically an analog signal. The analog signal is then passed on (e.g., via a cable connection) to a data collection and processing recorder 120. The data collection and processing recorder 120 includes one or more analog-to-digital converters (ADC(s)) 122 that convert the analog signal to a digital electrical signal, and one or more microcontroller(s) 124. The microcontroller(s) 124 are computing device with one or more processors (such as the computing devices described in relation to FIG. 4 below) and can be configured to process the digital electrical signal output by the ADC(s) 122 to perform a spectral analysis and obtain spectral characteristics of the signal. In some implementations, the one or more ADC(s) 122 and the one or more microcontroller(s) 124 of the data collection and processing recorder 120 can be daisy-chained together. The spectral characteristics of the converted digital electrical signal are preliminarily compared with reference and threshold values (e.g., stored in the knowledge base 126, described below), and the characteristics are sent to a server 130 (e.g., a server of the cloud platform described above) for (i) storage in the knowledge base 126 and (ii) further processing by the decision-making block 128 using one or more Fourier transforms, Wavelett transforms, Hilbert transforms, other digital signal processing techniques, machine learning approaches (e.g., neural networks), fuzzy logic algorithms, and/or other methods to make control decisions, as described in further detail below. In some cases, the decision-making block 128 can be

implemented to include the diagnostic software, analytic modules, and/or other software modules described elsewhere in this document. The acoustic sensor 104, the converter 108, and the data collection and processing recorder 120 can be jointly referred to (sometimes in conjunction with other components such as rechargeable batteries) as a sensing device. In some implementations, the components of the sensing device can be included together in a single housing. In other implementations, however, at least some of the components of the sensing device can be located remotely from one another.

In the example shown in FIG. 1, the server 130 is a remote server that can communicate with the data collection and processing recorder 120 over a cable connection or over a wireless connection. The server 130 can be a computing device such as those described in relation to FIG. 4 below. However, in some implementations, the server 130 may not be a single computing device but may instead correspond to multiple computing devices (e.g., multiple servers) within a cloud computing system such as the cloud platform/hardware described above. The server 130 includes a knowledge base 126 and a decision-making block 128. The knowledge base 126 stores information about the industrial equipment 102 such as a structural diagram of a diagnostic object of the industrial equipment 102, an identification of which components of the industrial equipment 102 are most often subjected to breakdown, information about instability due to sensitivity to the environment and defects, etc. In many cases, different components or units of the industrial equipment 102 can have their own set of frequencies at which particular defects are manifested. Information about these frequencies can be stored in the knowledge base 126 as well. In the implementations described herein, each type of defect is treated as corresponding to one of a limited set of groups available in a noise spectrum, with different types of defects corresponding to different groups. Analysis of the different types of defects allows the development of a diagnostic model of the industrial equipment 102 in the form of fault function tables, which can be used to identify particular kinds of defects and determine their speed of fault development (which can in turn allow for comprehensive automated control of the technical condition of the industrial equipment 102). In some implementations, the knowledge base 126 can be populated with the foregoing information through experimentation conducted prior to monitoring the industrial equipment 102 in a real-world setting. However, in some implementations, the knowledge base 126 can continue to be developed and added to as measurements are collected in real-time by the system 100.

Due to the peculiarities of noise-like signals from the industrial equipment (e.g., a significant periodic low-frequency component and high level of random noise), it can

sometimes be impractical to analyze captured signals in the time domain to identify and localize defects. It can also be difficult to isolate a useful signal by linear filtration procedures, as the signal is correlated with a periodic component. For these reasons, in some implementations, the main input parameter for noise diagnosis can be the frequency spectrum of the captured acoustic signals (e.g., after converting them into digitized electrical signals). In some implementations, the entire spectrum of noise can be used for analysis without the use of a noise filter. The frequency spectrum of the signals can be obtained using a Fourier transform (e.g., using the fast Fourier transform method) or a wavelet transform (e.g., using a fast wavelet converter). Both approaches can be implemented, in some cases, using the microcontroller(s) 124. Spectral analysis (e.g., as performed by the microcontroller(s) 124) is then based on the identification of the most characteristic and sensitive areas of signal frequencies in the frequency spectrum. To analyze the resulting noise spectrum, it is important to know which fluctuations and frequencies correspond to defects, information about which can be stored in the knowledge base 126. This further motivates the development of the knowledge base 126, as described above. The key characteristics for assessing the industrial equipment 102 are the frequency and amplitude of the signal, since the presence of a particular frequency component in the spectrum can be indicative of the occurrence of a corresponding defect, and the amplitude can be indicative of the location of the defect. Identification of increased signal amplitudes at frequencies that coincide with the frequencies of possible damage in the industrial equipment 102 or resonant frequencies of the industrial equipment 102 can thus help to detect and identify emerging defects and forecast/monitor their development in the industrial equipment 102. In addition, in some implementations, the condition of the industrial equipment 102 can be considered unsatisfactory when the number of harmonics increases and the amplitude of oscillations in the spectrum increases. In summary, by comparing diagnostic indicators (e.g., frequencies and amplitudes) from the frequency spectrum of the captured acoustic noise signals with one or more reference values (e.g., reference values stored in the knowledge base 126), it is possible to identify defects, faults, and/or other undesirable conditions in the industrial equipment 102.

As mentioned above, the spectral characteristics determined by the microcontroller(s) 124 can be sent to the server 130 for further processing by the decision-making block 128. The decision-making block 128 can include one or more machine learning models (e.g., neural networks), fuzzy logic algorithms, and/or other methods that make control decisions. The one or more machine learning models can be trained on previously captured or simulated

acoustic signals. Such training data can be labeled with useful information for supervised learning techniques such as whether or not the training example corresponds to the existence of a condition in the industrial equipment, a location of any conditions in the industrial equipment, and/or a type of the condition(s). Thus, the one or more machine learning models  
5 can be trained to identify conditions in the industrial equipment 102, localize the conditions, and/or classify the conditions based on a captured acoustic signal. In some implementations, the one or more machine learning models can employ one or more techniques including decision trees, linear regression, neural networks, multinomial logistic regression, Naive Bayes (NB), trained Gaussian NB, NB with dynamic time warping, multiple linear  
10 regression, Shannon entropy, support vector machine (SVM), one versus one support vector machine, k-means clustering, Q-learning, temporal difference (TD), neural networks, deep adversarial networks, and the like. In some implementations, the machine learning models can be implemented using an active learning approach such that operational data generated from the industrial equipment 102 is continually fed back to the machine learning models to  
15 further train the machine learning models. Through this process, the machine learning models can continually improve in performance by collecting additional training data from the industrial equipment 102 that the machine learning models are intended to help monitor. In some implementations, the decision-making block 128 can analyze and process the spectral characteristics received from the microcontroller(s) 124 to identify a defect 106 in the  
20 industrial equipment 102 as a particular type of defect, estimate a location of the defect 106 in the industrial equipment 102, estimate a speed of fault development, and/or estimate a remaining service life of the industrial equipment 102. Based on this information, the decision-making block 128 can also automatically make decisions such as when and how to replace and/or repair particular units or components of the industrial equipment 102. In some  
25 implementations, the decision-making block 128 can be integrated with one or more production asset management systems (e.g., computerized maintenance management systems (CMMS), manufacturing execution systems (MES), enterprise resource planning (ERP) systems, etc.).

In some implementations, the decision-making block 128 can also utilize algorithms  
30 that determine the technical condition of industrial equipment based on kinematic schemes and parametric models referred to as “digital twins.” For example, a digital twin can be a virtual model of industrial equipment representing how the equipment operates under “normal” or “good” conditions and can be parameterized by real data. In some implementations, the decision-making block 128 can compare real-time data with digital twin

data representing “normal” operation of the equipment in order to analyze the state of the equipment. Such approaches can be particularly useful for monitoring or diagnosing dynamic equipment such as pumps, compressors, ventilators, wind turbines, etc.

As shown in FIG. 1, the data collection and processing recorder 120 is also connected  
5 to a computing device 150 (e.g., a laptop or personal computer), which can include a display 140 and is connected to a flash memory 160. The connection can be a wired cable connection or a wireless connection. In some cases, the display 140 can be part of the computing device 150 itself. In other cases, the display 140 can be a separate device in communication with the computing device 150. In some implementations, the computing device 150 can be an  
10 example of the computing devices described in relation to FIG. 4 below. The display 140 can be configured to present information about any identified conditions in the industrial equipment 102. For example, the display 140 can present a visual representation of the frequency spectrum produced by the microcontroller(s) 124, an indicator identifying whether or not a condition exists in the industrial equipment 102, an indicator identifying a location of  
15 any identified condition(s) in the industrial equipment 102, an indicator identifying a classified type of any identified condition(s) in the industrial equipment 102, and/or an estimated remaining service life of the industrial equipment 102. In some implementations, the displayed information can be presented with probabilistic information including estimates representing a level of confidence associated with the displayed information. In some  
20 implementations, the display 140 can be configured to present information about a recommendation for repairing or replacing a unit or component of the industrial equipment 102. In this manner, the computing device 150 can serve as a user interface that allows a human to review the outputs of the monitoring and diagnostic system 100. The computing device 150 can also serve as a user interface that allows a human to control the operations of  
25 the monitoring and diagnostic system 100.

Referring now to FIGS. 2A-2B, additional example systems 200A, 200B for monitoring industrial equipment is shown. The systems 200A, 200B depicted in FIGS. 2A-2B share many similar features to the system 100 depicted in FIG. 1, and like components are labeled with like reference numerals. However, where FIG. 1 includes a generic sensor 104  
30 connected to a converter 108, FIGS. 2A-2B depict particular embodiments that include a fiber optic sensor (FOS) that converts noise signals (in FIG. 2A) and vibroacoustic signals (in FIG. 2B) into electrical signals (e.g., using fiber optic interferometry). In both examples, the fiber optic sensor includes a sensing element 204, an electronic control unit 208, and a data collection and processing recorder 120.

In FIG. 2A, the sensing element 204 of the fiber optic sensor is positioned nearby (but not in direct contact) with the monitored industrial equipment 102 and is configured to record noise signals originated from the industrial equipment 102. In such cases, the fiber optic sensor can be referred to as a “microphone” since it is able to detect noise signals. Example applications where such implementations can be advantageous are described below in relation to FIGS. 5-13.

In FIG. 2B, the sensing element 204 of the fiber optic sensor is positioned on the surface of the industrial equipment 102 (e.g., disposed on the equipment, wound around the equipment, etc.) and is configured to record vibroacoustic signals transmitted through the industrial equipment 102. Such implementations can be particularly useful for capturing vibroacoustic signals or acoustic emission pulses transmitted through the industrial equipment 102 that may not emit any audible noise signals into the environment for remote sensing. Example applications where such implementations can be advantageous are described below in relation to FIGS. 5-13.

Referring to both FIG. 2A and FIG. 2B, the sensing element 204 can have a wide variety of designs. However, in one embodiment the sensing element 204 can be a multi-turn loop or coil (e.g., a body made of different material with a fiber light guide wound on it), and with no electrical elements included in the coil. In some cases, the sensing element 204 can be implemented using an isotropic single-mode fiber (a fiber that is widely used in communication systems) as the fiber light guide. The attenuation coefficient in such a fiber is approximately 0.1-0.2 dB per kilometer, and the sensitivity of the sensing element 204 can be increased by increasing the total length of the fiber, for example up to 100km. These properties can allow for highly sensitive and accurate measurements as well as remote control without the use of additional signal conversion and/or amplification devices. Depending on the implementation, the sensing element can be either framed or frameless, and it may be either coated or uncoated. In framed implementations, the frame can be the object of inspection itself (e.g., the industrial equipment of interest), on which the optical is wound.

In some implementations, the sensing element 204 of the fiber optic sensor does not require a power supply because it includes only a coil and optical fiber, and because the sensor signal is light radiation that is transmitted through the optical fiber. The sensing element 204 can also have high protection against external electromagnetic influences due to the dielectric nature of the fiber.

The electronic control unit 208 includes a laser 210 (powered by a laser driver), a photodiode 214 (or other photodetector), and an analog signal preamplifier 216. In some

implementations, however, the electronic unit can include one or more other components including photodiodes, splitters, polarizers, modulators, lasers (e.g., laser diodes or super-luminescent lasers), etc. In some implementations, the electronic components of the electronic control unit can be powered, for example, using a battery source such as

5 rechargeable batteries. While it is possible, in some implementations, for the separate components of the electronic control unit 208 to be positioned remotely from one another (e.g., as distinct devices), they can sometimes be grouped together into a single unit, as shown in FIGS. 2A-2B. The acoustic sensor 104, the converter 108, and the data collection and processing recorder 120 can be jointly referred to (sometimes in conjunction with other

10 components such as rechargeable batteries) as a fiber optic sensor. In some implementations, the components of the fiber optic sensor can be included together in a single housing. In other implementations, however, at least some of the components of the sensing device can be located remotely from one another. For example, in some implementations, the electronic control unit 208 can be disposed remotely from the sensing element 204 (e.g., 1 km away, 10

15 km away, 50 km away, greater than 50 km away, up to 100km away, etc.), and light that is collected by the sensing element 204 can be guided to the electronic control unit 208 through the use of a fiber optic cable without the need for amplification. The fiber optic cable can be a single-mode fiber optic cable with a length of up to 100km.

The electronic control unit 208 is able to (i) transmit optical signals (e.g., light output

20 by the laser 210) to the sensing element 204 and then (ii) receive, at the photodiode 214, optical signals indicative of the light received at the sensing element 204. The photodiode 214 receives the optical signals (e.g., via a fiber optic cable) and converts the optical signals into electrical signals. The preamplifier 216 can then amplify the electrical output from the photodiode 214 to produce an electronic signal output of the electronic control unit 208 that

25 can be subjected to further processing. In some cases, the preamplifier 216 may not be necessary, and in some implementations, additional processing steps may be included before and after amplification by the preamplifier 216.

The fiber optic sensor shown in FIGS. 2A-2B can have several additional advantages compared to other acoustic sensors. For example, the fiber optic sensor can be immune to

30 electromagnetic fields and interference (e.g., interference from electromagnetic disturbances, lightning discharges, proximity to a power line, current pulses in the power network, etc.) and can also be immune to fire and explosion hazards due to the absence of electric currents. The fiber optic sensor can also have higher sensitivity to sound and/or vibrations (e.g., depending on the wavelength and a power of the associated light source (e.g., laser 210), a shape and

area of the sensing element 204, and a length of the fiber-optic cable), create lower signal distortion, be resistant to radiation, and be resistant to harsh climatic conditions (e.g., 100% humidity) and aggressive chemical environments. For example, in various implementations, the sensing element 204 can be disposed (and function) in air, in water, in the ground, in concrete, on the ground, on the surface of equipment and structures, in electrical cables, and/or in aggressive environments. The fiber optic sensor can also reduce the need for electrical power, grounding, and galvanic isolation since the sensing element 204 is free of electrically conductive elements. The fiber optic sensor can also be located at a long distance (e.g., tens of kilometers) from the industrial equipment 102 being monitored. The fiber optic sensor can also enable the connection of many sensors in series in a single chain. The fiber optic sensor is also not a source of radio waves. The sensing element 204 of the fiber optic sensor is also free of feedback interference. The fiber optic sensor is also resistant to electrocution, corrosion (e.g., due to chemical solvents, oils, water, etc.), and chemical and mechanical stress. The fiber optic sensor also has a high environmental index and can reduce the load on a structure due to its low weight and compact size. The fiber optic sensor also has the advantage of a long service life (e.g., over 25 years) with an initial verification that covers the entire service life. The fiber optic sensor is also relatively inexpensive and allows for multiplexing, with several sensors in a single fiber line being integrable with a single optical source. The fiber optic sensor can also be operable in a wide range of temperatures (e.g., -400 °C to 850 °C for standard fiber optic sensors and -2700 °C to 7000 °C for special temperature-resistant fiber optic sensors).

Depending on the configuration of the sensing element 204, the fiber optic sensor can function as a microphone that is omnidirectional, unidirectional or cardioid. In one implementation, the directional diagram of the microphone is extremely wide—all 360° in azimuth and up to 170° in the vertical plane. When using, for example, a parabolic sound reflector, the microphone may have a narrow directional pattern—a super-cardioid. The amplitude-frequency characteristic in the entire operating range is flat. The sensitivity of the fiber optic sensor is determined primarily by the area of the optical circuit (e.g., the area of the coil plus the fiber optic light guide winding). In particular, the length of the fiber optic light guide and the diameter of the coil, the material and design of the sensing element 204, the specifications of the laser 210, and the specifications of the photodiode 214 can all be optimized depending on the purpose of use.

Fiber optic sensors such as those described herein can be divided into several main types based on their principle of operation: scattered, interference, and intrafiber array

sensors, scattered sensors, or “distributed fiber sensors.” The principle of the fiber optic sensor’s operation is based on the analysis of the backscatter or forward scattering signal in the fiber. One promising and frequently used method is Brillouin reflectometry. Sensor systems of this type are used to measure temperature and mechanical deformation. Other  
5 fiber optic sensors are based on intrafiber grids. Fiber optic sensors can also be positioned on lattices and be representative of point sensors that, when combined into arrays, form a quasi-distributed system. Some fiber optic sensors operate based on the “Bragg”, or long-period refractive index lattice. Still other fiber optic sensors can be configured to operate as an interference fiber optic system. Fiber optic interferometers are based on the effect of light  
10 interference, when two light signals, interacting with each other, amplify or cancel each other. The effect depends on the phase of the incoming optical signal, which varies with the change in the distance travelled by the light beam, namely with the change in the so-called optical path. In monitoring and diagnostic systems, this method can be particularly effective for recording vibrations, noise (acoustic signal) and acoustic emission pulses. Methods that  
15 use interferometry have many different configurations, such as Mach-Zehnder, Fabry-Perot, Michelson, Sagnac, and ring resonator configurations. Any of these schemes, as well as others known by those skilled in the art, can be used in various implementations of the systems 200A, 200B.

Fiber-optic based microphones, hydrophones (e.g., waterproof microphones), and  
20 vibration sensors such as those described herein have an advantage over existing sensors (e.g., piezoceramic sensors, distributed fiber-optic sensors, sensors based on Bragg grids, etc.) in terms of sensitivity, security and range of measured information, and they have the potential to successfully replace traditional acoustic and vibration signal sensors. These improvements can expand the functionality of monitoring and diagnostic systems for  
25 industrial equipment such as the systems 100, 200A, and 200B shown in FIGS. 1, 2A, and 2B.

Referring now to FIG. 3, a process 300 for monitoring industrial equipment is shown and described. In some implementations, the operations of the process 300 can be executed by monitoring and diagnostic systems such as those described in relation to FIGS. 1, 2A, and  
30 2B (e.g., systems 100, 200A, and 200B).

Operations of the process 300 include capturing, by a sensor, a signal indicative of vibroacoustic vibrations or acoustic noise originating from the industrial equipment (302). For example, the sensor can include a fiber optic sensor including a fiber optic light guide, a light source, and a photodetector. Capturing the signal indicative of the vibroacoustic

vibrations or acoustic noise originating from the industrial equipment can include outputting light from the light source (304); receiving, at a fiber optic light guide, at least a portion of the light outputted by the light source (306); and outputting, via the photodetector, an electrical signal corresponding to the light that is received at the fiber optic light guide (308).

5 The light source can correspond to the laser 210 and the photodetector can correspond to the photodiode 214. The fiber optic light guide can correspond to the fiber optic light guide of the sensing element 204. The electrical signal output by the photodetector can be indicative of the vibracoustic signals in the industrial equipment or acoustic noise originating from the industrial equipment (e.g., the industrial equipment 102, and more specifically, the defect  
10 106).

Operations of the process 300 also include processing an input signal derived from the signal captured by the sensor to identify a condition in the industrial equipment. For example, the condition in the industrial equipment can correspond to a weak point, a plastic deformation, a fracture, a crack, a fistula, a leak, or an abnormal flow in the  
15 industrial equipment.

Additional operations of the process 300 can include converting the signal captured by the sensor into a digital electrical signal (e.g., via the ADC(s) 122). The process 300 can also include (i) processing the input signal derived from the signal captured by the sensor using a Fourier transform or a fast wavelet converter (e.g., using the microcontroller(s) 124),  
20 and (ii) comparing diagnostic indicators derived from the input signal with one or more reference values (e.g., one or more reference values or threshold values stored in the knowledge base 126). In some implementations, the process 300 can also include identifying the condition in the industrial equipment using a machine learning model (e.g., a neural network model included in the decision-making block 128). In some implementations, the  
25 process 300 can also include estimating a location of the condition in the industrial equipment using a machine learning model. In some implementations, the process 300 can also include estimating a remaining service life of the industrial equipment using a machine learning model.

FIG. 4 shows an example of a computing device 400 and a mobile computing device  
30 450 that are employed to execute implementations of the present disclosure. For example, the computing device 400 and/or the mobile computing device 450 can correspond to computing devices such as the microcontroller(s) 124, the server 130, and the computing device 150 described above in relation to FIGS. 1, 2A, and 2B. The computing device 400 and/or the mobile computing device 450 can also be employed to execute one or more steps of the

process 300 including step 310. In some implementations, each of the microcontroller(s) 124, the server 130, and the computing device 150 can include a singular computing device 400 or mobile computing device 450. However, in other implementations, each of the microcontroller(s) 124, the server 130, and the computing device 150 can include multiple computing devices 400 and/or mobile computing devices 450 that jointly perform the operations disclosed above in a distributed manner (e.g., via cloud computing). Moreover, in some implementations, computing tasks performed by the microcontroller(s) 124, the server 130, and the computing device 150 can be redistributed amongst one another without limitation, unless otherwise stated herein.

The computing device 400 is intended to represent various forms of digital computers, such as laptops, desktops, workstations, personal digital assistants, servers, blade servers, mainframes, and other appropriate computers. The mobile computing device 450 is intended to represent various forms of mobile devices, such as personal digital assistants, cellular telephones, smart-phones, AR devices, and other similar computing devices. The components shown here, their connections and relationships, and their functions, are meant to be examples only, and are not meant to be limiting.

The computing device 400 includes a processor 402, a memory 404, a storage device 406, a high-speed interface 408, and a low-speed interface 412. In some implementations, the high-speed interface 408 connects to the memory 404 and multiple high-speed expansion ports 410. In some implementations, the low-speed interface 412 connects to a low-speed expansion port 414 and the storage device 406. Each of the processor 402, the memory 404, the storage device 406, the high-speed interface 408, the high-speed expansion ports 410, and the low-speed interface 412, are interconnected using various buses, and may be mounted on a common motherboard or in other manners as appropriate. The processor 402 can process instructions for execution within the computing device 400, including instructions stored in the memory 404 and/or on the storage device 406 to display graphical information for a graphical user interface (GUI) on an external input/output device, such as a display 416 coupled to the high-speed interface 408. In other implementations, multiple processors and/or multiple buses may be used, as appropriate, along with multiple memories and types of memory. In addition, multiple computing devices may be connected, with each device providing portions of the necessary operations (e.g., as a server bank, a group of blade servers, or a multi-processor system).

The memory 404 stores information within the computing device 400. In some implementations, the memory 404 is a volatile memory unit or units. In some

implementations, the memory 404 is a non-volatile memory unit or units. The memory 404 may also be another form of a computer-readable medium, such as a magnetic or optical disk.

The storage device 406 is capable of providing mass storage for the computing device 400. In some implementations, the storage device 406 may be or include a computer-readable  
5 medium, such as a floppy disk device, a hard disk device, an optical disk device, a tape device, a flash memory, or other similar solid-state memory device, or an array of devices, including devices in a storage area network or other configurations. Instructions can be stored in an information carrier. The instructions, when executed by one or more processing devices, such as processor 402, perform one or more methods, such as those described above. The  
10 instructions can also be stored by one or more storage devices, such as computer-readable or machine-readable mediums, such as the memory 404, the storage device 406, or memory on the processor 402.

The high-speed interface 408 manages bandwidth-intensive operations for the computing device 400, while the low-speed interface 412 manages lower bandwidth-  
15 intensive operations. Such allocation of functions is an example only. In some implementations, the high-speed interface 408 is coupled to the memory 404, the display 416 (e.g., through a graphics processor or accelerator), and to the high-speed expansion ports 410, which may accept various expansion cards. In the implementation, the low-speed interface 412 is coupled to the storage device 406 and the low-speed expansion port 414. The low-  
20 speed expansion port 414, which may include various communication ports (e.g., Universal Serial Bus (USB), Bluetooth, Ethernet, wireless Ethernet) may be coupled to one or more input/output devices. Such input/output devices may include a scanner, a printing device, or a keyboard or mouse. The input/output devices may also be coupled to the low-speed expansion port 414 through a network adapter. Such network input/output devices may  
25 include, for example, a switch or router.

The computing device 400 may be implemented in a number of different forms, as shown in FIG. 4. For example, it may be implemented as a standard server 420, or multiple times in a group of such servers. In addition, it may be implemented in a personal computer such as a laptop computer 422. It may also be implemented as part of a rack server system  
30 424. Alternatively, components from the computing device 400 may be combined with other components in a mobile device, such as a mobile computing device 450. Each of such devices may contain one or more of the computing device 400 and the mobile computing device 450, and an entire system may be made up of multiple computing devices communicating with each other.

The mobile computing device 450 includes a processor 452; a memory 464; an input/output device, such as a display 454; a communication interface 466; and a transceiver 468; among other components. The mobile computing device 450 may also be provided with a storage device, such as a micro-drive or other device, to provide additional storage. Each of  
5 the processor 452, the memory 464, the display 454, the communication interface 466, and the transceiver 468, are interconnected using various buses, and several of the components may be mounted on a common motherboard or in other manners as appropriate. In some implementations, the mobile computing device 450 may include a camera device(s).

The processor 452 can execute instructions within the mobile computing device 450,  
10 including instructions stored in the memory 464. The processor 452 may be implemented as a chipset of chips that include separate and multiple analog and digital processors. For example, the processor 452 may be a Complex Instruction Set Computers (CISC) processor, a Reduced Instruction Set Computer (RISC) processor, or a Minimal Instruction Set Computer (MISC) processor. The processor 452 may provide, for example, for coordination  
15 of the other components of the mobile computing device 450, such as control of user interfaces (UIs), applications run by the mobile computing device 450, and/or wireless communication by the mobile computing device 450.

The processor 452 may communicate with a user through a control interface 458 and a display interface 456 coupled to the display 454. The display 454 may be, for example, a  
20 Thin-Film-Transistor Liquid Crystal Display (TFT) display, an Organic Light Emitting Diode (OLED) display, or other appropriate display technology. The display interface 456 may include appropriate circuitry for driving the display 454 to present graphical and other information to a user. The control interface 458 may receive commands from a user and convert them for submission to the processor 452. In addition, an external interface 462 may  
25 provide communication with the processor 452, so as to enable near area communication of the mobile computing device 450 with other devices. The external interface 462 may provide, for example, for wired communication in some implementations, or for wireless communication in other implementations, and multiple interfaces may also be used.

The memory 464 stores information within the mobile computing device 450. The  
30 memory 464 can be implemented as one or more of a computer-readable medium or media, a volatile memory unit or units, or a non-volatile memory unit or units. An expansion memory 474 may also be provided and connected to the mobile computing device 450 through an expansion interface 472, which may include, for example, a Single in Line Memory Module (SIMM) card interface. The expansion memory 474 may provide extra storage space for the

mobile computing device 450, or may also store applications or other information for the mobile computing device 450. Specifically, the expansion memory 474 may include instructions to carry out or supplement the processes described above, and may include secure information also. Thus, for example, the expansion memory 474 may be provided as a security module for the mobile computing device 450, and may be programmed with instructions that permit secure use of the mobile computing device 450. In addition, secure applications may be provided via the SIMM cards, along with additional information, such as placing identifying information on the SIMM card in a non-hackable manner.

The memory may include, for example, flash memory and/or non-volatile random access memory (NVRAM), as discussed below. In some implementations, instructions are stored in an information carrier. The instructions, when executed by one or more processing devices, such as processor 452, perform one or more methods, such as those described above. The instructions can also be stored by one or more storage devices, such as one or more computer-readable or machine-readable mediums, such as the memory 464, the expansion memory 474, or memory on the processor 452. In some implementations, the instructions can be received in a propagated signal, such as, over the transceiver 468 or the external interface 462.

The mobile computing device 450 may communicate wirelessly through the communication interface 466, which may include digital signal processing circuitry where necessary. The communication interface 466 may provide for communications under various modes or protocols, such as Global System for Mobile communications (GSM) voice calls, Short Message Service (SMS), Enhanced Messaging Service (EMS), Multimedia Messaging Service (MMS) messaging, code division multiple access (CDMA), time division multiple access (TDMA), Personal Digital Cellular (PDC), Wideband Code Division Multiple Access (WCDMA), CDMA2000, General Packet Radio Service (GPRS). Such communication may occur, for example, through the transceiver 468 using a radio frequency. In addition, short-range communication, such as using a Bluetooth or Wi-Fi, may occur. In addition, a Global Positioning System (GPS) receiver module 470 may provide additional navigation- and location-related wireless data to the mobile computing device 450, which may be used as appropriate by applications running on the mobile computing device 450.

The mobile computing device 450 may also communicate audibly using an audio codec 460, which may receive spoken information from a user and convert it to usable digital information. The audio codec 460 may likewise generate audible sound for a user, such as through a speaker, e.g., in a handset of the mobile computing device 450. Such sound may

include sound from voice telephone calls, may include recorded sound (e.g., voice messages, music files, etc.) and may also include sound generated by applications operating on the mobile computing device 450.

The mobile computing device 450 may be implemented in a number of different forms, as shown in FIG. 4. For example, it may be implemented a phone device 480, a personal digital assistant 482, and a tablet device (not shown). The mobile computing device 450 may also be implemented as a component of a smart-phone, AR device, or other similar mobile device.

Computing device 400 and/or 450 can also include USB flash drives. The USB flash drives may store operating systems and other applications. The USB flash drives can include input/output components, such as a wireless transmitter or USB connector that may be inserted into a USB port of another computing device.

Referring now to FIGS. 5-13, various applications are shown for the use of fiber optic sensors to monitor/diagnose industrial equipment in accordance with the techniques described in this document.

FIG. 5 shows a fiber optic sensor including a sensing element 504 and an electronic control unit 508. These elements can correspond, respectively, the sensing element 204 and the electronic control unit 208 shown and described with respect to FIGS. 2A-2B. As shown in FIG. 5, in a first implementation, the sensing element 504 can be installed on a surface of a wind turbine 502 and the electronic control unit 508 can be disposed at a distance from the operator of the wind turbine (e.g., a human operator). In this implementation, the fiber optic sensor records vibroacoustic signals and acoustic emission pulses, which can be analyzed by the monitoring and diagnosis systems described in this document to identify trends in parameter changes and identify/predict the occurrence of undesirable events. In a second implementation, the sensing element can be installed nearby (but not on) the wind turbine 502, and the electronic control unit 508 can be disposed nearby but at a distance from the operator of the wind turbine (e.g., a human operator). In this implementation, the sensor can record noise from the wind turbine and the surroundings, which can be analyzed by the monitoring and diagnosis systems described in this document to identify trends in parameter changes and identify/predict the occurrence of undesirable events.

FIG. 6 shows a fiber optic sensor including a sensing element 604 and an electronic control unit 608. These elements can correspond, respectively, the sensing element 204 and the electronic control unit 208 shown and described with respect to FIGS. 2A-2B. As shown in FIG. 6, the sensing element 504 can be installed on the surface of an object such as an

infrastructure facility 602 (e.g., on a wall, foundation, etc.) and the electronic control unit 508 can be disposed at a distance from the operator. In other implementations, at least one of the sensing element 604 or the electronic control unit 608 can alternatively be disposed in the ground. Examples of infrastructure facilities 602 include buildings, structures, tunnels, railway tracks, etc. The fiber optic sensor records vibroacoustic signals and acoustic emission pulses, which can be analyzed by the monitoring and diagnosis systems described in this document to identify trends in parameter changes and identify/predict the occurrence of undesirable events.

FIG. 7 shows a multiplexed fiber optic sensor system including multiple sensing elements 704 and electronic control units 708. These elements can correspond, respectively, the sensing element 204 and the electronic control unit 208 shown and described with respect to FIGS. 2A-2B. The system prepares the collection of parameters of vibroacoustic signals and/or noise, the accumulation and operational analysis of this information, the construction of trends in parameter changes and the prediction of the occurrence of undesirable events. For example, monitoring and diagnosis systems applied to the oil and gas processing industry or chemical industries can be used to monitor equipment (e.g., pumps, compressors, valves, tanks, etc.), operate complex complexes (e.g., main and collector oil and gas pipelines, and pipe racks) monitor wells, detect leaks in pipelines, perform scraper tracking, etc. As shown in FIG. 7, one or more of the sensing elements 704 (such as a fiber optic reel) can be installed on the body of infrastructure or equipment (e.g. oil and gas processing infrastructure or equipment such as the pipeline 702). The corresponding electronic unit(s) 708 can be disposed at a distance from the operator, and a vibroacoustic signal and acoustic emission pulses are recorded. One or more other sensing elements 704 (e.g., uncoated cables or fibers) can be would around the pipeline 702. The corresponding electronic unit(s) 708 can be disposed at a distance from the operator, and a vibroacoustic signal and acoustic emission pulses are recorded. One or more other sensing element 704 can be installed nearby (but not in direct contact with) the monitored equipment (e.g., equipment 701). The corresponding electronic unit(s) 708 can be disposed at a distance from the operator, and in this instance, noise measurements can be recorded.

FIG. 8 shows a multiplexed fiber optic sensor system including multiple sensing elements 804 and electronic control units 808. These elements can correspond, respectively, the sensing element 204 and the electronic control unit 208 shown and described with respect to FIGS. 2A-2B. The system prepares the collection of parameters of vibroacoustic signals and/or noise, the accumulation and operational analysis of this information, the construction

of trends in parameter changes and the prediction of the occurrence of undesirable events. As shown in FIG. 8, one or more of the sensing elements 804 can be installed on an oil overflow unit 801. The corresponding electronic unit(s) 808 can be disposed at a distance from the operator, and a vibroacoustic signal and acoustic emission pulses are recorded. One or more other sensing elements 804 (e.g., uncoated cables or fibers) can be wound around a pipeline 802 of a pumping unit of the oil overflow system. The corresponding electronic unit(s) 808 can be disposed the operator, and a vibroacoustic signal and acoustic emission pulses are recorded. One or more other sensing elements 804 can be installed nearby a pumping unit. The corresponding electronic unit(s) 808 can be disposed at a distance from the operator, and in this instance, noise measurements can be recorded.

FIG. 9 shows a fiber optic sensor including a sensing element 904 and an electronic control unit 908. These elements can correspond, respectively, the sensing element 204 and the electronic control unit 208 shown and described with respect to FIGS. 2A-2B. As shown in FIG. 9, the sensing element 904 can be installed onboard a moving vehicle such as an aircraft 902, and the electronic control unit 908 can be disposed at a distance from the operator (also onboard the aircraft 902). The fiber optic sensor records vibroacoustic signals and acoustic emission pulses which can be analyzed by the monitoring and diagnosis systems described in this document to identify trends in parameter changes and identify/predict the occurrence of undesirable events.

FIG. 10 shows a fiber optic sensor including a sensing element 1004 and an electronic control unit 1008. These elements can correspond, respectively, the sensing element 204 and the electronic control unit 208 shown and described with respect to FIGS. 2A-2B. As shown in FIG. 10, the sensing element 1004 can be installed around (but not in direct contact with) a standing apparatus such as the grounded aircraft 1002, and the electronic control unit 1008 can be disposed at a distance from the operator (also around the standing apparatus). The fiber optic sensor records noise measurements, which can be analyzed by the monitoring and diagnosis systems described in this document to identify trends in parameter changes and identify/predict the occurrence of undesirable events.

FIG. 11 shows multiple fiber optic sensors, each including a sensing element 1104 and an electronic control unit 1108. These elements can correspond, respectively, the sensing element 204 and the electronic control unit 208 shown and described with respect to FIGS. 2A-2B. The system prepares the collection of parameters of vibroacoustic signals and/or noise, the accumulation and operational analysis of this information, the construction of trends in parameter changes and the prediction of the occurrence of undesirable events. As

shown in FIG. 11, one or more of the sensing elements 1104 can be installed on the surface of monitored pieces of general industrial equipment 1102. The corresponding electronic unit(s) 1108 can be disposed at a distance from the operator, and a vibroacoustic signal and acoustic emission pulses are recorded. One or more other sensing elements 804 can be installed  
5 nearby (but not in direct contact with) the monitored pieces of general industrial equipment 1102. The corresponding electronic unit(s) 1108 can be disposed at a distance from the operator, and in this instance, noise measurements can be recorded.

FIG. 12 shows multiple fiber optic sensors, each including a sensing element 1204 and an electronic control unit 1208. These elements can correspond, respectively, the sensing  
10 element 204 and the electronic control unit 208 shown and described with respect to FIGS. 2A-2B. The sensors prepare the collection of parameters of vibroacoustic signals and/or noise, the accumulation and operational analysis of this information, the construction of trends in parameter changes and the prediction of the occurrence of undesirable events. As shown in FIG. 12, one or more of the sensing elements 1204 can be installed onboard a  
15 moving vehicle, on the surface of a monitored object such as the floating facility/ship 1201. The corresponding electronic unit(s) 1208 can be disposed at a distance from the operator, and a vibroacoustic signal, acoustic emission pulses, and noise are recorded. One or more other sensing elements 1204 can be installed nearby (but not in direct contact with) a monitored piece of equipment such as the engine 1202. The corresponding electronic unit(s)  
20 1208 can be disposed at a distance from the operator, and in this instance, noise measurements can be recorded.

FIG. 13 shows a fiber optic sensor including a sensing element 1304 and an electronic control unit 1308. These elements can correspond, respectively, the sensing element 204 and the electronic control unit 208 shown and described with respect to FIGS. 2A-2B. As shown  
25 in FIG. 13, in a first implementation, the sensing element 1304 can be installed onboard a moving transportation vehicle such as the train 1302, and the electronic control unit 508 can be disposed at a distance from the operator. In this implementation, the fiber optic sensor records vibroacoustic signals and acoustic emission pulses, which can be analyzed by the monitoring and diagnosis systems described in this document to identify trends in parameter  
30 changes and identify/predict the occurrence of undesirable events. In a second implementation, the sensing element can be installed nearby (but not on) the train 1302, and the electronic control unit 508 can be disposed at a distance from the operator. In this implementation, the sensor can record noise from the train 1302 and the surroundings, which can be analyzed by the monitoring and diagnosis systems described in this document to

identify trends in parameter changes and identify/predict the occurrence of undesirable events.

#### OTHER EMBODIMENTS

Other embodiments and applications not specifically described herein are also within  
5 the scope of the following claims. Elements of different implementations described herein  
may be combined to form other embodiments not specifically set forth above. Elements may  
be left out of the structures described herein without adversely affecting their operation.  
Furthermore, various separate elements may be combined into one or more individual  
elements to perform the functions described herein. The following are numbered  
10 embodiments intended to further illustrate, but not limit, the scope of the invention.

1. A system for monitoring and diagnosing industrial equipment based on the  
analysis of vibroacoustic signals and noise, the system comprising:

a data acquisition unit comprising at least one fiber-optic sensor (FOS)  
15 connected (i) via one or more daisy-chained microcontrollers and ADCs to a  
computer with flash memory, and (ii) via a wireless, mobile network, satellite,  
Bluetooth, and/or wired cable communication device to one or more servers (e.g., one  
or more cloud servers);

a model unit that simulates the industrial equipment; and  
20 an analysis unit that analyzes a state of the industrial equipment based on data  
received from the data acquisition unit and the model(s) of the industrial equipment  
(e.g., issuing a conclusion on the normal or abnormal functioning of the industrial  
equipment based on the analysis).

25 2. The system of embodiment 1, wherein the FOS comprises a sensing element and  
an electronic unit connected by a single-mode fiber-optic cable with a length of up to 100 km  
without an amplifier.

3. The system of embodiment 2, wherein the sensing element comprises a multi-turn  
30 loop (e.g., a coil) made of a single-mode optical fiber.

4. The system of embodiment 2, wherein the sensing element may be framed or  
frameless. (The control object itself can act as a frame, onto which the fiber optic cable or

uncoated fiber is wound (for example, fiber optic cable or fiber optic is wound onto oil and gas pipelines and other pipes)).

5        5. The system of embodiment 3, wherein the optical fiber of the sensing element may be coated or uncoated.

10        6. The system of embodiment 1, wherein the FOS operates according to the scheme of Mach-Zehnder, Fabry-Perot, Sagnac, Michelson phase interferometers or a combination thereof.

7. The system of embodiment 2, wherein the electronic unit comprises photodiodes, splitters, polarizers, modulators, lasers (e.g., laser diodes or super-luminescent lasers), and/or other elements.

15        8. The system of embodiment 2, wherein a sensitivity of the FOS depends on a wavelength and a power of an associated light source (e.g., a laser), a shape and area of the sensing element, a length of the fiber-optic cable, and a length of the fiber optic in the circuit.

20        9. The system of embodiment 2, wherein the sensing element can be in the air, in water, in the ground, in concrete, on the ground, on equipment and in aggressive environments;

wherein the sensing element registers vibroacoustic signals while being on the equipment, on the ground, in the ground, in concrete, or in water; and

25        wherein the sensing element registers noise while being in air.

30        10. The system of embodiment 1, wherein the analysis unit operates as a cloud service using Fourier transforms, Wavelett transforms, Hilbert transforms, other digital signal processing techniques, machine learning approaches (e.g., neural networks), fuzzy logic algorithms, and/or other methods.

11. The system of embodiment 1, wherein at least one of the data acquisition unit or the analysis unit is integrated with one or more production asset management systems (e.g., computerized maintenance management systems (CMMS), manufacturing execution systems (MES), enterprise resource planning (ERP) systems, etc.).

12. The system of embodiment 1, wherein the analysis unit utilizes a mathematical modelling approach in which a “digital twin” of the industrial equipment is parameterized by real data.

5

13. The system of embodiment 1, wherein the condition prediction of the equipment is based on an in-depth analysis of the current state of the equipment, which is possible by combining the acquired vibroacoustic signals and noise measurement data with a virtual model of the equipment (also referred to as a “digital twin”).

10

14. A method for monitoring and diagnostic of industrial equipment based on the analysis of vibroacoustic signals and noise, containing the stages:

- Receive vibroacoustic signals or noise from industrial equipment by means of at least one FOS

15

- Signals are digitized by the ADC and sent in digitized form to a computer for pre-processing

- Processed signals are sent to the cloud service for further analysis.

**WHAT IS CLAIMED IS:**

1. A system for monitoring industrial equipment, the system comprising:  
a sensor configured to capture a signal indicative of vibroacoustic vibrations or  
5 acoustic noise originating from the industrial equipment; and  
one or more computing devices comprising one or more processors, the one or more  
processors configured to process an input signal derived from the signal captured by the  
sensor to identify a condition in the industrial equipment.
- 10 2. The system of claim 1, wherein the sensor comprises a fiber optic sensor  
comprising a fiber optic light guide, a light source, and a photodetector.
3. The system of claim 2, wherein the light source is a laser.
- 15 4. The system of claim 2, wherein the photodetector is a photodiode.
5. The system of claim 2, wherein (i) the light source is configured to output  
light that is received, at least in part, at the fiber optic light guide, and (ii) the photodetector is  
configured to output an electrical signal corresponding to the light that is received at the fiber  
20 optic light guide.
6. The system of claim 5, wherein the electrical signal output by the  
photodetector is indicative of the acoustic noise originating from the industrial equipment.
- 25 7. The system of claim 2, wherein the fiber optic sensor further comprises a pre-  
amplifier configured to amplify the electrical signal output by the photodetector.
8. The system of claim 1, wherein the sensor is disposed at a distance from the  
industrial equipment.
- 30 9. The system of claim 1, further comprising a converter configured to convert  
the signal captured by the sensor into a digital electrical signal.

10. The system of claim 1, wherein the one or more processors are configured to (i) process the input signal derived from the signal captured by the sensor using a Fourier transform or a fast wavelet converter, and (ii) compare diagnostic indicators derived from the input signal with one or more reference values.

5

11. The system of claim 10, wherein the one or more processors are further configured to identify the condition in the industrial equipment using a machine learning model.

10

12. The system of claim 11, wherein the identified condition in the industrial equipment is a weak point, a plastic deformation, a fracture, a crack, a fistula, a leak, or an abnormal flow in the industrial equipment.

15

13. The system of claim 10, wherein the one or more processors are further configured to estimate a location of the condition in the industrial equipment using a machine learning model.

20

14. The system of claim 10, wherein the one or more processors are further configured to estimate a remaining service life of the industrial equipment using a machine learning model.

25

15. The system of claim 1, wherein the industrial equipment comprises at least one of a pipeline, a tank, a valve, a seal, a pipe connection, a gland assembly, a gas separator, a filter, a pump, or a compressor.

16. The system of claim 1, wherein the industrial equipment is composed, at least in part, from fiberglass and/or glass fiber.

30

17. The system of claim 1, comprising a display in communication with the one or more processors, the display configured to present information about the identified condition.

18. A method for monitoring industrial equipment, the method comprising:  
capturing, by a sensor, a signal indicative of vibroacoustic vibrations or acoustic noise originating from the industrial equipment; and

processing an input signal derived from the signal captured by the sensor to identify a condition in the industrial equipment.

19. The method of claim 18, wherein the sensor comprises a fiber optic sensor  
5 comprising a fiber optic light guide, a light source, and a photodetector.

20. The method of claim 19, wherein capturing the signal indicative of the  
acoustic noise originating from the industrial equipment comprises:  
outputting light from the light source;  
10 receiving, at the fiber optic light guide, at least a portion of the light outputted by the  
light source; and  
outputting, via the photodetector, an electrical signal corresponding to the light that is  
received at the fiber optic light guide.

21. The method of claim 20, wherein the electrical signal output by the  
15 photodetector is indicative of the acoustic noise originating from the industrial equipment.

22. The method of claim 18, comprising converting the signal captured by the  
sensor into a digital electrical signal.

20 23. The method of claim 18, comprising (i) processing the input signal derived  
from the signal captured by the sensor using a Fourier transform or a fast wavelet converter,  
and (ii) comparing diagnostic indicators derived from the input signal with one or more  
reference values.

25 24. The method of claim 23, comprising identifying the condition in the industrial  
equipment using a machine learning model.

25. The method of claim 23, comprising estimating a location of the condition in  
30 the industrial equipment using a machine learning model.

26. The method of claim 23, comprising estimating a remaining service life of the  
industrial equipment using a machine learning model.

27. An industrial equipment monitoring system comprising:  
a sensor configured to capture signals indicating vibroacoustic vibrations in the industrial equipment or acoustic noise emanating from the industrial equipment; and  
one or more computing devices comprising one or more processors, the one or more  
5 processors configured to process an input signal received from the signals captured by the sensor to identify a status of the industrial equipment.

28. The system of claim 27, wherein the sensor contains a fiber optic sensing element containing a fiber optic light guide and an electronic unit containing a light source  
10 and a photodetector.

29. The system of claim 28, wherein the light source is a laser.

30. The system of claim 28, wherein the photodetector is a photodiode.  
15

31. The system of claim 28, wherein (i) the light source is configured to output light that is received at least in part on the fiber optic sensing element and (ii) the photodetector is configured to output an electrical signal corresponding to the light received on the fiber optic sensing element.  
20

32. The system of claim 31, wherein the electrical signal emitted by the photodetector indicates the vibroacoustic vibrations in the industrial equipment or the acoustic noise emanating from the industrial equipment.

25 33. The system of claim 28, wherein the sensor further comprises a preamplifier configured to amplify the electrical signal emitted by the photodetector.

34. The system of claim 27, wherein the sensor for recording the vibroacoustic vibrations is located on the surface of the equipment, and for recording the acoustic noise is  
30 located at a distance from the industrial equipment.

35. The system of claim 27, further comprising a transducer configured to convert the signal captured by the sensor into a digital electrical signal.

36. The system of claim 28, wherein the sensing element and the electronic unit are connected by a single-mode fiber optic cable with a length of up to 100 km without an amplifier.

5 37. The system of claim 28, wherein the sensing element is a multi-turn loop (e.g., a coil) made of single-mode optical fiber

38. The system of claim 37, wherein the sensing element may be framed or frameless.

10

39. The system of claim 37, wherein the optical fiber in the sensing element may be coated or uncoated.

40. The system of claim 28, wherein the sensor operates according to at least one of a Mach-Zehnder scheme, Fabry-Perot scheme, Sagnac scheme, Michelson phase interferometer scheme or a combination thereof.

15

41. The system of claim 28, wherein the electronic unit may comprise photodiodes, splitters, polarizers, modulators, lasers (e.g., semiconductor diode or superluminescent laser), and other components.

20

42. The system of claim 28, wherein a sensitivity of the sensor depends on a wavelength and power of the light source, a shape and area of the sensing element, and a length of the optical fiber in the circuit.

25

43. The system of claim 28, wherein the sensing element may be in air, in water, in the ground, in concrete, on the ground, on the industrial equipment, and/or in aggressive environments,

wherein while the sensing element is on the equipment, on the ground, in the ground, or in concrete, the sensor registers vibroacoustic vibrations, and

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wherein while the sensing element is in the air the sensor registers acoustic noise.

44. The system of claim 27 wherein the one or more processors are configured to (i) process the input signal obtained from the signals captured by the sensor using a Fourier

transform or fast wavelet transducer, and (ii) compare diagnostic values obtained from the input signal with one or more reference values.

45. The system of claim 44, wherein the one or more processors are further  
5 configured to identify the status of the industrial equipment using a machine learning model.

46. The system of claim 45, wherein the identified status of the industrial  
equipment comprises an identified condition including a weak point, plastic deformation,  
fracture, fracture, crack, fistula, leakage or abnormal flow in the industrial equipment.  
10

47. The system of claim 44 wherein the one or more processors are further  
configured to estimate a location a condition in the industrial equipment using a machine  
learning model.

48. The system of claim 44, wherein the one or more processors are further  
15 configured to estimate a remaining useful life of the industrial equipment using a machine  
learning model.

49. The system of claim 27, wherein the industrial equipment comprises at least  
20 one of a pipeline, a tank, a valve, a seal, a pipe connection, a gland assembly, a gas separator,  
a filter, a pump, or a compressor.

50. The system of claim 27, wherein the industrial equipment is composed at least  
in part of glass fiber and/or glass fiber.  
25

51. The system of claim 27, comprising a display interacting with the one or more  
processors to display information about the identified status of the industrial equipment.

52. A method for monitoring industrial equipment, including:  
30 capturing a signal indicating vibroacoustic vibrations in the industrial equipment or  
acoustic noise emanating from the industrial equipment using a sensor; and  
processing an input signal received from the signal captured by the sensor to  
determine a status of the industrial equipment.

53. The method of claim 52, wherein the sensor comprises a fiber optic sensing element comprising a fiber optic light guide and an electronic unit comprising a light source and a photodetector.

5 54. The method of claim 52, wherein the sensor contains a sensing element and an electronic unit, are connected by a single-mode fiber-optic cable up to 100 km long without an amplifier.

55. The method of claim 54, wherein the sensing element is a multi-turn loop  
10 (e.g., coil) made of single-mode optical fiber.

56. The method of claim 54, wherein the sensing element can be framed and frameless.

15 57. The method of claim 54, wherein the optical fiber in the sensing element can be coated or uncoated.

58. The method of claim 52, wherein the sensor operates according to at least one of a Mach-Zehnder scheme, Fabry-Perot scheme, Sagnac scheme, Michelson phase  
20 interferometer scheme, or a combination thereof.

59. The method of claim 53, wherein the electronic unit may comprise photodiodes, splitters, polarizers, modulators, lasers (semiconductor diode or superluminescent laser), and other elements.

25

60. The method of claim 53, wherein a sensitivity of the sensor depends on a wavelength and power of the light source, a shape and area of the sensing element, and a length of the optical fiber in the circuit.

30 61. The method of claim 53, wherein the sensing element can be in air, in water, in the ground, in concrete, on the ground, on the industrial equipment, and/or in aggressive environments,

wherein while the sensing element is on the industrial equipment, on the ground, in the ground, or in concrete, the sensor registers vibroacoustic vibrations, and

wherein while the sensing element is in the air, the sensor registers acoustic noise.

62. The method of claim 53, wherein capturing the signal indicating vibroacoustic vibrations in the industrial equipment or the acoustic noise emanating from the industrial equipment comprises:

5 outputting light from the light source;  
receiving on the fiber optic sensing element at least one part of the light outputted by the light source; and  
outputting through the photodetector an electrical signal corresponding to the light  
10 received on the fiber optic sensing element.

63. The method of claim 62, wherein the electrical signal outputted by the photodetector is indicative of the vibroacoustic vibrations in the industrial equipment or the acoustic noise emanating from the industrial equipment.

15

64. The method of claim 52, comprising converting the signal captured by the sensor into a digital electrical signal.

65. The method of claim 52, comprising (i) processing the input signal received from the signal captured by the sensor using a Fourier transform or fast wavelet transducer, and (ii) comparing diagnostic parameters obtained from the input signal with one or more reference values.

20

66. The method of claim 52, wherein processing the input signal received from the signal captured by the sensor to determine the status of the industrial equipment comprises identifying a condition in the industrial equipment using a machine learning model.

25

67. The method of claim 52, wherein processing the input signal received from the signal captured by the sensor to determine the status of the industrial equipment comprises estimating a location of a condition in the industrial equipment using a machine learning model.

30

68. The method of claim 52, wherein processing the input signal received from the signal captured by the sensor to determine the status of the industrial equipment comprises estimating a residual life of the industrial equipment using a machine learning model.